ArcticNet ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ

Impacts of Environmental Change in the Canadian Coastal Arctic

A Compendium of Research Conducted during ArcticNet Phase I (2004-2008)

VOLUME 2

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Reinhard Pienitz, Mickaël Lemay, Josée Michaud, Katie Blasco and Julie Veillette.

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

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

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

ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐃᓂᖃᖅᑎᑕᐅᔪᖅ ᓚᕚ, ᑰᐸᐃᒃ ᓯᑎ, ᑲᓇᑕ

ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐱᑕᖃᕈᓐᓇᖅᑎᑕᐅᔪᖅ ᑳᒃᑯᓐᓇᖓᑦ ᑮᓇᐅᔭᒃᓴᖃᖅᑎᑕᐅᓪᓗᓂ ᑐᑭᓯᒐᓱᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᑐᑭᓯᓐᓂᐊᖃᑎᒌᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ, ᑲᑐᑎᔭᐅᓪᓗᓂ ᐱᓕᕆᐊᕆᔭᐅᔪᖅ ᑳᒃᑯᓐᓇᖓᑦ ᓄᓇᒥᐅᑕᓂᒃ ᖃᐅᔨᓴᐃᓪᒪᕆᑦ ᐊᒻᒪᓗ ᐃᑯᒪᓕᕆᓂᖏ ᖃᐅᔨᓴᖅᑎᑦ ᑲᑎᒪᔨᖏᑦ, ᑲᓇᑕᒥ ᐃᓕᓐᓂᐊᕐᕕᒃ ᐃᓗᓯᓕᕆᓂᖏ ᖃᐅᔨᓴᐃᓂᖅ, ᐃᓅᓯᒥ ᖃᐅᔨᓴᐃᓂᓪᒪᕆᒃ ᐊᒻᒪᓗ ᐃᓅᔾᔪᑎᕆᔪᓐᓇᖅᑕᑦᑎᓐᓄᑦ ᖃᐅᔨᓴᐃᓂᖅ ᑲᑎᒪᔨᖏᑦ, ᐊᒻᒪᓗ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ.

ᐅᑯᐊ ᐱᑐᒃᓯᒪᕖᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ ᐊᔾᔨᐅᓐᖏᑑᔪᒥᒃ ᐱᓇᓱᐊᖃᑎᒋᔭᖕᒑᑦ ᐊᕙᑖᓂᑦ ᐃᓕᓐᓂᐊᕐᕕᒃᔪᐊᓂ, ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ, ᒐᕙᒪᒃᑯᑦ ᐊᒻᒪᓗ ᑮᓇᐅᔭᓕᐅᕈᓯᐊᖃᑎᒃ ᐊᐅᓚᑦᓯᔨᐅᔪᑦ ᑐᕌᖅᑐᑦ ᑐᓄᑎᒍᓐᓇᖅᓗᒍ ᑲᓇᑕᒥᐅᑦ ᖃᐅᔨᓴᖅᓯᓐᖓᑦ ᐊᒻᒪ ᓇᕐᒥᓂᖅᑐᓕᕆᓂᖅ ᐱᓕᕆᐊᓐᓇᑦᓯᐊᖅᑐᑦ ᑕᒪᑐᒨᖓ ᒪᑭᑕᓇᓱᐊᕐᓂᕐᒧᑦ ᐊᒻᒪᓗ ᐃᓅᓯᕐᒥ ᐃᑲᔪᑎᓂᐊᖅᑐᓄᑦ ᑕᒪᐃᓐᓄᑦ ᑲᓇᑕᒥᐅᓄᑦ. ᑕᐃᒪᓗ ᐃᓗᓪᓕᕆᓗᐋᖅᑕᖓ ᐃᓚᖓ ᒐᕙᒪᒃᑯᑦ ᓄᑖᓂᒃ ᐱᕆᐊᓪᓚᕈᑎᓕᕆᓂᖅ ᐋᕿᒃᓯᒪᐅᑎᖏᑦ, ᐅᑯᐊ ᑲᓇᑕᑦᓕᒫᑦ, ᐊᒥᓱᑦ ᐃᓂᖅᑎᕆᓐᓇᖅᑐᑦ ᐊᒻᒪᓗ ᐊᒥᓱᑦ ᖃᓄᐃᓐᓇᖅᑐᑦ ᑲᑎᖓᔪᑦ ᐱᐅᓂᖅᓵᖑᔪᒥᒃ ᖃᐅᔨᓴᐃᓂᕐᒥᒃ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑕᐅᓕᕈᓐᓇᖅᑐᓂᒃ ᐊᒻᒪᓗ ᐋᕿᒃᓯᒪᐅᑎᖏᑦ ᖃᑭᒐᓱᐊᕈᑎᕆᔪᓐᓇᖅᑐᓂᒃ.

ᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᑦ ᐱᑐᒃᓯᒪᖃᑎᒋᔭᖕᖏᑦ ᒃᑯᓐᓇᖓᑦ ᑐᑭᓯᒐᓱᐊᖃᑎᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᐱᐅᑦ ᑲᓇᑕᒥ ᑎᒥᖑᖅᑎᑕᐅᓯᒪᓕᑦ ᓇᐅᔭᓕᐅᖅᑎᐅᓚᓕᐊᖃᑎᒃ ᑯᐊᐳᓴᓐ ᐊᑯᑦ ᐊᑎᖅᑲᖅᓗᑎᒃ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ 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.

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Foreword

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

Martin Fortier, Executive Director of ArcticNet

ᐊᒃᑐᖅᑕᐅᓂᖓᓄᑦ ᓯᓚᑎᑦᑎᓂᑦ ᐊᓯᑦᔨᖅᑐᓂᑦ ᑲᓇᑕᒥᐅᑦ ᓯᒻᔭᖏᓐᓂ ᐅᑭᐅᖅᑕᖅᑐᒥ

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ᐱᒋᐊᕐᓂᖓ

ᐅᓇ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓄᓇᖓ ᓄᓇᕐᔪᐊᒥ ᐊᒃᑐᖅᑕᐅᖅᑳᕐᓂᐊᖅᑐᖅ ᐊᒻᒪᓗ ᐊᖏᓛᖑᔪᒥᒃ ᓱᑯᑕᐅᓗᓂ
ᑕᒪᑐᒪᖓᑦ ᓂᒋᐊᓂᒐᖅᑐᓂᑦ ᐅᖅᑰᓯᕙᓪᓕᐊᓂᖓᓄᑦ ᓄᓇᕐᔪᐊᑦ. ᐅᓄᖅᑐᑦ ᑕᒻᔭᐅᓕᖅᑐᑦ ᖃᐅᔨᑎ-
ᑦᑎᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ ᐅᕐᑰᓯᓂᖓᓄᑦ ᖃᐅᔾᔪᑎᖃᖅᑯᑎᒃ ᓯᓚᐅᑉ ᖃᓄᐃᓐᓂᖓᓂᒃ ᓴᓇᕐᕈᑕᐅᔪᓂᒃ ᓇ,
ᓇᐃᖅᑐᖅ ᑕᑯᔭᐅᔪᖅ ᓄᓇᑐᐃᓐᓇᒥ, ᑕᓇᐅᕐᒥ ᐊᒻᒪᓗ ᓄᓇᕐᔪᐊ ᓯᓚᑖᓂ. ᓇᐃᓈᖅᑐᒍ ᐅᖃᕈᓐᓇᖅᑐᒍᑦ
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ᐊᒥᓱᑦ ᐊᔾᔨᒌᓐᖏᑦᑐᑦ ᓯᓚᓐᓂᐊᖅᑐᑦ, ᐃᓅᓯᓕᕆᓂᕐᒥᒃ ᑮᓇᐅᔭᑎᒍᑦ ᐱᕙᓪᓕᐊᓂᖅ ᐊᒻᒪᓗ ᓄᓇᖏᓐᓄᑦ
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ᐊᒻᒪᓗ ᐊᑐᐊᒐᐃᑦ ᐅᑯᐊ ᐃᑲᔪᕐᓂᐊᖅᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᓂᒃ ᐊᒻᒪᓗ ᑲᒻᐸᓂᐅᔪᓂᒃ ᐱᓂᒃᓴᕙᒦᖅᓯᒪᓗᑎᒃ
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ᐅᓇ ᑕᐅᑦᑐᓇᔭᕋᑦ ᓴᓇᓗᒍ ᓯᕗᓂᒃᓴᕋᑦ, ᖁᔭᓐᓇᒦᒃ ᑕᒻᔭᐅᖕᒪᑦ ᑐᓴᐅᒪᖃᑎᒌᖕᓂᖅ ᖃᐅᔨᒪᖃᑎᒌᖕᓂᖅ,
ᒥᐊᓂᕆᓂᖅ, ᐋᖅᑭᒃᓱᐃᓂᖅ ᐊᒻᒪᓗ ᐃᓗᓪᓕᖅᓱᐃᓂᖅ, ᖃᐅᔨᓴᖅᑎᒻᒪᕇᑦ ᐊᒻᒪᓗ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᑦ ᑲᑎᓯᒪᔭ
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ᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑎᒦᑦ. ᖁᔭᓐᓇᒦᒃ ᑕᒪᑦᓯ ᑐᑭᓯᓇᓱᐊᖅᑎᒦᑦ ᖃᐅᔨᓴᖅᑎᑦ, ᐃᓕᓐᓂᐊᖅᑐᑦ, ᐊᓯᖏᓪᓗ
ᖃᐅᔨᓴᖅᑎᑦ, ᓴᓇᖅᑎᕆᔭᕋᑦ ᐊᒻᒪᓗ ᐱᓇᓱᐊᖅᑎᕆᔭᕋᑦ ᐃᑲᔪᖅᑐᑦ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑎᒦᒃᑯᓄᑦ
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ᐱᓇᓱᐊᖅᑎᒦᓚᐅᖅᑐᑦ ᐅᓇ ᑎᑎᕋᖅᓯᒪᔪᖅ ᐱᔭᕇᑦᑎᐊᕋᓱᓪᓗᒍ.

Louis Fortier, Scientific Director of ArcticNet

Martin Fortier, Executive Director of ArcticNet

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 premières étapes franchies au cours des quatre premières années (Phase I) 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

Martin Fortier, directeur exécutif d’ArcticNet

INTRODUCTION

ArcticNet Compendium Editorial Team:

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Recently completed scientific studies provide evidence for the precipitous shrinking of the Arctic Ocean area covered by thick multi-year ice, as well as the dramatic retreat and break-up of the Arctic's largest ice shelves. At the same time, clear signs of Antarctic ice sheet deterioration and accelerated mass loss from the Greenland ice sheet are being reported. In the terrestrial Canadian Arctic, the rapid melt of permafrost soils is profoundly transforming northern landscapes, placing infrastructures at risk and adding new challenges for the rapid economic development of the North. Southern plants and animals are extending their distributional ranges northwards at unprecedented rates, while the indigenous, specialized biota of the Arctic is increasingly vulnerable. This avalanche of swift changes in Arctic environments over recent years has far reaching impacts on the well-being and lifestyles of Northerners, and has raised concerns over the consequences to the cultural life and health of northern peoples, the ecological integrity and functioning of northern ecosystems, economic growth and the accessibility to natural resources, as well as Canadian sovereignty and national and international Arctic policy. Research in the Arctic is therefore confronted with the challenge of responding to a whole range of questions, such as: What are the causes of such changes? What are the implications of these changes for our daily lives? How can we collectively and individually adapt? The overarching objective of the Canadian Network of Centres of Excellence (NCE) program ArcticNet is to find answers and adaptation strategies in response to these pressing questions.

This Compendium of Research (Volume 2) presents an overview of Phase I of ArcticNet, which ran from 1 April 2004 to 31 March 2008. During this initial 4-year period, the basic structure of the ArcticNet research program was developed and oriented toward its main mission, namely "To bring together Canadian and foreign Arctic expertise to conduct Integrated

Regional Impact Studies (IRIS) of the consequences of climate warming, environmental changes and societal changes in key areas of the coastal Canadian Arctic". ArcticNet Phase I was organized under four complementary research themes: 1) Climate change impacts in the Canadian High Arctic: a comparative study along the east-west gradient in physical and societal conditions; 2) Food, water and resources in the shifting north-south thermal gradient of the terrestrial eastern Canadian Arctic; 3) Managing the largest Canadian watershed in a new climate: land-ocean interactions in Subarctic Hudson Bay; and 4) Science to policy-makers and people.

ArcticNet Phase I has profoundly transformed and accelerated the evolution of Canadian northern science by launching a coordinated suite of new approaches that led to long-term benefits in many areas of research. By creating a pan-Canadian network of Arctic research groups, ArcticNet catalyzed and facilitated work partnerships and exchanges. Many new partnerships were established with Inuit organizations and communities, with federal departments, industry, territorial agencies, municipalities and more than 20 research centres of excellence within Canada and abroad. ArcticNet's multidisciplinary, integrated approach in natural, health, and socio-economic fields extended both nationally and internationally as researchers contributed to a number of global projects through the International Polar Year (IPY) – Microbiological and Ecological Responses to Global Environmental change in the polar regions (MERGE), Arctic Wildlife Observatories Linking Vulnerable EcoSystems (ArcticWOLVES) and the Circumpolar Flaw Lead System Study (CFL) – and through other projects such as the Russian and Italian Nansen and Amundsen Basins Observational System (NABOS) programs. These international collaborations allowed Canadian Arctic research contributions to make an impact within a broader circumpolar context.

ArcticNet also provided a unique and exceptional research environment for students (the next generation of Canadian scientists), postdoctoral fellows and technical staff to develop skills and undergo training in the field of Arctic sciences. The quality and originality of ArcticNet's research is reflected by the many publications in some of the world's best scientific journals and textbooks, and the new data, insights and knowledge that these contributions present. Most relevant to Northerners, Inuit communities have become enthusiastic partners in the gathering of data and many researchers have developed close working relationships with northern communities, providing diverse knowledge products for use in the North, which integrate both local (traditional) and scientific knowledge. The development of the ArcticNet/CCIN Polar Data Catalogue (presented in the ArcticNet Compendium of Research Volume 1) ensures the long-term sustainability and accessibility of these and other datasets in addition to providing a powerful tool for information searching, sharing and outreach.

The first volume of the ArcticNet Phase I Compendium of Research published in 2010 presented a detailed description of ArcticNet's mission, objectives, as well as its strategic framework approach aiming at the production of the Integrated Regional Impact Studies (IRISes). Volume 1 also provided an overview of the four themes of ArcticNet Phase I, and presented detailed information, approaches, results and achievements for Theme 1 and 2 projects. As a complement to Volume 1, this Compendium (Volume 2) presents a detailed description of the research realized within Themes 3 and 4 during the first phase of ArcticNet. Theme 3 (Chapter 1) focused on the until recently overlooked Hudson Bay region, including its physical structure, the chemical and biological aspects of its unique environment, and the impacts of climate change on its human and wildlife populations. Theme 4 (Chapter 2) examined the social, economic and political aspects and implications

of environmental change across the Canadian Arctic and focused on how best to disseminate this information to decision-makers. Finally, Chapter 3 provides a compilation of refereed articles, book chapters, books and monographs that were published for all four themes over the period 2004 to 2011. This publication list is continuously updated on the ArcticNet website (www.arcticnet.ulaval.ca) and on the ArcticNet publication database (www.aina.ucalgary.ca/astis) a subset of the Arctic Science and Technology Information System (ASTIS) database.

In its initial phase, ArcticNet achieved its first major goal of establishing exchanges and links amongst disciplines, necessitated by the diverse nature of its integrated research projects. In describing the changes, causes, consequences and responses to climate change within each project, the new ArcticNet IRIS structure (from 2008 onwards) provides exciting opportunities to further build capacity and experience among northern residents and territorial policy-makers. This is best achieved by using approaches that contribute to enhanced resilience in Arctic communities and by developing linkages between natural science specialists, networks of expertise in northern health, and specialists in societal issues such as cultural change, adaptation, and the recognition and respect of Inuit perspectives.

The preparation of this Compendium was aided by many people and organizations. We especially would like to thank Sylvain Tougas, Carl Barrette, Leslie Coates, Jay Anderson, Dan Leitch, Ashley Gaden, Martin Fortier, Louis Fortier, and all ArcticNet researchers and research partners for their valuable contributions to this document.

1. Managing the Largest Canadian Watershed in a New Climate: Land-Ocean Interactions in Subarctic Hudson Bay (Theme 3 Overview)

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Introduction

The larger scientific community has largely overlooked Hudson Bay until recent years – an oversight that is currently being rectified by the ArcticNet consortium. The ArcticNet Theme 3 research agenda focused on physical, chemical and social aspects of environment and life around Hudson Bay, including the lowlands that define its western side, Foxe Basin in the north, the Belcher Islands, the communities along the Quebec and Manitoba shores, and the fiords of Atlantic Labrador. To this end, several land- and water-based research projects were carried out to define the background physical state of Hudson Bay, to assess the role and character of river inflows, to collect data on chemical species and their origins, and to interact with residents and Aboriginal communities to study health and social issues of common interest.

Modelling experiments conducted during and after the data collection phases were used to integrate the data into a more holistic view of Hudson Bay, defining, for example, the annual cycles of salinity, temperature, ice formation and melt, and Hudson Bay currents. Measurements of air and water chemistry were used to identify sources and sinks of pollutants and atmospheric gases (particularly CO_2 and mercury). Partnerships with shoreline communities were instrumental in the collection of data to establish the present state of health and to assess the impacts of a warming climate on the ecosystem.

Theme 3 research activities established the baselines that will characterize and direct future research for generations to come, including feeding the Integrated Regional Impact Study (IRIS) for Hudson Bay as ArcticNet moved into Phase II. Data collected will be compared to future climates to characterize changes in the local climate, and incorporated into prediction models.

Study Area

Hudson Bay is a virtually landlocked, immense inland sea that covers over 832,000 km^2 in the centre of Canada (Figure 1). It has characteristics that are unique among the world's oceans: a low salinity, a large volume of freshwater input from numerous rivers that drain central North America, a winter season in which it is ice covered, and a limited connection with the Atlantic Ocean. Hudson Bay is the site of considerable hydroelectric development which has taken place over recent decades, with large power-generation projects moderating freshwater flows on both the east and west sides. One of its major communities, Churchill, is world-famous for its polar bears, but also provides an increasingly attractive terminus for shipping between North America and Europe.

Figure 1. *The Hudson Bay (Theme 3) study region. Source: Atlas of Canada.*

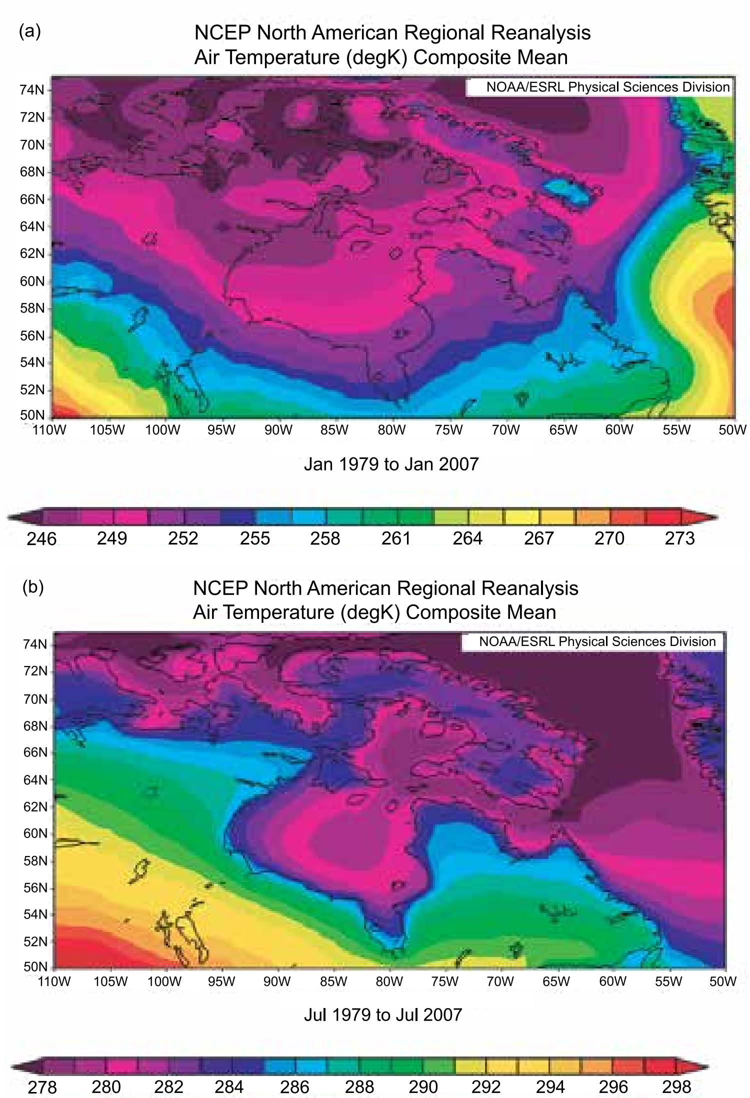
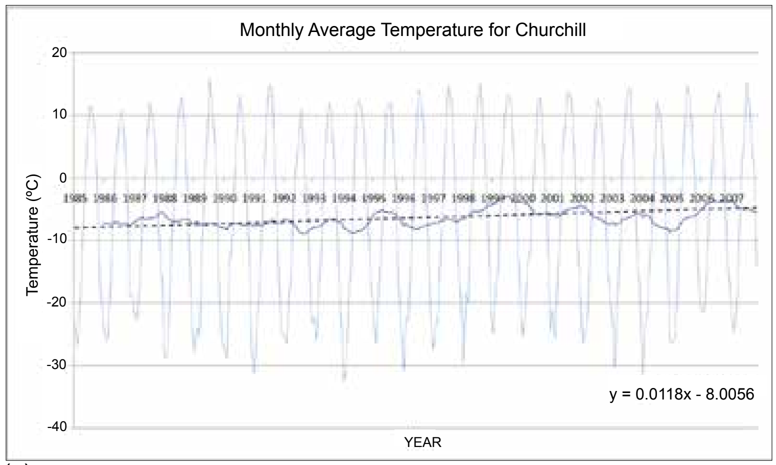
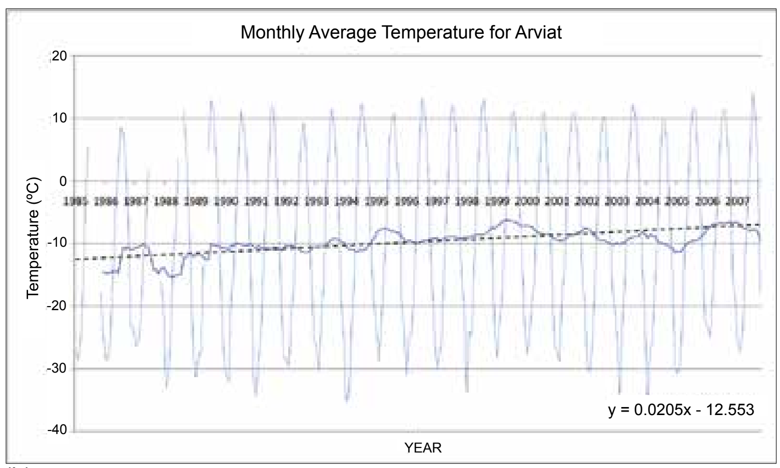


Figure 2. *Temperature distribution (degrees Kelvin (K); 0°C= -273.15 K) for January (a) and July (b) over Hudson Bay, averaged between 1979 and 2007. Source: NCEP NARR.*

Annual average air temperature around Hudson Bay is heavily influenced by the presence of ice. Figures 2(a) and 2(b) illustrate the cooling effect of Hudson Bay and show the average temperatures for January and July. Temperatures in January range between -16ºC and -27ºC, and decrease with increasing latitude. The coldest temperatures are concentrated over the northwest coastal areas, where communities such as Rankin Inlet and Coral Harbour have daily average temperatures of around -30ºC in January. Summer air over Hudson Bay itself remains cool (5-10ºC) and acts to influence the surface temperatures at its coastlines, especially its island communities of Sanikiluaq and Coral Harbour. The Belcher, Coats and Mansel Islands are subject to temperatures in the mid to high single digits during the summer on average. Warmer annual temperatures in association with later freeze-ups and earlier melting of the ice in Hudson Bay have been recorded in the recent past and will have implications on all physical systems within Hudson Bay (Figure 3).



(a)



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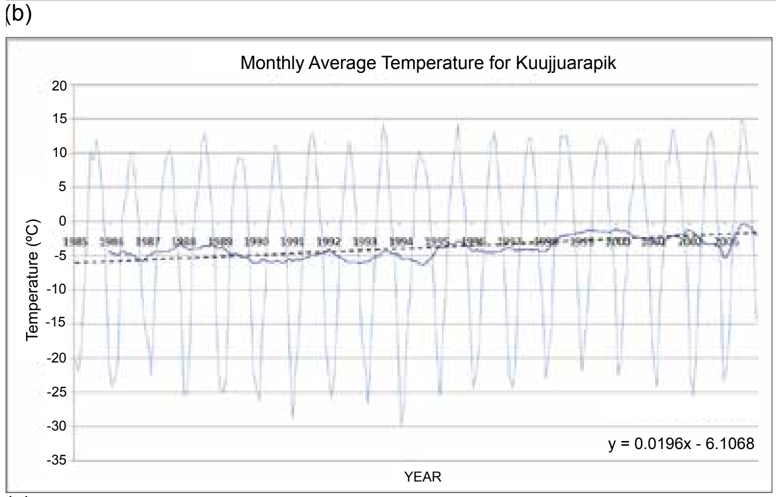


(c)

Figure 3. *Time series of monthly temperature for three Hudson Bay communities [(a) Churchill, Manitoba; (b) Arviat, Nunavut; (c) Kuujjuarapik, Quebec (Nunavik)]. A plot of moving average (t=12) and a linear trend has been overlaid. Positive trend lines indicate an overall warming trend at each of the three locations over the last 20 years. Source: EC_MSC.*

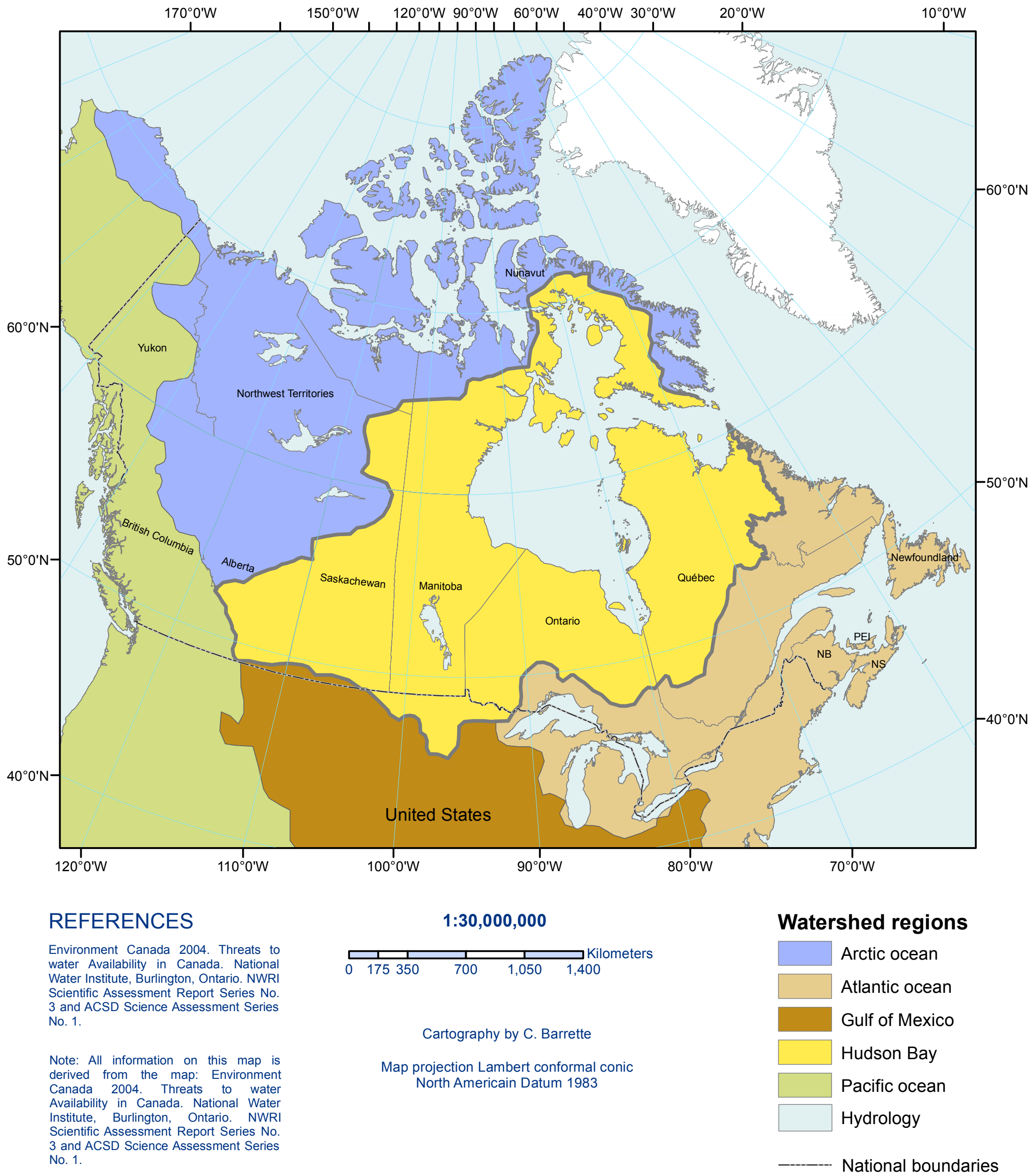


Figure 4. *The watersheds of Canada. The Hudson Bay Watershed is indicated in yellow. Source: Atlas of Canada.*

Precipitation in the region also decreases with increasing latitude, and can range from as much as 600-800 mm annually in the southern areas to 200-400 mm in the northern extremes of Hudson Bay. The majority of precipitation reaches the southern bowl of Hudson Bay during the summer months. While the regions around Hudson Bay typically receive a low amount of precipitation, the freshwater input into Hudson Bay is one of the key features that make this region particularly significant. The Hudson Bay watershed is the largest in the country, stretching over five provinces, Nunavut and the Northwest Territories, and northern regions of Minnesota, North Dakota, South Dakota and Montana (Figure 4). The

Nelson River in Manitoba and La Grande Rivière de la Baleine (Great Whale River) in Quebec are the two major fresh waterways into Hudson Bay.

During the summer, the ice-free Hudson Bay harbours an active ecosystem. It is generally ice-free from mid- to late August until late October. Ice fills the bay by January and remains mainly frozen until May. As mentioned above, the long duration of ice in Hudson Bay during the winter allows cold polar air masses to penetrate further south in the eastern half of the country. This not only affects annual temperatures, but the vegetation capable of surviving in the vicinity. Permafrost, shrub, lichen, bare soil and rock dominate Hudson Bay's shorelines (Figure 5). The coastal area is known to be a large store of methane, an effective greenhouse gas (GHG). Warmer temperatures in the region have allowed a portion of the permafrost layer to melt, not only allowing for the release of methane, but also the deterioration of social infrastructure and natural habitat.

Research Projects and Objectives

In support of the ArcticNet framework, Theme 3 selected seven projects to address a number of objectives in the investigation of the Hudson Bay region. The collection of baseline physical, chemical, meteorological and hydrological datasets, as well as the collection of health and social data to evaluate the impact of past and future environmental changes and to form the basis of modelling experiments was among the key objectives of Theme 3. Each of the seven projects within Theme 3 is listed below along with their individual intentions.

Project 3.1 – *Ocean-Ice-Atmosphere Coupling and Climate Variability* – investigated the physical structure of Hudson Bay and its watersheds, evaluating the physical framework that influences the chemical, biological, and social changes studied in other components of Theme 3, with the major focus on the impact of freshwater inputs to the Bay and its effect on marine processes. A significant component of the research effort of Project 3.1 was the collection of data to feed numerical models that mimic the physical, biological, and chemical structure of Hudson Bay, which can be extended into the future to assess the risks and challenges of climate change.

Project 3.2 – *The Hudson Bay Coastal Zone in a Changing Climate System* – had two-fold objectives. The first focused on the ecological and physical characteristics of land cover environments within the Hudson Bay Lowlands, measuring the movement of heat, carbon, and water within peat, fen, and coastal ecosystems. The second component adopted a hydrological emphasis, tracking the movement of carbon and water from the lowlands to Hudson Bay estuary and into deeper water. Each of these components may have a significant feedback role in a global warming scenario – a role that can only be elicited by sophisticated climate modelling. Such modelling is the goal of Phase II of ArcticNet.

Project 3.3 – *Climate Variability / Change and Marine Ecosystem Resources in Hudson Bay* – aimed to assess how climate-induced variability and the change in sea temperature, ice cover, and the timing and intensity of river inflows affect biological productivity, fish stocks and marine mammals in Hudson Bay. Water characteristics in Hudson Bay reflect inputs from the Pacific by way of Foxe Basin, from the Atlantic, through Hudson Strait, and from freshwater rivers that represent one of the largest drainage basins in North America. These three sources, plus the addition of significant inputs of freshwater from the melting of ice, give Hudson Bay a unique marine character.

Project 3.4 – *Carbon and Contaminant Cycling in the Coastal Environment* – had the main objective of producing a mass-balance model of mercury in the environment that determines the sources and fluxes of the many forms of mercury and its compounds. Organisms high in the Arctic and Subarctic marine food webs often contain elevated levels of

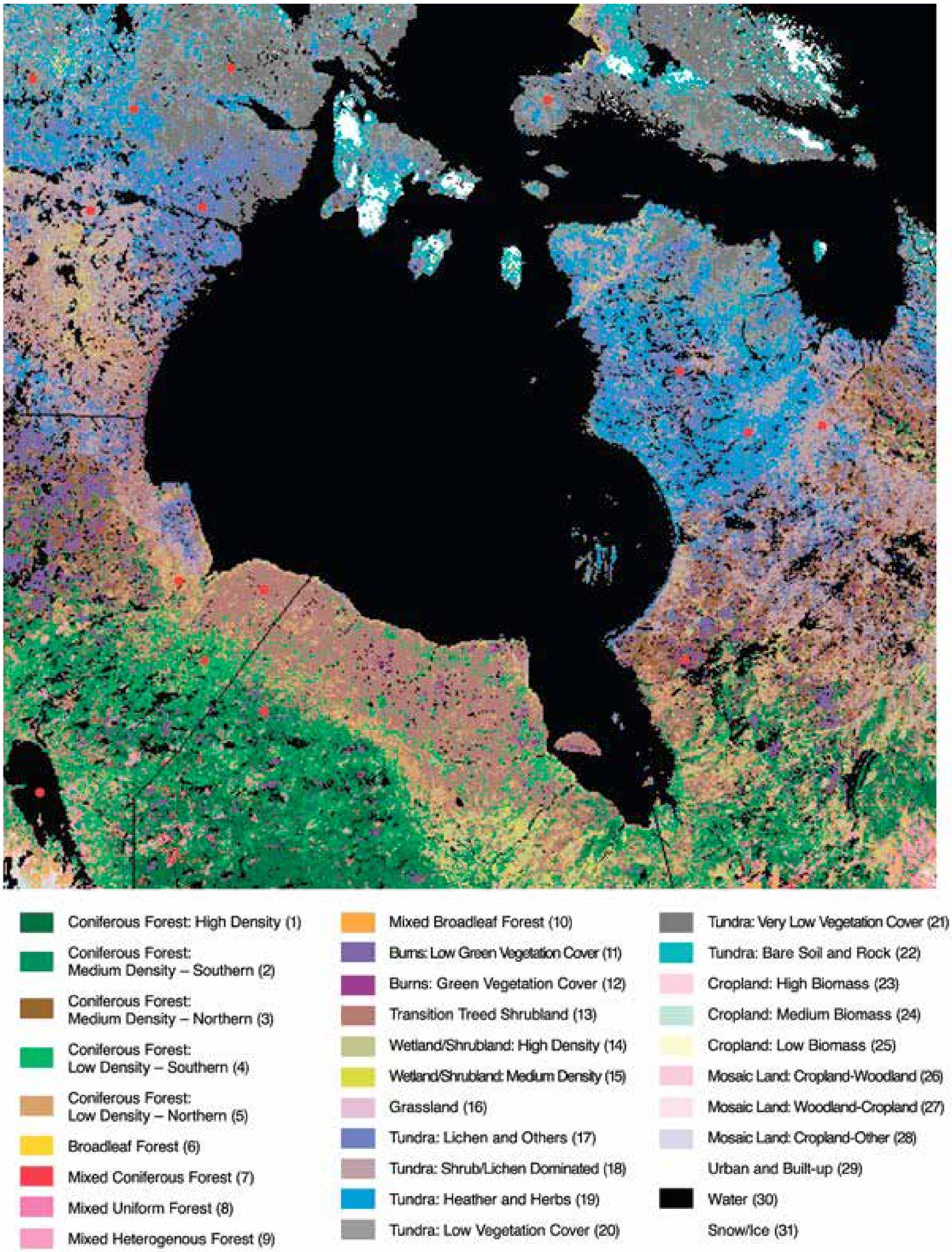


Figure 5. *Vegetation and landscape types in the Hudson Bay region. Source: Atlas of Canada.*

methylmercury (MeHg), a potent neurotoxin, which accumulates in top predators by the process of bioaccumulation. Consumption of typical country foods exposes northern peoples to the health risks associated with the metal. The source of MeHg in these Arctic habitats was unclear. With this knowledge in hand, the impact of global warming on the fluxes of mercury in Arctic ecosystems can be predicted.

Project 3.5 – *Persistent Organic Pollutants (POPs) and Human Health* – focused on the health effects to humans and animals that may result from exposure to POPs in the Arctic. Persistent organic pollutants are a set of chemicals that are toxic, persist in the environment for long periods of time, are capable of long-range movement, and biomagnify as they move up through the food chain. POPs have been linked to adverse effects on human health and animals, such as cancer, damage to the nervous system, reproductive disorders, and disruption of the immune system. Project 3.5's geographical scope extended beyond the confines of Hudson Bay to cover the entire Canadian Arctic. It was divided into two subprojects: the first was a study of POPs in traditional foods and dietary exposure; the second was an assessment of the toxicity of POPs.

Project 3.6 – *People and Environmental Change: Linking Traditional and Scientific Knowledge* – attempted to document the impacts of climate-induced changes on the people of Hudson Bay, on wildlife, and on the physical environment, linking traditional knowledge and western scientific investigation. Observation data collected at selected sites around Hudson Bay are typically of too short a duration to provide definitive evidence of climate change, but some of these shortcomings can be mitigated by substitution of multi-generational knowledge of the northern environment. Methods of linking the two traditions, with the goal of recommending adaptation and mitigation strategies, were important components of the research.

Project 3.7 – *Nunatsiavut Nuluak: Baseline Inventory and Comparative Assessment of Three Northern Labrador Fiord-based Marine Ecosystems* – aimed to use three marine ecosystems in the fiords of Atlantic Labrador (Anaktalak Bay, Saglek Bay and Nachvak Fiord) to collect baseline data that will help address Inuit concerns about the integrity of the marine environment in light of development pressures and climate change. The study integrated Inuit knowledge throughout the research design, including the selection of indicators and the collection and analysis of data.

Project Integration within the ArcticNet Strategic Framework

Theme 3 focused on the most southerly section of ArcticNet's region – a region beset by changes from hydro development, rapidly thinning ice, and a close proximity to southern urban centres. Because Hudson Bay is largely isolated from the more northerly Arctic climates and is affected by large freshwater flows, it has certain unique physical features. Physically, its links with the North come from relatively small exchanges of water through Foxe Basin and (to some extent) through Hudson Strait, but culturally, it is strongly tied by community and by the Inuit culture that surrounds its shores.

Theme 3 also shared a culture with ArcticNet: a multidisciplinary research effort that incorporates scientists and managers in the natural, human health, and social sciences with their partners in Inuit organizations, Hudson Bay communities, federal and provincial agencies, and the private sector to study the impacts of climate change. The dataset collected by Theme 3 was a major achievement, taking Hudson Bay from a relatively ignored and poorly studied water body to one that is now an integral part of the Canadian geographical scene. To further the awareness of Hudson Bay within the public and political domain, ArcticNet has partnered with the

International Institute for Sustainable Development (IISD) and Nunavuummi Tasiujarjuamiuguqatigiit Katutjiqatigiingit (NTK): Nunavut Hudson Bay Inter-Agency Working Group towards a Hudson Bay Inland Sea Initiative (HBISI). The HBISI will include a Hudson Bay Awareness Summit, and aims to address the various multi-jurisdictional challenges of Hudson Bay over the course of the next few years. The goal of this collaboration is to bring awareness to the need to focus and coordinate efforts on policy, science and governance needs for the Hudson Bay Inland Sea among all the stakeholders. The research conducted within Theme 3 was used to structure the integrated regional impact assessment (IRIS) for the Hudson Bay area as ArcticNet moved into the IRIS framework for Phase II. Figure 6 illustrates how each of the projects in Theme 3 corresponded to the abiotic, biotic and human systems within the study area.

Project Achievements

Within the efforts of Theme 3, long-term research initiatives within the Hudson Bay region were initiated, and working relationships for operation within communities and industries within the region were built. The datasets collected in each of the seven projects within Theme 3 have led to significant findings within each of the IRIS elements: abiotic systems, biotic systems, and human systems. The respective findings within each of these IRIS components are summarized below.

Abiotic Systems

Great advances were made in the understanding of the Hudson Bay physical system, the role of freshwater input, and the linkages between weather patterns, ice cycles and the ecosystem. One of the largest corridors for freshwater into Hudson Bay, the Nelson River, has been characterized in terms of

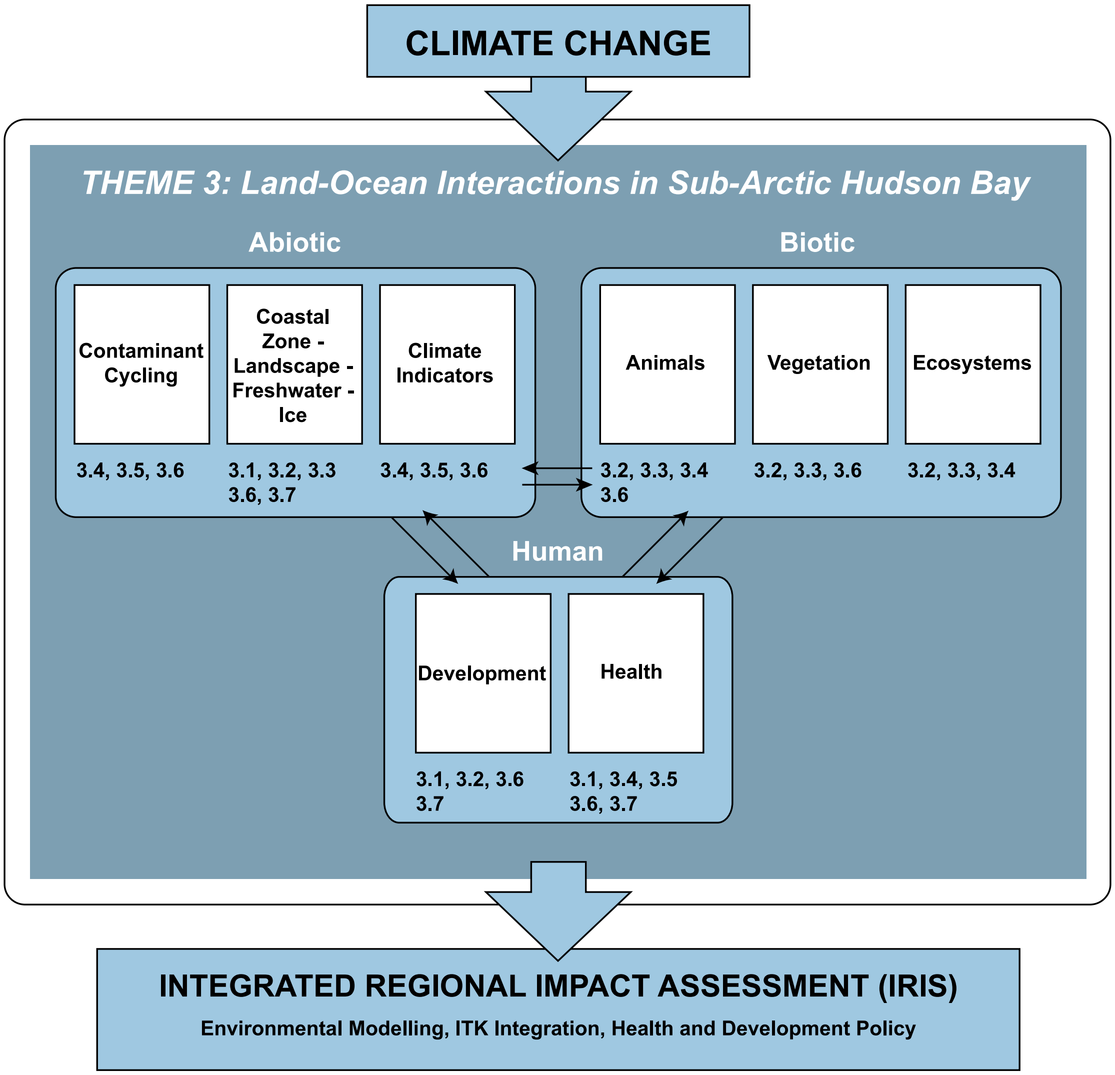
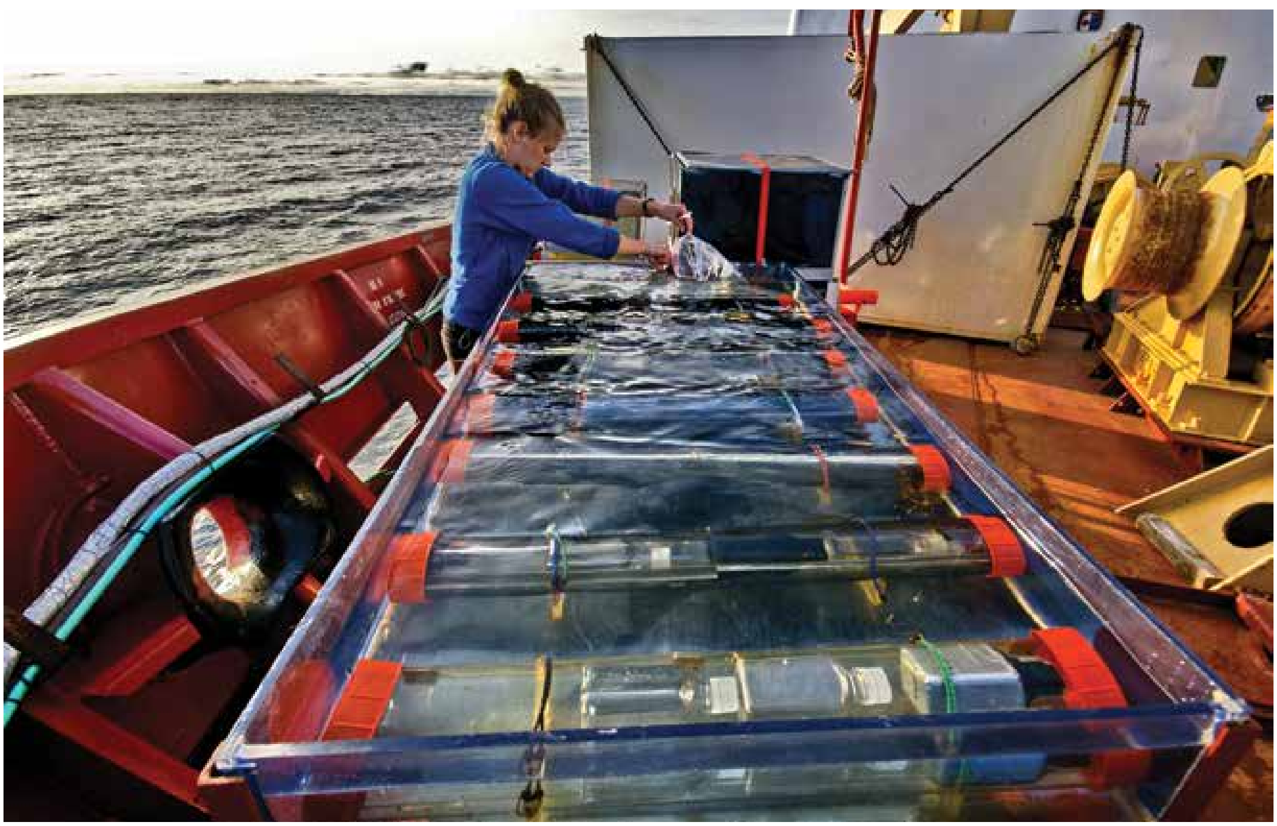


Figure 6. *Theme 3 flowchart and Integrated Regional Impact Study (IRIS) framework.*

turbidity and sediment flux, as well as CDOM (coloured dissolved organic matter) inputs into Hudson Bay. Late under-ice and early break-up processes in the estuary at the Churchill ice camp were modeled, constructed from hydrological and meteorological data, ice observations and measurements of salinity, nutrients, chlorophyll and particulates in the water column. It was found that as melting begins, the under-ice river flow creates a brackish surface layer that is impounded by the rubble. The river carries nutrients and heat into the near-shore environment, aiding the break-up of the landfast ice as spring advances. In winter, conditions in the estuary are highly variable, with the physical interaction of the river plume, overlying landfast ice, and the rubble zone along the margin of the landfast ice. Less dense freshwater flowing into the estuary creates a brackish zone at the water surface, under the ice, and impounded by the rubble zone. This brackish zone is rich in nutrients, and supports early primary production before it is terminated by the breakdown of the ice cover. As the spring freshet begins, heat from the river is injected into the estuary, leading to the early break-up of the landfast ice. Once the rubble zone is breached, the river plume disperses quickly into Hudson Bay. Away from the estuary, sunlight absorbed in the open water of the flaw lead brought on an early melt.

The Theme 3 studies also revealed the complex behaviour of tundra and coastal environments, especially with respect to the release and uptake of GHG. Habitats can be sources for one greenhouse species while at the same time acting as a sink for another. Changes from wet to dry conditions can reverse these relationships, either individually or collectively. Hudson Bay itself seems to be a relatively poor CO_2 sink, in large part because of carbon fluxes from the river inflows. Future landscapes are expected to contain many more ponds because of permafrost melting as the Hudson Bay Lowlands respond to climate warming. Currently, ponds tend to be isolated water storage reservoirs, but with higher precipitation and larger numbers, they become sources of water – a characteristic that may lead to increased probability of flooding in future years.

For the investigation of contaminant cycling, ongoing year-round measurements of mercury compounds in the Churchill area allowed the seasonal variation of mercury in the atmosphere to be defined. Fluctuations of the gaseous species are more variable in the spring and summer, and less so in the winter. Atmospheric mercury depletion episodes, or AMDEs, result in the deposition of mercury into the snowpack, but this is followed by a rapid diffusion of the compounds back into the atmosphere over a period of several days. AMDEs are not a significant source of mercury in Hudson Bay, but overall, atmospheric deposition was a major source of mercury to the system. The total flow of mercury into Hudson Bay from rivers was estimated to be 1 ton annually, with 70 kg of that in the form of methylated species. Ocean sources of mercury were limited, with



0.8 tons estimated to flow into Hudson Bay through Foxe Basin. Flows in Hudson Strait were net exporters of mercury, with an estimated annual influx of 5 tons in the flow through the Baffin Current, and an export of 15 tons in the southeast outflow current. Nearly 9 tons were deposited from the atmosphere. Marine sediment concentrations of mercury were low throughout Hudson Bay though somewhat variable from site to site. Upper layers of sediments tended to carry more mercury than lower, and concentrations were linked closely to the percent of organic carbon in the samples. The results were intriguing, as they indicated a temporal evolution of the flow of mercury into Hudson Bay, suggesting that mercury deposition has changed over the past century. This result offered the potential to elicit differences in the riverine mercury delivery from the diverse watersheds around Hudson Bay. Contaminants in the form of persistent organic compounds, or POPs, were also measured within components of the marine food chain.

Biotic Systems

Within Hudson Bay, Arctic zooplankton and fish species dominate their respective communities, but estuarine and Atlantic species can be found in coastal regions in both Hudson Bay and Strait. Larger mammals reflect eastern Arctic origins, with seals, belugas, and polar bears best known to the public. Hudson Bay, because of its southern location and variable water sources over a large range of latitudes, has been identified as a sensitive region for the double impacts of climate change and resource development. These impacts will affect renewable resources within Hudson Bay by altering the food web, with consequences for traditional hunting and fishing on the coastal and island populations. Satellite observations of phytoplankton showed that Hudson Bay has relatively low productivity and small seasonal fluctuations. River estuaries are significant, with the greatest variability in phytoplankton biomass and the largest input of dissolved organic carbon. Algal species showed remarkable differences in composition between brackish river plume and higher salinity marine sites. The distribution of nutrients was also highly variable across Hudson Bay, with nitrates highest in the west, particularly in Foxe Basin and near James Bay. Silicates were found in high concentration at the mouth of James Bay, but were very low in northern regions where, in contrast, dissolved reactive phosphorus concentrations were highest because of nutrient-rich flows from the Pacific. Nitrogen appeared to be the limiting nutrient in ocean water, while phosphorus was likely to be limiting in the river outflows. In silicate-poor waters in Foxe Basin, diatoms may have consumed the entire surface inventory of silicon contained in the Pacific waters that flowed from the Arctic islands.

Phytoplankton concentrations were inversely correlated with the strength of the surface stratification, a sign that vertical mixing is a critical component in biological productivity. Phytoplankton production increased toward Hudson Strait, where stratification is weakest. The central part of Hudson Bay has a low abundance of zooplankton and fish, but production was higher in coastal regions and in selected areas around the Belcher Islands and northeastern Hudson Bay where stratification weakened.

Hydrophones deployed year-round with the oceanographic moorings revealed a surprising frequency of whales throughout the year, including bowheads, consistent with reports from traditional hunters. Some beluga overwintered in recurrent polynyas, especially near the Belcher Islands, but all those that were tagged exited Hudson Bay between September and November, overwintering off the Labrador coast.

Toxicity levels found within the scope of Theme 3 were significant. Older compounds such as DDT and PCBs are being phased out, but replacement chemicals are emerging as the new generation of pollutants, such as BDEs (brominated dyphenyl ethers) and PFCs (perfluorinated compounds). Organic pollutants were endemic in food samples collected across the Arctic, with higher levels typically found in marine mammals rather than fish or land animals. Traditional foods contributed higher levels than market foods, with highest exposures in middle-aged men. In Nunatsiavut, the data indicate that Nachvak Fiord and Anaktalak Bay are relatively pristine environments, but Saglek Fiord is still affected by the past history of PCB exposure despite the removal of the land-based source. A statistically significant decline of PCB levels in liver between 1998 and 2006 suggests that the uptake from shoreline contamination is gradually declining. The divergent results in the ringed seal population invited further study, but may be a result of behavioural differences or migration. PFCs were concentrated in caribou flesh, providing 43 to 75 percent of the daily exposure. However, the uptake of new POPs is relatively low and poses minimal risk to the population. In some regions, the exposure to classic POPs is decreasing, a trend that is being monitored and verified during Phase II.

In terms of vegetation, it was found that lichen and mosses, and their moisture content, are significantly linked to the CO_2 fluxes found in the area. Data collected within the lowlands revealed that drought enhanced the release of CO_2 from the tundra to the atmosphere. Wet tundra environments released substantial amounts of methane, while drier environments were methane sinks. Tundra habitats proved to have a complex pattern of release and uptake for major GHG that responded strongly to the precipitation climate of the season. Carbon budgets in ponds are controlled by algal growth, with a strong daytime uptake of CO_2. Lichens and mosses were capable of very large precipitation interception rates and water storage. Peat also had a large water storage capacity, with water flowing freely only during wetter periods.

Human Systems

Social aspects of change were emphasized, with cooperative projects on youth perspectives and education, social well-being, economic impacts (hunting, travel), adaptation to changes in river outflow, and perspectives on changing sea ice. Community members took a leading role in setting research objectives, directing studies to such areas as wildlife mortality driven by sea ice conditions, impacts on seasonal travel routes, security of food supplies, subsistence hunting, as well as fishing and health.

Impacts due to climate change are intertwined with other societal impacts brought on by modernization in Inuit communities and subsequent changes in lifestyles. A shift in the reliability of traditional knowledge due to unfamiliar consequences of global warming may cause concern to a traditional hunter and also affect the transfer of knowledge to the younger generation from elders and mentors. The importance of hunting and fishing to Inuit culture may succumb to the onslaught of television and market food. In addition to these stresses, communities are now acquiring the knowledge and evidence that toxic contaminants (POPs, MeHg) are being found in the traditional food supply. Northerners are required to cope with a myriad of changes so that perceptions of health and well-being are very different from those in the South. Environmental change may have more profound consequences than merely adaptation to a new climate regime.

Current and future work is focused on incorporating ongoing surveys and knowledge of Inuit hunters about the timing and variability of sea ice formation across a range of specific habitats. In one case, aerial surveys, mathematical models, workshops, interviews, and local knowledge of sea ice were integrated to study the distribution, dynamics, and abundance of eider ducks. The youth community has been involved in the research process to facilitate mentoring and inspire young people to pursue higher education. Local experts have been trained in some aspects of data collection, report writing, and public dissemination of results. A Community-Based Monitoring program (CBM) ensured that local participants were trained and employed in data collection – especially in winter – at Sanikiluaq and other sites, to augment the short summer research season.

1.1 Ocean-Ice-Atmosphere Coupling and Climate Variability (Project 3.1)

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1.1.1 Abstract

From 2005 to 2008, the scientific activities of this project consisted of field studies of winter ice conditions and under-ice processes, and summer estuarine processes at the mouths of the Churchill and Nelson rivers, as well as sampling missions onboard the icebreakers CCGS *Amundsen* and *Pierre Radisson*. In 2005 and 2006, a partnership with Manitoba Hydro was established to conduct extensive investigations of estuarine processes at the mouth of the Nelson River. This project allowed for the realization of the first extensive multi-season measurements of late winter and break-up period processes in a small Arctic estuary, that of the Churchill River, and for the subsequent development of a comprehensive conceptual model of physical and biological processes under ice and during break-up at the estuary-ocean margin. In 2005, the first comprehensive survey of chromophoric dissolved organic matter (CDOM) distribution in Hudson Bay was completed. Using CDOM as a tracer of freshwater sources, the study showed that, compared to the contribution of sea ice melt, the contribution of terrestrial runoff to the mixed layer decreases as the water moves cyclonically around the bay. The contribution of terrestrial runoff peaks at the outflow from James Bay. This project also investigated the climatology of sea ice within the major estuaries and through a bay-wide analysis of ocean-sea ice-atmosphere coupling.

1.1.2 Key Messages

- The contribution of river runoff to freshwater in Hudson Bay is largely confined to a narrow littoral zone along the southern shore, but reaches over 200 km off most of the eastern shore, including around the Belcher Islands (Granskog et al. 2007).
- The contribution of freshwater from sea ice melt to the upper mixed layer is twice as great in the southeastern part of Hudson Bay as in the far northwest (Granskog et al. 2007), supporting conclusions from remote sensing that the ice cover tends to drift to the southeast as it melts.
- The start date of the open water route to Churchill has advanced by 3 weeks since 1970 (Tivy et al. 2007).
- Sea ice no longer forms in the winter within the Nelson River Estuary due to large freshwater flows from hydroelectric regulation.
- Freshwater fluxes to Hudson Bay are very high in winter due to increased winter precipitation and flow regulation; this flow spreads under the sea ice and is affecting ocean-sea ice coupling.
- Stamukhi (sea ice ridges) play an important role in retaining freshwater underneath the landfast first-year sea ice surrounding Hudson Bay. The timing of break-up of this feature is important to physical-biological coupling in the bay (Kuzyk et al. 2008).

1.1.3 Objectives

The overarching objective of this project was to describe the impact of freshwater quality and quantity on marine processes within Hudson Bay. The team's main approaches were:

- To determine fluxes, pathways and the fate of suspended solids and dissolved organic matter transferred through the Churchill and Nelson estuaries during the open water season with (1) mixing in the estuary determined by wind-waves, tides and marine currents, and under ice, and (2) mixing determined by tides and marine currents alone;

- To investigate the relative significance of fluvial loading and littoral resuspension for concentrations of suspended solids in the estuaries and Hudson Bay;
- To study the effect of suspended solids and dissolved organic matter on radiative transfer in the estuary and nearby Hudson Bay;
- To describe the sea ice regime of Hudson Bay as a function of environmental forcing by using remote sensing and modelling approaches to (1) describe the annual cycle of formation and decay for sea ice in the bay, (2) test for temporal trends in sea ice formation and decay within the bay, and (3) determine atmospheric, oceanic and hydrologic forcing on annual and inter-annual variability in ice formation and decay.

1.1.4 Introduction

The project investigated the impacts of freshwater quality and quantity on marine processes within Hudson Bay. Observational data included oceanographic, hydrographical, snow/sea ice geophysical, and surface energy balance variables collected over a range of spatial and temporal scales. Sampling was concentrated around two sites in the Churchill and Nelson river estuaries, but also included Hudson Bay-wide sampling via the CCGS *Amundsen*. This project was integrated with the project on carbon, water, and energy cycling in the Hudson Bay Lowlands (see section 1.2), which provided magnitude and timing of freshwater fluxes. It was also integrated with the project on climate variability/change and marine ecosystem resources in Hudson Bay (see section 1.3), which evaluated the impacts of potential changes in freshwater fluxes and the consequences of the timing of these fluxes on marine ecosystem function under a variety of climate and anthropogenic (*e.g.*, hydroelectric development, shipping) change scenarios. There was also close collaboration with the project on carbon and contaminant cycling in the coastal environment (see section 1.4), which investigated the sources and sinks of contaminants within this system, as well as with the project on people and environmental change (see section 1.6), which examined the human dimension of the observed changes occurring within Hudson Bay. These observational data were examined within a framework of model prediction, field information and remote sensing information of climate state variables throughout the annual cycle, as a means to define a baseline for freshwater-marine coupling and discerning climate change from variability induced by anthropogenic activities. These studies were carried out with support from and in collaboration with Manitoba Hydro and Omnitrax (owner-operator of the Port of Churchill), two primary industry partners within ArcticNet.

Climate models predict warming in the Hudson Bay watershed that may alter the amount and timing of runoff, and hence 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 – the diversion of Churchill River flows into the Nelson River and a shift of a third of total discharge from summer to winter. The study of transfer pathways through river estuaries into Hudson Bay has improved the understanding of the effects of these changes.

Spring melt of winter ice cover provides approximately as much freshwater to Hudson Bay as does runoff from the watershed (Prinsenberg 1984). Freshwater derived from ice is diluted in all dissolved and particulate substances compared to runoff. It differs also in its spatial distribution in the bay. Previous studies (*e.g.*, Gagnon and Gough 2005) have examined ice regimes within Hudson Bay using a limited number of sample points. Within this project, the sea ice regime of Hudson Bay was examined in its full spatial extent using both Canadian Ice Service and various remote-sensing data (Scharien 2007).

1.1.5 Activities

In cooperation with other Theme 3 projects, an ice camp was established in 2005 near the mouth of the Churchill River to measure radiative properties of the ice and to sample in the Churchill River Estuary before and during spring break-up. Studies at the field camp continued during autumn 2005 and spring 2006. Ice studies were completed by remote sensing of historic trends in ice development and break-up in the entire Hudson Bay. In cooperation with the project on carbon, water, and energy cycling in the Hudson Bay Lowlands (see section 1.2), field sampling was conducted in the Churchill (summers 2006, 2007) and Nelson (summers 2005, 2006, 2007; Table 1, Figure 1) estuaries from land bases and from the vessels CCGS *Amundsen*, CCGS *Pierre Radisson* and R/V *Strait Signet* (chartered by Manitoba Hydro). In each estuary, oceanographic properties were measured using a combination of water sampling and oceanographic profiling from the ships, smaller shore-based boats and fixed moorings. Data included physical (temperature, salinity) and optical (turbidity, inherent optical properties) profiles, and water quality from samples at discrete depths (suspended sediments, chlorophyll, dissolved and suspended organic carbon, nitrogen, phosphorus and silica, chromophoric dissolved organic carbon and oxygen isotopes).

Cooperation with the cycling in Hudson Bay Lowlands project (see section 1.2) provided the opportunity to initiate an elaborate plan to sample the natural system of freshwater and marine components of the Nelson River and estuary, examining how the freswater plume evolves through the annual cycle under the influence of freshwater forcing (staging and flow) relative to marine influences (waves, currents, tides and the sea ice cycle). Significant industry partner resources were also involved in many aspects of this project, including the charter of a research vessel, total capital costs of two annual moorings, the capital and installation costs of seasonal moorings, and environmental consultants (with

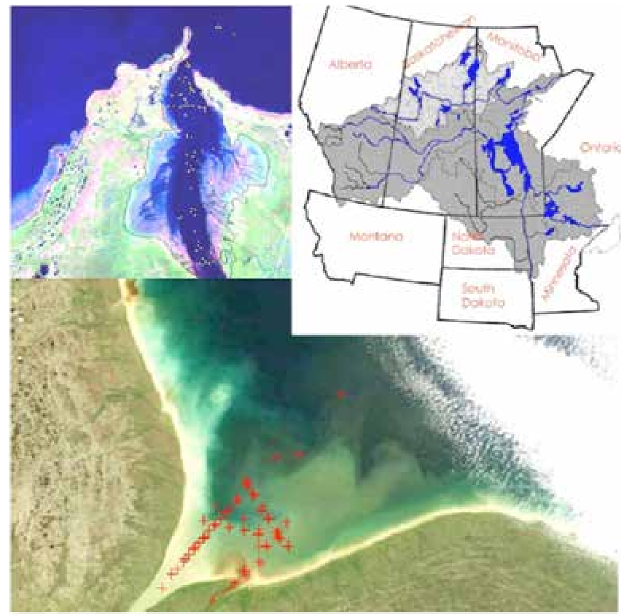

Figure 1. *Water sample and profile locations in the Churchill (upper left; satellite image is at low tide) and Nelson-Hayes (bottom) estuaries. Upper right: watersheds of the Churchill and Nelson rivers. Note that more than three-quarters of upper Churchill River flow is diverted into the Nelson River watershed at Southern Indian Lake.*

Manitoba Hydro) who worked collaboratively with our ArcticNet teams. The study focused on the summer/autumn period and was integrated fully with the CCGS *Amundsen* visits to this sampling "supersite".

In addition to work at the Churchill and Nelson supersites, visits by the CCGS *Amundsen* and *Pierre Radisson* provided the opportunity to sample (parameters as described above) throughout Hudson Strait, Foxe Basin and southern and eastern Hudson Bay in 2005, southern Hudson Bay in 2006, and Hudson Strait and southern and eastern Hudson Bay in 2007. For the study of freshwater-marine interactions, over 700 discrete water samples were collected at nearly 100 stations, and analyzed for major nutrients, suspended solids, chlorophyll and tracer $\delta^{18}O$ and CDOM (Table 1). Eleven annual moorings were deployed off the southwest coast and near the mouth of the Rivière de la Grande Baleine in Hudson Bay (2005-2007, Table 2).

Table 1. *Project 3.1 water quality samples and instrument profiles in Hudson Bay, 2005-2007. Stations in the Nelson and Churchill estuaries are grouped separately.*

YEAR	MISSION DATES	REGION	STATIONS (SAMPLES)	INSTRUMENT PROFILES
2005	October	Hudson Bay	86 (387)	86
	July, October	Nelson estuary	17 (83)	44
2006	June-September	Churchill estuary	14 (24)	97
	August, September	Nelson estuary	30 (90)	119
2007	July-August	Hudson Bay	50 (88)	50
	June-September	Churchill estuary	6 (55)	27
	August	Nelson estuary	17 (17)	10

Manitoba Hydro funded the deployment of three annual moorings in the Nelson River estuary. In the summers of 2005 and 2006, Manitoba Hydro deployed an additional 18 seasonal moorings in the Nelson River mouth and in its estuary. In addition, this partner supported ArcticNet activities in the estuary through the charter of the scientific R/V *Strait Signet* in 2006, and by providing full logistical support for other activities in the estuary in the summers of 2005 and 2006. In 2005 and 2006, Manitoba Hydro also carried out extensive field investigations in order to develop baseline data for assessing environmental impacts of future hydroelectric projects. Data collected include bathymetry and light detection and ranging (LIDAR) of the banks from which a detailed bathymetric map was prepared, velocity measurements using acoustic doppler current profiler (ADCP) technology, suspended and bottom sediment sampling, and meteorological, water level and wave measurements. In addition to data describing suspended sediments – both concentration and particle size analysis – bottom sediments in the estuary were sampled and characterized at multiple locations throughout the estuary.

Table 2. *Moorings deployed in Hudson Bay, 2005–2007.*

YEAR	DEPLOYMENT MONTH	MOORINGS (SENSORS)
2005	September	4 (18)
2006	September	3 (8)
2007	August	4 (10)

Community contacts and the incorporation of outside participants have been emphasized throughout the planning and research phases of this project. In 2005, the community of Sanikiluaq (Belcher Islands, Nunavut) participated in the expansion of the Community Based Monitoring program (CBM) to Hudson Bay, initiating a pilot CBM. Project members visited Sanikiluaq to train community monitors and help install an on-ice meteorological station. The Nunavummi Tasiujarjuamiuguqatigiit Katutjiqatiqatijgiingit (NTK – Nunavut Hudson Bay Inter-Agency Working Group) and the Municipality of Sanikiluaq held a workshop in Winnipeg with the expressed purpose of improving communication between the community and Theme 3 of ArcticNet. At this meeting, Theme 3 scientists investigated more effective ways of developing the CBM program and provided an informal evaluation of contractor reports, which had been commissioned by the Municipality of Sanikiluaq for hearings with Hydro-Québec. Theme 3 researchers have also begun collaborating with NTK and the International Institute for Sustainable Development (IISD) towards a Hudson Bay Inland Sea Initiative (HBISI). In IRIS 3, the HBISI will include a Hudson Bay Awareness Summit to address the various multi-jurisdictional challenges of the bay. The goal of this collaboration is to focus and coordinate efforts on policy, science and governance needs for the Hudson Bay Inland Sea among all stakeholders.

1.1.6 Results

1) Nelson River estuary

The persistence of a turbid plume that is visible from satellite imagery, reaching as far as 100 km from the mouths of the Nelson and Hayes rivers, indicates that fluvial loading influences suspended solid concentrations (SSC) in the region. Nonetheless, instantaneous SSC in the estuary is poorly correlated with salinity (Figures 2 and 3) indicating that SSC is not determined simply by fluvial loading but rather by local sedimentation and erosion/resuspension processes. High turbulence in a scour zone at the intersection of fluvial and tidal currents (Figure 2) develops SSC as much as an order of magnitude higher than upstream, although this enhanced SSC is quickly reduced by sedimentation in the outer estuary. Remote sensing data also shows persistently turbid coastal waters along the entire Hudson Bay Lowlands portion of the bay shore, with concentrations and spatial extent only weakly dependent on proximity to large river mouths, indicating that littoral erosion also contributes SSC to Hudson Bay. In contrast to SSC, CDOM varies with salinity, at least in the estuarine region (Figure 3). CDOM concentrations differ between the Nelson and Hayes rivers, as well as among other rivers flowing into Hudson Bay (Granskog et al. 2007). Distinct salinity-CDOM relationships allow for the determination of instantaneous relative contribution of each river to the Nelson-Hayes plume.

2) Churchill River estuary

Kuzyk et al. (2008) described late under-ice and early break-up period processes in the estuary of the Churchill River, a small river in western Hudson Bay, using hydrological and meteorological data, ice

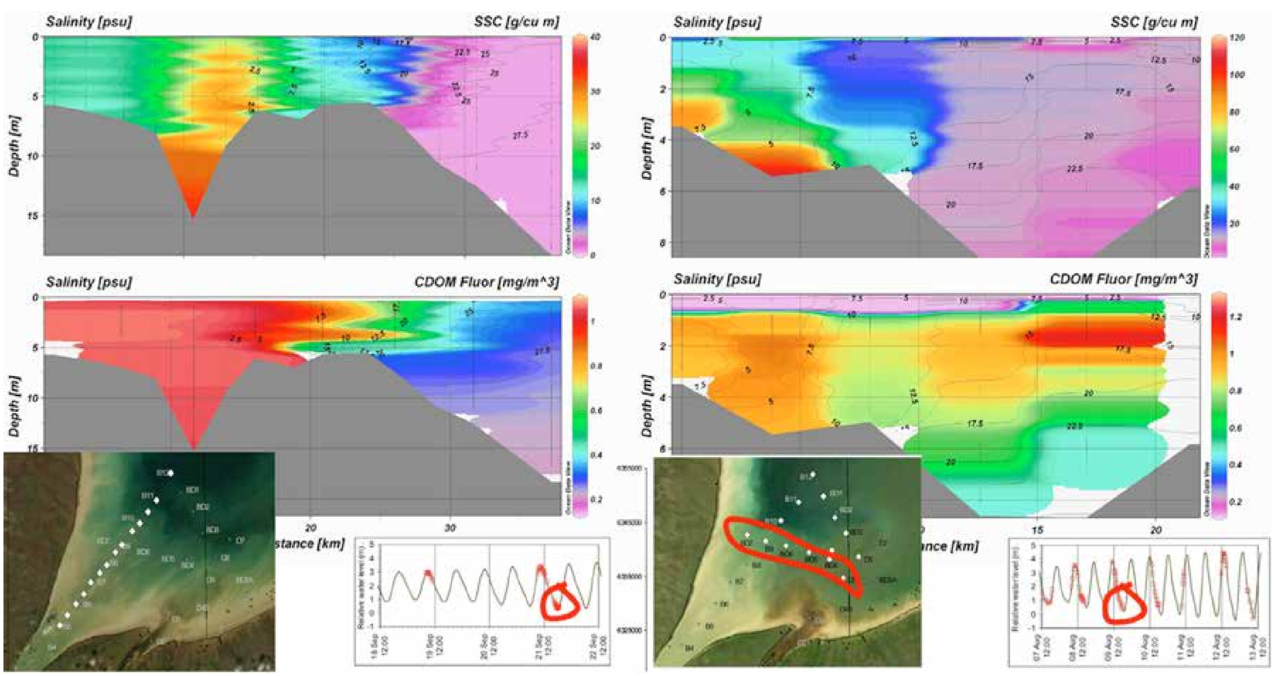

Figure 2. *SSC and CDOM along the centre axis of the Nelson estuary (left, circled set on tide chart) and across the Nelson and Hayes river plumes (right). SSC is determined using a local relationship with turbidity (r^2 = 0.96, n = 13). Satellite images are true colour renditions from MODIS.*

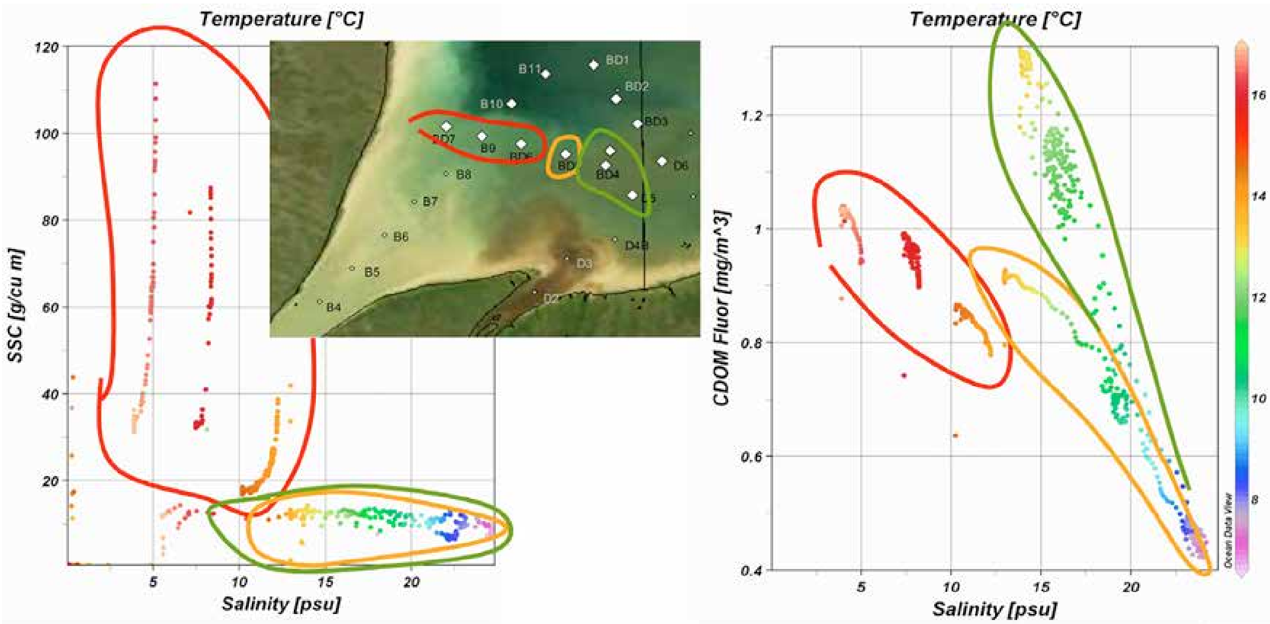

Figure 3. *SSC (left) and CDOM (right) versus salinity in the Nelson-Hayes estuary. Temperature is indicated by colour legend on right. Profile location groups are indicated by same colour bounds on plots and satellite image.*

observations and models, as well as measurements of salinity, oxygen isotopes, nutrients, chlorophyll *a* and particulate properties at in-estuary and non-estuarine sites under landfast ice and the shore flaw lead. This analysis shows the relative influence of sea ice and river water on the region's freshwater budget. In Button Bay, outside the influence of the river plume in winter, ice production in the flaw lead causes salinization until the end of March, followed by a gradual freshening of the water column through April-May. In the same region in late May, the high flows of spring freshet and the deterioration of the ice rubble zone around the Churchill River estuary allow river plume waters to spread to Button Bay, initiating stratification.

Before the onset of melt, conditions in the estuary depend on the physical interaction of river inflow, the overlying landfast ice, and the rubble zone along the seaward margin of the landfast ice, and consequently are highly variable through time. Figure 4 shows the deeper pycnocline in the pre-melt and early melt periods compared to that developed during the spring freshet. This thinner brackish water layer develops later in spite of the much higher river discharge of the spring freshet. The rubble zone impounds river discharge, creating a local region of reduced near-surface salinity, strong stratification, increased residence time, and increased nutrient concentrations, but is apparently eroded or broken down by flow from the spring freshet. Heat injected with the fluvial inflow advances ablation of landfast sea ice in the estuary compared to fast ice outside the zone of estuarine influence. In 2006, radiant energy absorbed in the flaw lead was the predominant heat source causing early melt. The influence of this heat source was predominant until the increase in both discharge and river water temperature (associated with the freshet) carried in even more heat, thereby causing widespread melt to occur earlier near the river mouth than outside the influence of the plume.

3) Freshwater-sources distribution in Hudson Bay by CDOM analysis

Granskog et al. (2007) used transects of salinity profiles perpendicular to shore near major rivers flowing into both eastern and southern Hudson Bay to

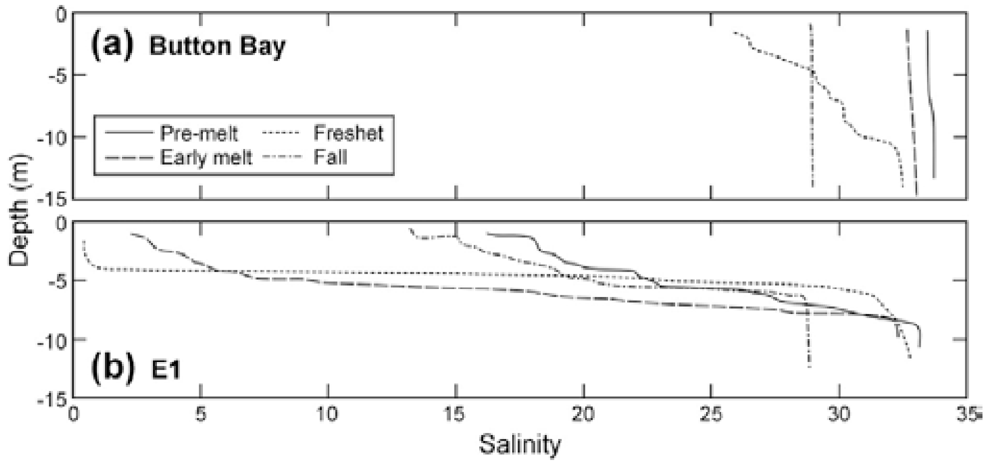

Figure 4. *Salinity profiles under the ice in (a) Button Bay (relatively isolated from the Churchill River estuary) and (b) near the mouth of the Churchill River in the pre-melt, early melt and freshet periods (spring 2005) and in open water in the fall of 2005 (Kuzyk et al. 2008).*

show that freshwater formed a brackish wedge as deep as 50 m near shore. The lowest salinities in surface waters (24 psu) were observed in surface layers reaching more than 50 km from shore near the Winisk River along the southern shore, and along the east side of the boundary with James Bay. In the same survey, the pycnocline was consistently at 20-30 m depth everywhere >100 km from shore. Patterns of freshwater distribution in the surface layer were described for the whole Hudson Bay by Granskog et al. (2007) using as a tracer the distribution of chromophoric dissolved organic matter (CDOM) in 470 water samples collected during the autumn Hudson Bay leg of the CCGS *Amundsen* 2005 cruise. Mixing of CDOM appeared conservative with salinity (Figure 5) although regional differences existed due to variable dissolved organic matter composition in the rivers discharging to the bay and the presence of sea ice melt, which has low CDOM concentrations and low salinity. This analysis indicates that river runoff is largely constrained to nearshore waters along the southern shores of Hudson Bay, but that, from James

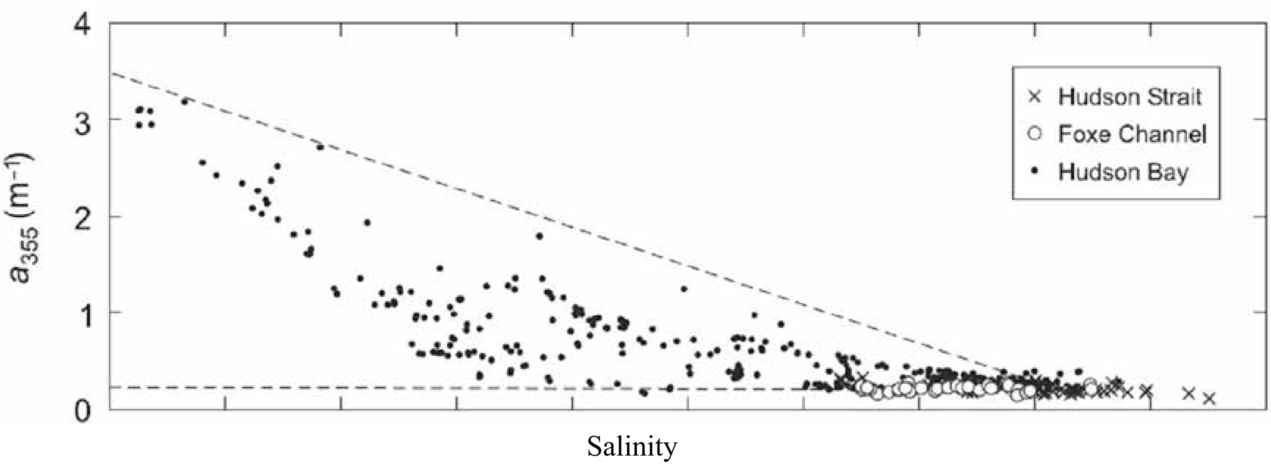

Figure 5. *a355 vs salinity (CDOM absorption at 355 nm) for data in the salinity range 25-35 in the Hudson Bay, Hudson Strait and Foxe Channel. Dashed lines show the conservative mixing of deep sea water with runoff and sea ice meltwater (Granskog et al. 2007).*

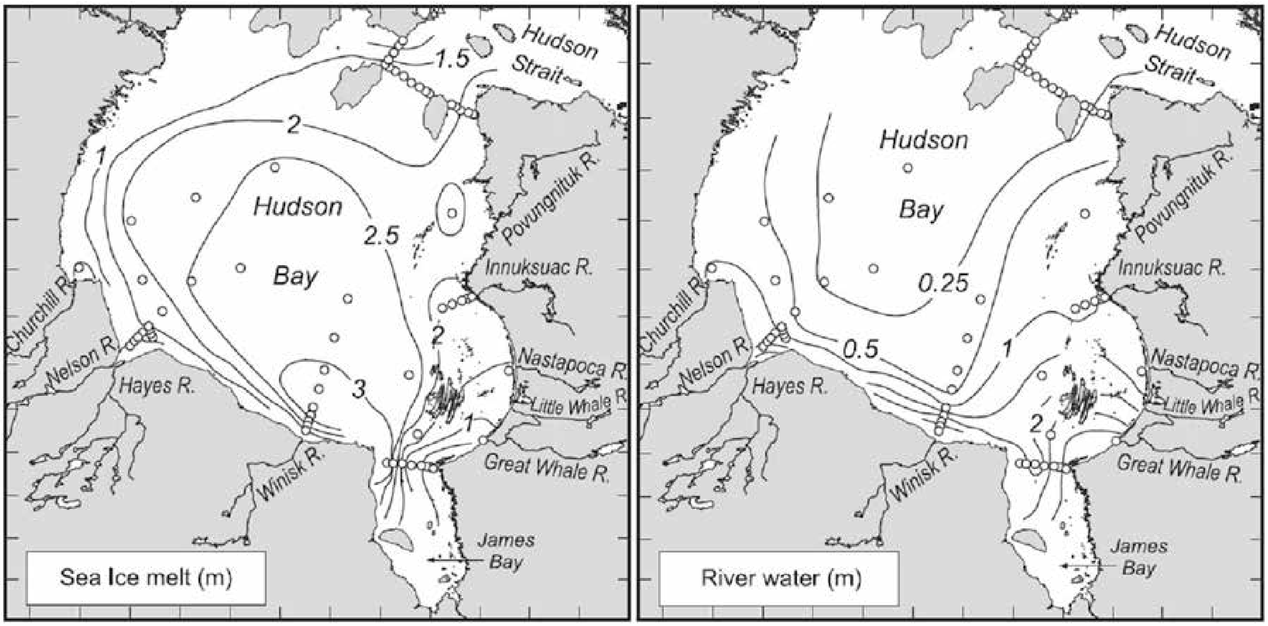

Figure 6. *Distribution of sea ice melt (left) and river runoff (right) thickness (m) inferred from mixing of salinity and CDOM from 3 sources: sea ice melt, runoff and deep sea water (Granskog et al. 2007). O= sampling sites.*

Bay to at least 61°N, its influence spreads more than 200 km from the eastern shore. This terrestrial run-off contribution is sufficient to noticeably reduce salinity in the surface mixed layers as far offshore as the Belcher Islands (Figure 6). Sea ice melt contributes most to the surface layer in south-eastern Hudson Bay, where it accounts for over three meters of the surface mixed layer, as compared to less than 1.5 m in the far northwest (Figure 6). This distribution is explained by the ice pack drifting southward as it melts – as expected from the general cyclonic circulation of the Hudson Bay waters, and evidenced by the satellite image record of ice motion during the break-up period.

4) Hudson Bay ice regime

Several datasets were used to describe the sea ice regime of Hudson Bay relative to environmental forcing, including weekly Canadian Ice Service (CIS) digital ice charts (1980-2005) gridded to 2.5 km resolution, and daily sea ice concentration data accumulated by the Special Sensor Microwave Imager (SSMI, 1980-2005) synthesized into weekly mean ice concentrations and their anomalies. SSMI is an internally consistent dataset of gap-free weekly ice information that compliments and extends the ice anomaly observations derived from the CIS. SSMI-derived maps are similar to those produced using the CIS dataset.

The CIS data describes ice type and concentration data, but contains gaps at the weekly scale. Nevertheless, it provides an excellent spatial representation of sea ice anomalies over the 26-year period. From the CIS data, several sea ice products for Hudson Bay were prepared, including maps of historic mean ice concentration, maps of trends in sea ice concentration by ice type, maps of coefficients of determination and statistical significance of trends, and maps of mean squared error (ice variability) which highlight zones of variability. From SSMI data, a 26-year, gap-free ice concentration record for Hudson Bay, Hudson Strait and Foxe Basin was prepared (Figure 7).

Atmospheric data used in this study were compiled from the Meteorological Service of Canada station data from 14 communities around Hudson Bay, as well as from gridded North American Regional Reanalysis data from the National Centres for Environmental Prediction. These atmospheric data were examined to explain observed trends in sea ice concentration and distribution. Upper air data were also used to examine ice motion within Hudson Bay, in particular its relative vorticity over a 20-year period (after Lukovich and Barber 2006) to identify seasonal trends in vorticity that may explain observed changes in sea ice dynamics.

5) Melt-period albedo

Through most of the winter months, sea ice surface albedo is generally high (> 0.8) because a layer of dry snow covers the sea ice. When melt begins, the ice is partitioned into multiple surface types ranging from highly reflective white ice to absorptive blue ice, thereby introducing high spatial and temporal variability in albedo and associated radiative transfer of photosynthetically available radiation (PAR) to the base of the sea ice. The shortwave albedo is a major component in determining the surface energy balance and thus the evolution of the spring melt cycle and sub-ice PAR. In March-May 2005, spectral albedo was measured at sites ranging from highly reflective white ice to absorptive blue ice in Button Bay, near the mouth of the Churchill River (Ehn et al. 2006). Integrated (350 - 1050 nm) albedo varied between 0.52 and 0.95 at the blue ice sites, and only between 0.73 and 0.91 at white ice sites. Spectrally, variability was least at 450-550 nm (*i.e.*, at the wavelengths of maximum solar energy reaching the Earth's surface) although still 0.66-0.96 and 0.79-0.91 at blue and white ice, respectively. Both ice site types showed rapid changes in the albedo in response to typical Subarctic climate conditions, frequent incursions of southerly air, resulting snow and rain events and the generally high maximum solar insolation levels. Diurnal variations alone, due to daytime melting and nighttime refreezing, were responsible for most of the variability in broadband albedo. This work is key to understanding how earlier spring weather will affect the ocean-sea ice-atmosphere interface in the context of climate warming in Hudson Bay.

6) Use of SAR for determining first-year sea ice albedo during the melt period

The parameterization of sea ice albedo during the melt period, which is characterized by high spatial and temporal variability in the fractional coverage of melt ponds, represents a significant challenge for both the modeling and remote sensing communities. Widespread cloud cover inhibits the use of optical sensors for providing large-scale estimates of sea ice surface albedo. Scharien et al. (2007) compared C-band (5.3 GHz) Synthetic Aperture RADAR (SAR) data from ENVISAT-ASAR with surface climatological albedo estimates derived from high-resolution Quickbird VIS-NIR imagery to demonstrate the utility of high-resolution, dual-polarized (VV, HH) SAR for detecting variations in albedo of melt pond covered landfast first-year sea ice (FYI) adjacent to Hudson Bay. This study shows that the use of co-polarization ratio γ improves correlation to albedo when compared to conventional like-polarized SAR backscattering coefficients. A regression model demonstrates that γ can be used as an estimator for

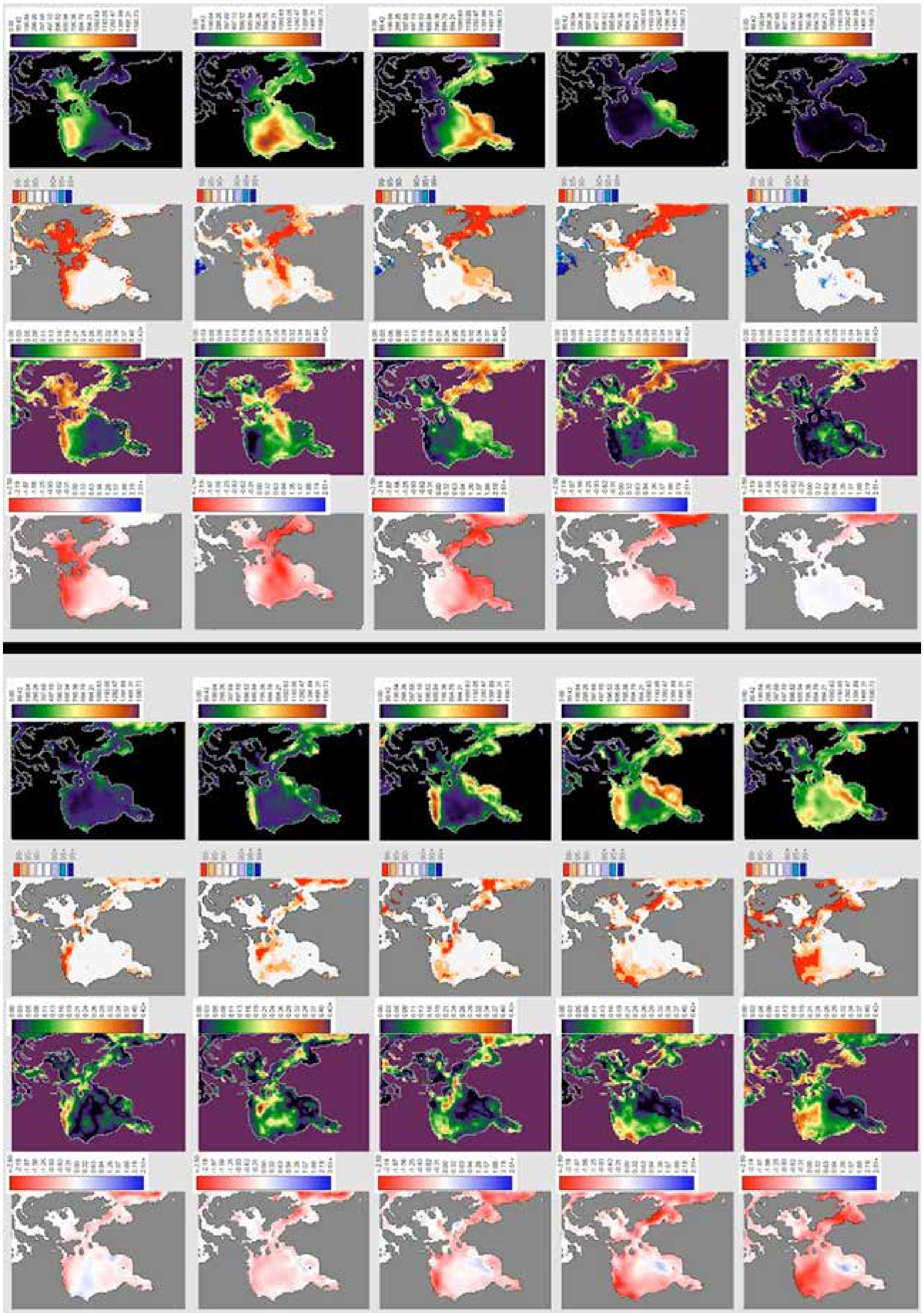

Figure 7. *Sea ice anomalies during ice development periods using SSMI data showing anomaly slopes per year for the period 1980-2005 with statistics describing the slope (columns 2-4: r^2, significance, and mean squared error) for weeks 18, 20, 22, 24 and 26 (by rows in left panel) and 46, 48, 50, 52, and 02 (right) (adapted from Hochheim and Barber 2010, Hochheim et al. 2010).*

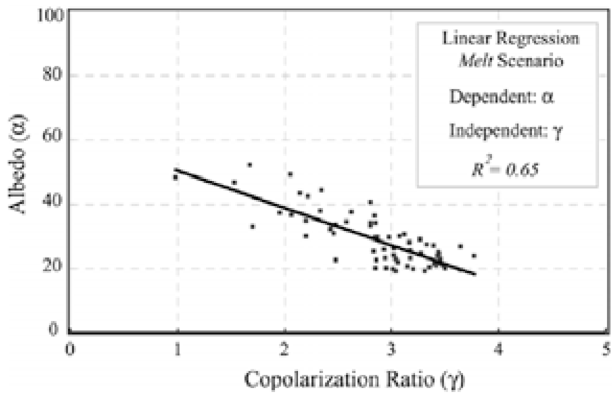

Figure 8. *Relationship between the SAR co-polarization ratio and surface albedo (Scharien et al. 2007).*

landfast-FYI albedo to within ± 5.2% (Figure 8). This relationship holds if SAR images are at a shallow enough incidence angle to induce separation between like-polarized channels and where Bragg surface scattering, characteristic of relatively shallow FYI melt ponds, occurs.

1.1.7 Discussion and conclusions

With high dissolved organic matter (DOM) concentrations in Arctic rivers, the influence of CDOM on coastal and ocean systems can be significant, yet the distribution, characteristics and potential consequences of CDOM in these waters remained largely unknown until the 2005 expedition of the CCGS *Amundsen*. Because of its shallow depth and small size, Hudson Bay receives a disproportionately large influx of river runoff compared to the Arctic Ocean. The dissolved organic solids carried into the bay by this runoff can have significant effects on the absorption of sunlight within the water column, the warming of surface waters (and subsequent impact on ice melt), nutrient availability, binding of pollutants, water chemistry, and interpretation of satellite imagery. Hydro development in the watersheds surrounding Hudson Bay has diverted and altered the normal seasonal flow of organic materials into the bay, and deserves assessment of its long-term impact. Measurements of CDOM, absorption, and salinity during the 2005 cruise of the CCGS *Amundsen* opened a new avenue of investigation into the relationships between river outflow and the properties of Hudson Bay waters.

As Granskog et al. (2007) reported, measurements during the 2005 cruise showed that mixing of CDOM is roughly conservative with salinity, with regional differences due to variable DOM composition among the rivers discharging to Hudson Bay and the presence of sea ice melt. High CDOM values were found primarily in the low salinity coastal waters. Western rivers – the Churchill, Nelson, and Hayes – carry a significantly higher load of organic carbon than those to the south and east. Using CDOM as a tracer, Granskog et al. (2007) showed that the river water contribution to the mixed layer decreases as the water moves cyclonically around the margin, but peaks at the outflow from James Bay. Runoff contributed a mean of 1.2 m (0.1 - 6.9 m) of freshwater in the mixed layer whereas sea ice contributed 1.6 m (0 - 3.9 m). Based on CDOM concentrations, Hudson Bay has considerably lower ultraviolet penetration depths than water in the North Water Polynya region (at the north end of Baffin Bay) while Foxe Channel and Hudson Strait waters to the north appear to be more transparent. Due to strong inshore-offshore gradients in CDOM-related transparency, deep chlorophyll maxima are typical only of the offshore regions, whereas chlorophyll maxima are shallow in the less transparent coastal waters.

The work of the project members in Button Bay complemented that conducted during the CCGS *Amundsen* cruise. Specifically, they conducted the first extensive multi-season measurements of late winter and break-up period processes in a small river estuary in the Arctic, and developed a comprehensive conceptual model of physical and biological processes within the Churchill estuary. Kuzyk et al. (2008) revealed the influence of ice structure at the landfast/rubble ice margin and freshwater ponding. Prior to the onset of melt, high nutrient supply and a long flushing time (~ 6 days) favour early primary production when conditions are still poor in the surrounding coastal environment. This favourable condition is terminated abruptly when breakdown of the ice rubble zone during the spring freshet releases the freshwater pool to spread more widely into the flaw lead or under the adjacent pack ice. The spatio-temporal complexity of the processes described by Kuzyk et al. (2008) showed that it may be difficult to make general predictions about the sensitivity and potential response of small Arctic and Subarctic estuaries to environmental change.

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1.2 The Hudson Bay Coastal Zone in a Changing Climate System (Project 3.2)

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1.2.1 Abstract

This project's research program consisted of field investigations within Subarctic tundra regions as well as aquatic and marine environments in and around the coastal watersheds of Hudson Bay between 2005 and 2008. The aim was to better understand the intra-system processes that cycle heat, water and carbon and inter-system linkages that deliver water and carbon from the headwaters of coastal watersheds to Hudson Bay. Researchers deployed a four-season monitoring network over land and water to provide the necessary information to better understand hydrometeorological processes within tundra ecosystems and their links to cycling of the major nutrients, GHG and system habitat, and to support the development and validation of a physically-based hydrological model. The research has quantified key hydrologic properties of tundra soils and established important parameterizations for the interception of rainfall by the lichen/moss ground cover. Interception rates and storage dictate rainfall contribution to soil/ground water storage and run-off and, as such, are important in the surface limb of the hydrological cycle. The canopy, though short, has amongst the highest rainfall interception rates of any natural vegetation canopies. Soil water has been observed to be a key factor in dictating tundra GHG exchange. Respiration exceeds photosynthetic CO_2 uptake during dry periods. Anaerobic habitats (wet) with high plant productivity (sedges) had high emissions of CH_4 and low rates of N_2O consumption, while aerobic environments (dry) characteristic of lichen mats and some mosses had low consumption rates of CH_4 and emission of N_2O. Differences in GHG emissions associated with slight gradients in soil conditions (moisture, peat accumulation, active layer depths) were not as pronounced as those between different plant community types, which suggest plant community types could be used to predict GHG emissions in similar environments. These findings imply that climate change-induced alteration of plant communities and particularly increased soil moisture, water levels and active layer depths in the landscape will increase GHG emissions and potentially contribute to further climate change feedbacks. Carbon-rich estuaries and low salinity coastal waters support net carbon emissions thereby lowering Hudson Bay's ice-free CO_2 uptake rates below other Arctic shelf environments. The relationship between marine carbon exchange dynamics, river discharge and associated load underpins the importance of integrated system science and demonstrates quite clearly that the impacts on coastal watersheds associated with climate change must be considered in Arctic marine sensitivity studies.

Two modelling initiatives were undertaken: 1) an assessment of parameterizations for the lower boundary fluxes using the Canadian Land Surface Scheme (CLASS) over the tundra environments, and 2) application and assessment of WATFLOOD and SLURP for application to the characteristic watersheds within the Hudson Bay Lowlands (HBL). In brief, the results indicate that the snowmelt process in the spring season produced the highest peak flow and the majority of the streamflow within a year. The findings support the notion that a shallow active layer inhibits infiltration of water, which enables the snowmelt from spring peak to flow. It is also evident that most small and moderate rainfall events during the summertime did not generate obvious runoff due to canopy interception, depression storage, soil layer porosity, and evapotranspiration. On the other hand, rainfall events that occurred in the fall months resulted in much more runoff than in the summertime because of reduced evapotranspiration. Overall, the modelling results indicate that time lags between the peaks of rainfall and runoff ranged from 2 to 8 days during the summer and fall, indicating considerable water storage capacity in the organic soil layer.

1.2.2 Key Messages

- Carbon-rich estuaries and low salinity coastal waters support net carbon emissions thereby reducing Hudson Bay's ice-free CO_2 uptake rates below other Arctic shelf environments.

- The Churchill River appears to be a CO_2 sink for much of the summer season in contrast to the behaviour of other northern rivers.
- "Hot-spots" of intense CH_4 emissions occurred in the sedge-dominated tundra areas of high moisture and plant productivity.
- Drying of the peat-dominated tundra pushes the system toward a net atmospheric CO_2 source.
- Subarctic ponds in the HBL act as CO_2 sinks.
- Subarctic fen systems appear to be strong summertime CO_2 sinks.

1.2.3 Objectives

The central objective of this project was to assess how linkages between Hudson Bay and the surrounding tundra ecosystems of the HBL will respond to climate change. Preliminary objectives for phase 1 were largely process-based and related to the linkages among the physical and biological systems of HBL tundra environments. Phase 1 objectives related to:

- *Ecological function*: To determine the characteristics of the emission/uptake of biogenic gases (methane, carbon dioxide and nitrous oxide) by tundra ecosystems and to document their sensitivity to environmental factors, including plant habitat, soil characteristics, hydrology and seasonally evolving microclimate.
- *Physical systems*: To determine the characteristics of the cycling of water and energy in and between tundra ecosystems and to document their sensitivity to environmental conditions (plant habitat, temperature, soil moisture and soil characteristics).
- *Hydrologic network*: To explore the linkages between watershed hydrology of the coastal tundra ecosystems and the physical and biogeochemical properties of the downstream estuarine and coastal marine environments. Also, to provide an initial assessment of the performance of physical hydrological models to simulate streamflow within the research domain.

Jointly, these objectives addressed critical knowledge gaps in the understanding of the cycling of water energy and nutrients in Subarctic environments (terrestrial, aquatic, estuarine). Parallel research by project members provided the foundation for the development of a physically robust hydrologic model for specific application to watersheds within the HBL.

1.2.4 Introduction

Arctic and Subarctic tundra ecosystems cover around 20% of North America, and roughly 2.5 million km^2 of Canada (Barbour and Billings 1999). This large area displays considerable variation in climate, soil flora and sizes of plant communities. The region is characterized by a cold climate, carbon-rich soils, expansive wetlands, seasonal darkness, a short growing season as well as variable precipitation and continuous to discontinuous permafrost. Collectively, the carbon-rich soils in the Arctic, Subarctic and High Boreal systems of Canada contain approximately 175.5 Gt carbon, equalling roughly 67% of the total soil carbon stock in Canada (Lal and Steward 1997), and approximately one-third of the world's soil carbon pool. A significant proportion of this soil carbon is located within the tundra ecosystems of the HBL. At approximately 324,000 km^2, they comprise the world's third largest wetland and second largest contiguous peatland (Ricketts et al. 1999). These ecosystems have historically served as a sink for atmospheric carbon because permafrost and waterlogged conditions severely restrict decomposition of plant matter.

A report of the Arctic Climate Impact Assessment (Hassol et al. 2004) has indicated that average Arctic temperature has increased at almost twice the rate as the rest of the world and current global climate simulations indicate that polar warming will continue to outpace that observed in other regions. Arctic ecosystems are strongly influenced by temperature, given that increases can lead to changes in permafrost extent, active layer depth, distribution of snow, plant community composition, hydrology and soil processes (Phoenix and Lee 2004). These changes will alter the emission/uptake characteristics of CO_2, CH_4 and N_2O, but the magnitude and direction of the response(s) for the myriad of tundra environments remains uncertain. Thus, the long-term fate of the vast northern soil carbon store is a legitimate concern because the circumpolar reserves of soil carbon, if liberated, would almost double global atmospheric CO_2 concentrations (Gorham 1991). In the HBL, the situation is particularly acute given the strong linkages between the region's climate and sea ice. The presence of summer sea ice in Hudson Bay promotes mesoscale airflow that extends the Bay's cooling influence over considerable distances inland (Rouse and Bello 1985). This coupling is in part responsible for delineating the southern limit of continuous permafrost and the northern treeline west and south of Hudson Bay, and seasonal reductions in sea ice extent are in part responsible for model predictions of warming in western Hudson Bay.

The Hudson Bay region is part of an extensive watershed that contains major hydroelectric development and production that hydrologically links Hudson Bay and southern Manitoba. The region houses a wide diversity of flora and fauna, including a significant denning area for the regional polar bear population. A profound effect of warming on the HBL would be the widespread melting of massive ground ice which would induce terrain slumping with effects on all surface features, including drainage patterns, terrain hydrologic characteristics, and sediment loads in rivers, thus affecting aquatic ecosystems and the downstream estuarine environments through increases in water turbidity and nutrient loads. Scientific studies, largely from temperate regions, indicate that the effect of river influx on estuaries is to supersaturate the water with respect to CO_2 (expressed in terms of fugacity of CO_2 (fCO_2)) relative to atmospheric levels (Borges 2005). Several factors are thought to contribute to this observation, including an abundance of labile organic carbon of terrestrial origin that supports bacterial respiration. Little research has been done on northern estuaries. Therefore, scientists have difficulties anticipating the downstream effects of changing watershed hydrology on the biophysical and biogeochemical processes and properties of these transitional systems.

The surface water storage and thermal modelling capabilities of existing hydrologic models are not suitable to model the low relief topography peatland soils and permafrost-dominated subsoils in the HBL. The understanding of the regions' biophysics and biogeochemistry is as of yet too crude to facilitate ecosystem modelling. Hence, it is difficult to predict with any certainty the region's hydrologic and ecological response to climate change.

Project researchers investigated the nature of coupling among the physical and biological systems within the tundra ecosystems of the HBL and, through collaboration with other projects of ArcticNet Theme 3 (*i.e.,* Ocean-Ice-Atmosphere Coupling (section 1.1) and Carbon and Contaminant Cycling (section 1.4)) that examined the nature and forcing on the hydrological transport of freshwater, organics and contaminant inputs into Hudson Bay.

1.2.5 Activities

1) 2004 - Ecological Function and Physical Systems

Project Network Investigators (NIs) completed a reconnaissance to identify sites for long-term ecological monitoring facilities. Existing datasets on surface meteorology and climate were gathered and an analysis of surface meteorology was undertaken. A sea ice flux station was deployed in December in the near-coastal zone in conjunction with researchers from Theme 3 projects (Ocean-Ice-Atmosphere Coupling and Carbon and Contaminant Cycling).

Data were used to characterize controls on sea ice thermodynamics and air-surface CO_2 exchange, and to provide boundary forcing on sub-ice biogeochemical and biophysical processes.

2) 2005 - Ecological Function and Physical Systems

In 2005, field sites were deployed and sampling/monitoring activities were initiated. In January 2005, the first of three comprehensive ecological monitoring facilities was deployed over a eutrophic fen. An extended snow survey was undertaken in March 2005 extending from the sub-boreal (Thompson, MB) to the Hudson Bay coast along a N-S transect in collaboration with researchers from the Meteorological Service of Canada. The purpose of the survey was to better understand the relationship between snow catchment and vegetation community. Two other ecological monitoring facilities were deployed in June within (i) a polygonized-peat plateau, and (ii) the coastal zone. These sites monitor components of the system's microclimate, including the heat budget, carbon fluxes, bulk meteorology and the water balance, and serve as foci for soil, water and plant sampling. Tower-based heat and carbon flux measurements represent the air-surface exchange integrated over surface patches hundreds of metres upwind of the sensor that are representative of landscape-scale biosphere-atmosphere exchanges.

Even apparently homogenous tundra is made up of different habitats that may show different energy and water-use characteristics that participate in GHG exchange to a lesser or greater extent, relative to neighbouring surfaces. Tower-based measurements alone do not provide a process-level understanding of heat, water and GHG cycling, hence fine-scale ecosystem monitoring was undertaken and included:

i. A network of rain gauges and weighing lysimeters deployed in June to monitor gross precipitation, and rainfall interception by a variety of vegetation canopies (forest to lichen/moss). Intercepted rain water is readily lost by the surface through evaporation, and constitutes a water source for the non-vascular lichen and moss species.

ii. A network of wells installed at the peatland site to monitor fluctuations in the water table to facilitate saturated hydraulic conductivity measurements as part of a pond water balance study and to explore the hydrologic coupling between ponds and tundra upland environments. A raft-based tower was deployed in the middle of a tundra pond to monitor evaporation in support of the water balance study.

iii. A transect of static vented chambers deployed at a peat and forested site, encompassing the dominant plant habitats in each ecosystem. Chambers were used to monitor surface GHG emissions (respiration of CO_2, CH_4 and N_2O). The purpose of this network was to better understand the relationship between landscape position, soil characteristics and plant habitat on gas emissions. Such relationships facilitated the scaling of fluxes according to surface cover and character. In a related project, GHGs were measured within the soil profile to gain information on the extent of microbial processes within the soil, and to better understand how these processes affect, and are related to, GHG emissions at the surface.

iv. A related project that made use of an automated CO_2 chamber flux system to monitor CO_2 exchange dynamics (respiration and photosynthesis – which is collectively termed net ecosystem exchange) from dominant lichen and moss species.

3) 2005 - Hydrologic Network

v. Two automated weather stations were deployed in the headwaters of a representative watershed of the HBL. Stations monitored bulk meteorology, radiation, and soil temperature and moisture. Water level recorders were installed in a major tributary stream of the Churchill River. The resulting river discharge and weather station data were used to develop and validate the hydrological model.

vi. Project personnel participated in the 2005 (September to October) cruise of the CCGS *Amundsen*. Sea-surface CO_2 fugacity (fCO_{2sw}) measurements were made at discrete stations within Hudson Bay and associated estuarine environments. Supporting data on atmospheric CO_2 concentration, water Chromophoric Dissolved Organic Matter (CDOM) concentration, sea-surface temperature and salinity were also available. The instantaneous flux of CO_2 was determined from ship-based measurements along the ship track. Fluxes of CO_2 were estimated following methods outlined by Else et al. (2008a).

4) 2006 - Ecological Function and Physical Systems

A focus of the 2006 activities was to broaden and extend baseline observations and field experiments in support of specific hypothesis-based process studies, the parameterization of processes for models, and model validation and initialisation. This season marked the last field program for the first cohort of ArcticNet graduate students. Activities added to the network included:

i. A tundra pond methane study involving the use of floating gas collectors that were deployed on ponds to capture gas bubbles originating from the pond benthic environment. Gas concentrations were subsequently determined using a gas chromatograph to derive an estimate of the methane ebullition flux. Complementary measurements of water depth, sediment thickness, organic fraction, redox and temperature were available to account for temporal and spatial variations in methane emission. Resulting measurements helped to determine the ponds' role in regional carbon budgets.

5) 2006 - Hydrologic Network

ii. Surveys were conducted in the estuaries of the Nelson, Hayes and Churchill rivers using the R/V *Strait Signet* (Nelson and Hayes) and by jet boat (Churchill, Nelson and Hayes). Transects extended 40 km, 25 km, and 3 km seaward from the freshwater mark in the Nelson, Hayes and Churchill rivers, respectively. Other transects were conducted transverse to these long transects. Three trips were conducted in total: early summer (Churchill), late summer and early autumn (Churchill, Nelson, and Hayes). Water quality parameters included: DOC, CDOM, $\delta^{18}O$, Chl/P, POC/N, TSS/LOI. Estuary water pCO_2 was measured in conjunction with water quality measurements to allow investigation into air-estuary carbon exchange and associated drivers.

iii. Helicopter- and surface-based reconnaissance within the experimental watershed was used to identify sites for seven stream/river level stage recorders that were subsequently deployed. There were two scales of sampling: large river sections farther afield from Churchill and accessible only by helicopter, and smaller river sections that were accessible by train and clustered within the peat and that dominated headwaters of the Deer River and Goose Creek – two tributaries of the Churchill River. Soil moisture and active layer depth transects were undertaken in association with the stream gauging. Water sampling was initiated in tundra ponds and along the reaches of gauged river sections for Hg, DOC, CDOM, POC/N, TSS/LOI and $\delta^{18}O$. Sampling was undertaken in conjunction with members of the Carbon and Contaminant Cycling project. The collaboration allowed researchers in both programs to convert concentrations to fluxes, given the availability of flow information from the sensors.

iv. A modelling strategy (2006-2008) has been developed as part of this project and centred on the assessment of existing physically-based hydrological models for application to rivers entering Hudson Bay through the HBL. Model assessment focused on the Deer River, which is a coastal tributary watershed of the Churchill River (Figure 1). Two models were selected for evaluation, including Semi-distributed Land Use-based Runoff Processes (SLURP, Kite 2002) and WATFLOOD (Soulis et al. 2000).

6) 2007 - Ecological Function and Physical Systems

2007: A new cohort of graduate and undergraduate students started their field programs in 2007. Baseline observations continued and field experiments were conducted in support of evolving hypothesis-based process studies. The resulting time series was necessary to capture inter-annual variability and to support the parameterisation of important processes. Field data were needed to place realistic bounds on modelled phenomena and for model validation.

i. Flux equipment from the coastal ecological monitoring station was removed allowing greater resources to be directed to the remaining peatland and fen sites. However, equipment to monitor basic meteorology remained at the coastal station.

ii. Emphasis for the monitoring of soil-plant GHG emission characteristics shifted from the peatland site to the fen site in 2007. A network of chambers, soil profile gas samplers and water wells was installed at the fen site

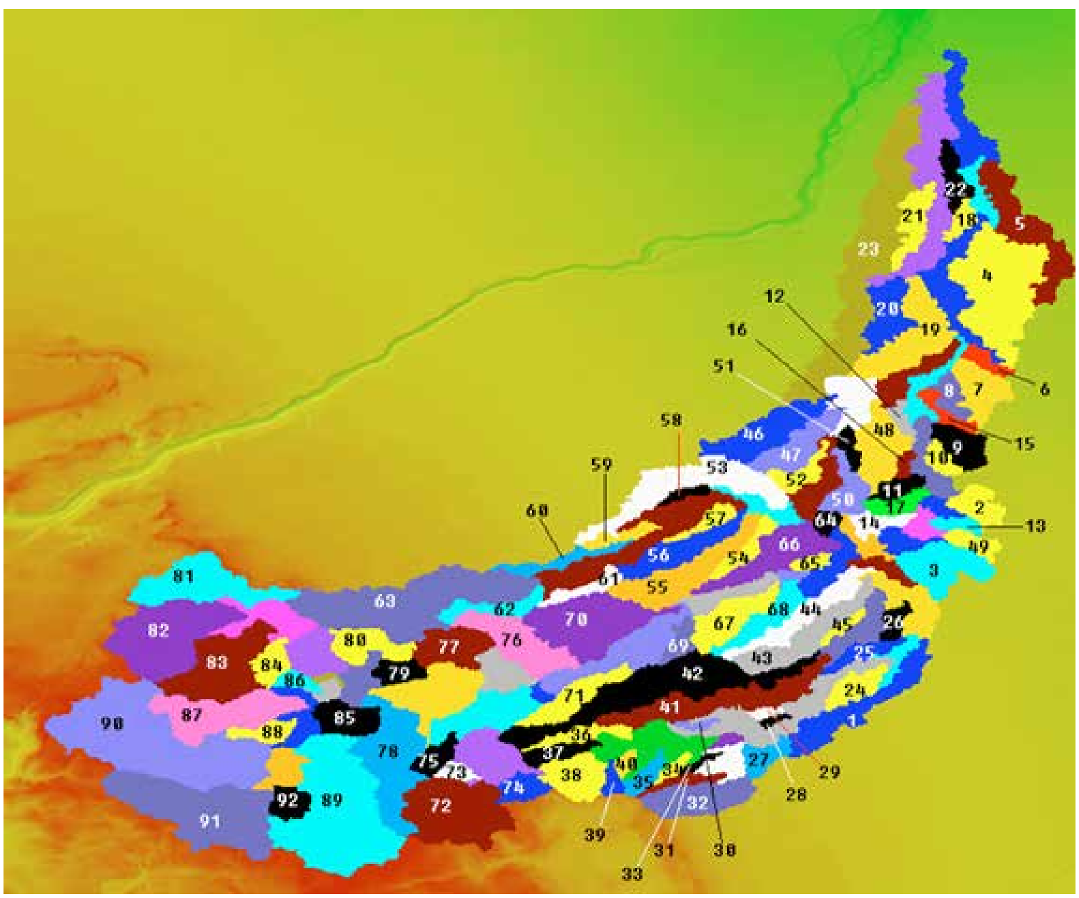

Figure 1. *Deer River sub-catchment boundaries. Numbers: sub-catchments (adapted from Jing and Chen 2011).*

to monitor methane and carbon dioxide emissions from the region's dominant microenvironments. Additional gas sampling transects were undertaken to provide insight into the inherent variability in gas exchange characteristics among hummocks and puddles, and to shed light onto the proportional contribution to the air-surface fluxes from the aquatic and terrestrial sub-systems. Information arising from this network allowed the researchers to determine footprint information on the tower-based flux measurement and provided a feature-based understanding of the gas exchange process.

iii. The tundra pond methane study of 2006 was expanded in 2007 to include CO_2. An infrared gas analyzer-based CO_2 sampler was used to monitor the partial pressure of CO_2 in the pond water. Benthic chambers were deployed at the pond bottom to monitor CO_2 uptake/efflux characteristics of the benthic algae, ultimately to quantify their impact in air-pond CO_2 exchange. Ancillary measurements of water pH, conductivity, temperature and oxidation-redox potential and oxygen were taken along with sediment temperature and reduction/oxidation reaction.

7) 2007 - Hydrologic Network

iv. Three main sampling programs were initiated within the Churchill estuary including: a) time series monitoring from a raft anchored in the middle of the river near its outlet of riverine pCO_2, for air-surface CO_2 flux, water temperature, pH and conductivity; b) long transects of air-surface CO_2 flux, water pCO_2 and chemistry along the estuary's freshwater to marine salinity gradient; c) high density CTD surveys to characterize the estuary's stratification and mixing characteristics.

v. CTD and water chemistry surveys were undertaken in the Nelson estuary in collaboration with members of the Ocean-Ice-Atmosphere Coupling project.

vi. Stream and river discharge monitoring and water sampling continued in 2007 and again focused on tributaries of the Churchill River within the coastal tundra.

1.2.6 Results

1) Greenhouse Gases – River and Estuarine

The lower reaches of the Churchill River near its estuary were found to be under-saturated in CO_2 relative to atmospheric values in June and July, switching to an oversaturated state mid- to late August and September. Net ecosystem production indicates that the river was autotrophic over the June to July period, switching to heterotrophic in mid-August. Overall, the lower reaches of the river were observed to be a sink for atmospheric CO_2 during the ice-free period (Stainton, unpublished). These results are striking, given that boreal rivers studied to date have been reported to be heterotrophic.

A strong relationship between dissolved CO_2 in sea water (fugacity of CO_2, fCO_{2sw}) and river discharge was identified during the fall (2005) cruise of the CCGS *Amundsen* (Else et al. 2008a, Granskog et al. 2007). The lower salinity coastal and estuarine waters were found to be supersaturated with respect to the atmosphere (in agreement with the work of Stainton et al. 2008), whereas offshore waters were observed to be undersaturated (Figure 2). Relationships of fCO_{2sw} with salinity, sea surface temperature (SST), and CDOM suggest that the supersaturation in the coastal zone is driven by a combination of the oxidation of riverine carbon and a decreasing solubility to CO_2 by the water with increasing water temperature. Instantaneous fluxes (*i.e.*, a negative flux is CO_2 uptake and a positive flux denotes outgassing) of CO_2 were calculated using ship-based tower measurements and were found to range from +14.8 mmol m^{-2} day^{-1} in James Bay to -22.3 mmol m^{-2} day^{-1} in Foxe Channel. Results indicated that nearshore estuarine environments act as CO_2 sources, while offshore regions of Hudson Bay act as a sink (Figure 3). Considering the assumption that air-sea exchange occurs only during the open-water season, these numbers suggest an annual contribution of -3.1 TgC for Hudson Bay, a value considerably

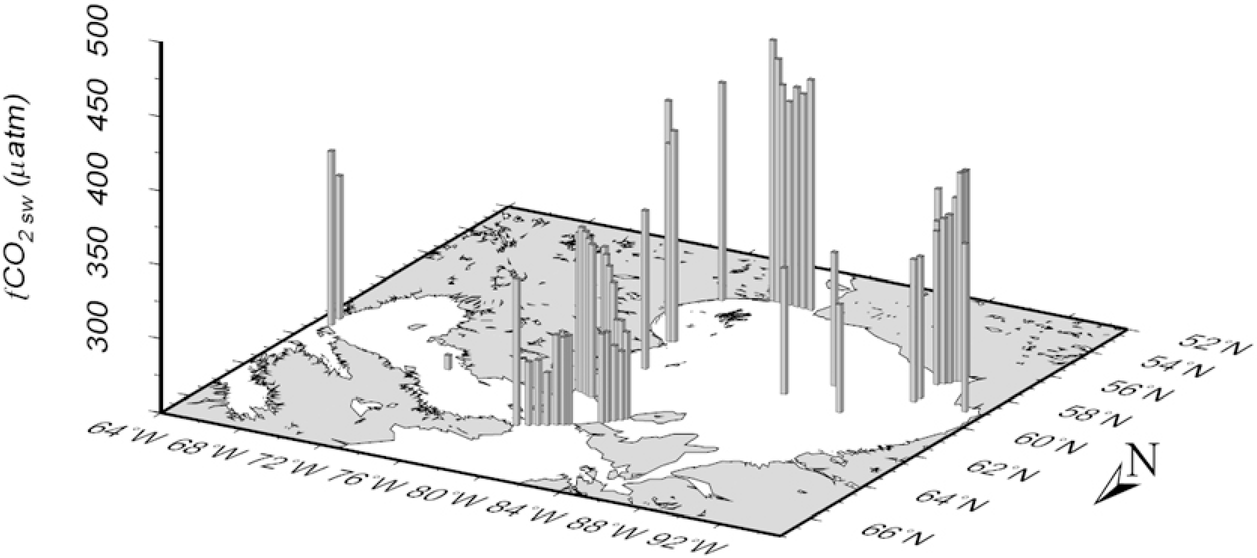

Figure 2. *Observed distribution of fCO_{2sw} in Hudson Bay. Note high values in the proximity of major estuaries (Else et al. 2008a).*

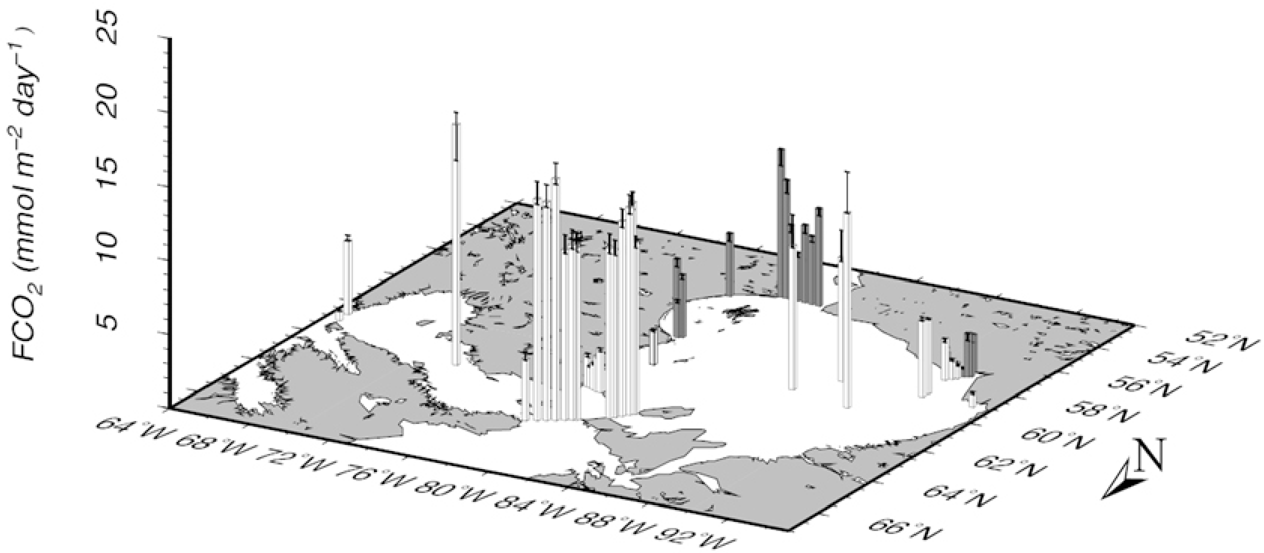

Figure 3. *Estimated long-term flux of CO_2 from NCEP reanalysis wind climatology and average fCO_{2atm}. Dark columns indicate positive fluxes (evasion) and white columns indicate negative fluxes (absorption). The error bars indicate the range of computed fluxes using the different transfer velocities (Else et al. 2008a).*

lower than expected for Arctic shelf environments. This low estimate is likely the result of CO_2 outgassing from the river estuaries and the associated freshwater plumes (Figure 4; Else et al. 2008b).

2) Greenhouse Gases – Tundra Systems

Results indicated that drought enhances the net flux of CO_2 from the tundra to the atmosphere. This net loss of CO_2 from the peat plateau is interrupted during times of vigorous leaf expansion during specific periods, which temporarily turns the peatland back into a net sink for carbon.

Wet tundra habitats, such as riparian areas, submerged peat ledges in ponds and sedge areas, continually showed high CH_4 production due to the increased moisture content and large amounts of plant biomass. Conversely, CH_4 consumption was related to low moisture content in areas with lichen-dominated plant biomass, such as polygon tops. Increased soil moisture and temperature coincided with increased respiration. GHG emissions were found to vary considerably between plant habitats. “Hot-spots” of intense CH_4 emissions occurred in the sedge-dominated areas of high moisture and plant productivity, while areas of low moisture and plant productivity resulted in low rates of CH_4 consumption. Conversely, areas of high moisture and plant productivity were sinks for N_2O, whereas low moisture and plant productivity areas were a source of N_2O, albeit at very low rates.

The differences in GHG emissions associated with slight gradients in soil conditions (moisture, peat accumulation, active layer depths) were not as great as those between different plant community types, which suggests that plant community types could be used to predict GHG emissions in similar environments.

Analysis of results from the pond benthic chambers indicated that the carbon budget in pond systems is benthically driven with strong daytime algal uptake of CO_2. Daytime uptake during the spring exceeds nocturnal losses both in magnitude and duration, in part explaining how dissolved CO_2 concentrations are pulled below atmospheric concentrations and forcing the ponds to act as carbon sinks. Shading experiments that isolate photosynthesis from respiration were undertaken.

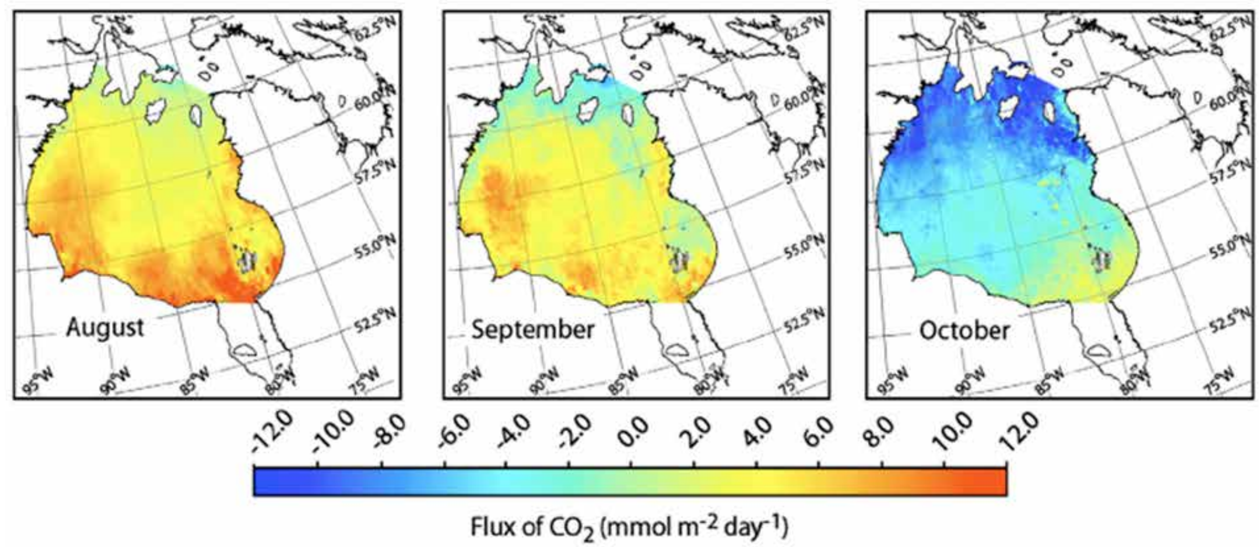

Figure 4. *Monthly maps of the flux of CO_2 for Hudson Bay during the 2005 open water season (Else et al. 2008b).*

Summertime CO_2 uptake from a Subarctic fen in the HBL is far in excess of most other Canadian Subarctic and Arctic sites. Measurements at the fen site between 2007 and 2008 indicated that the rate of uptake has increased, relative to rates observed in the 1990s according to published studies from the same site.

3) Water and Heat Budgets

The shortwave albedo is a major component in determining the surface energy balance, and thus the evolution of the spring melt cycle and the sub-ice light regime. In March-May 2005, Ehn et al. (2006) measured spectral albedo at sites ranging from highly reflective white ice to absorptive blue ice in Button Bay, near the mouth of the Churchill River. Integrated short-wave albedo varied between 0.52 and 0.95 at the blue ice sites, and only between 0.73 and 0.91 at white ice sites. Spectral variability was least at 450-550 nm (*i.e*., at the wavelengths of maximum solar energy reaching the Earth's surface) although still 0.66-0.96 and 0.79-0.91 at blue and white ice, respectively. Both types showed rapid changes in the albedo in response to typical Subarctic climate conditions, *i.e.,* frequent incursions of southerly air, resulting snow and rain events, and the generally high maximum solar insolation levels. Diurnal variations alone, due to daytime melting and night-time refreezing, were responsible for most of the variability in broadband albedo. This work was key to understanding how earlier spring weather can affect the ocean-sea ice-atmosphere interface as the temperatures are warming in Hudson Bay.

Evapotranspiration from the tundra sites showed pronounced variation in response to varying soil moisture (water table), rainfall, and radiant energy. The non-vascular lichen and moss species of the peat plateau possess very large maximum water storage capacities (S) compared to temperate and tropical forests (Gade 2006). This suggests that their ability to intercept rainfall is very large compared to other flora on Earth. The fungal component of lichens is responsible for their large water holding characteristic which is closely related to their biomass. Lichen storage capacities average 5 mm but are related to lichen biomass (B) following the average relationship, S = 2.15B. On the other hand, mosses can hold up to 25 mm of rain but relationships to biomass are much more variable with species ranging from 3.6 to 12.2 mm/kg/m^2.

Peat in this Subarctic watershed exhibited a 20-fold decrease in saturated hydraulic conductivity with increasing depth (between 10 and 30 cm) from 43.4 to 2.1 m d^{-1} (Yee 2007). This was consistent with an increase in compaction, bulk density and humification with depth, resulting in a decrease in porosity – all of which determine the soil's ability to carry and transmit water. These values were consistent with peatland values elsewhere which indicate generally poor conditions for groundwater flow compared to mineral soils. They also highlighted the importance of proximity of the water table to the ground surface for water to move quickly. As well, there were significant differences in saturated hydraulic conductivities between terrain units making up the watershed, ranked in order from highest to lowest as ice-wedge cracks, hummocks, drainage slopes and moraines.

The summers of 2005 and 2006 had strongly contrasting rainfall conditions and therefore can be used as an analog for understanding the possible effects of future climate-related changes on regional water balance components. Comparisons between years revealed that the least affected component of pond water budgets is evaporation. Lateral subsurface flow from Subarctic watersheds can provide large inputs of water to ponds, despite generally poor peat hydraulic conductivities. Deeper active layers did not necessarily imply greater sub-surface flow, owing to the impediments of highly compressed and decomposed peat at greater depths (Yee 2007). These findings are significant because shallow ponds are a ubiquitous component of the HBL occupying up to 40% of the landscape in polygonized wetlands. Due to permafrost melt and bank collapse, these ponds appear to be expanding in surface area and thus increasing their coverage of the landscape. Their primary function appears to be one of flood attenuation during «normal» years, thereby reducing the impact of lateral flow received downstream. However, with increasing precipitation, they appear to revert to sources of water, magnifying the lateral flow received by lower elevation landscape units towards Hudson Bay (Yee 2007). If all pond systems responded similarly, then the cascading effect of numerous linked watersheds should magnify the delivery of water to streams and, ultimately, higher summer rainfall should become the norm in Hudson Bay.

4) Modelling

A resistance-based model for the estimation of evapotranspiration from fen environments in the HBL was developed from field measurements and is suitable for application in surface modules for climate models (Raddatz et al. 2009).

Results from the hydrological modelling indicated that the snowmelt process in the spring season produced the highest peak flow and the majority of the streamflow within a year. The findings support the notion that a shallow active layer inhibits infiltration of water, which enables the snowmelt from spring peak to flow. It was also evident that most small and moderate rainfall events during the summertime did not generate obvious runoff due to the canopy interception, depression storage, soil layer porosity, and evapotranspiration. On the other hand, rainfall events that occurred in the fall months resulted in much more runoff than those in the summertime because of reduced evapotranspiration. Overall, the modelling results indicated that time lags between the peaks of rainfall and runoff ranged from 2 to 8 days during the summer and fall, indicating that there is considerable water storage capacity in the organic soil layer (Jing, unpublished).

Results showed that SLURP and WATFLOOD overestimated and underestimated the summertime runoff, respectively, which could possibly be attributed to the difference in evapotranspiration parameterizations used by the two models (Figure 5). In comparison with WATFLOOD, the occurrence of snowmelt and spring peak flow simulated by SLURP was relatively early in most of the simulation years partially due to the fact that SLURP employs an exponentially increasing snowmelt rate with date. SLURP performed better than WATFLOOD at simulating river and streamflow within the watershed (Jing et al. 2010).

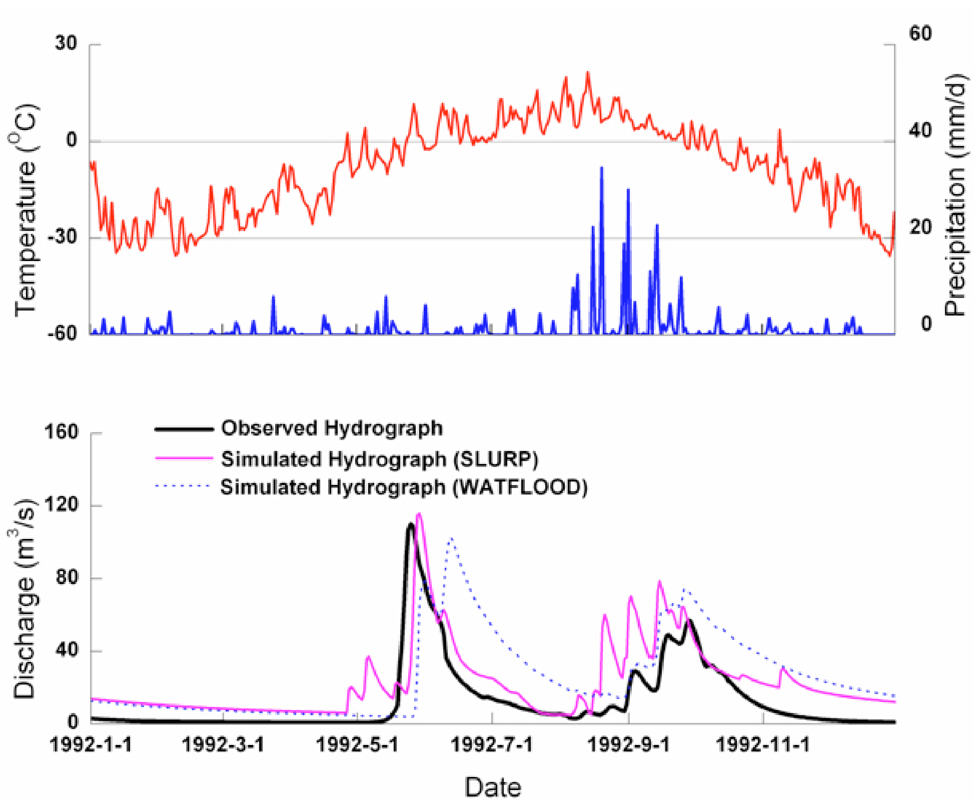

Figure 5. *Simulated and observed daily hydrographs for the Deer River watershed in 1992 (Jing et al. 2010).*

The surface boundary fluxes calculated using the CLASS, a module that links the atmosphere to biosphere in a commonly used robust watershed model, showed mixed results relative to measurements. The work compared simulated fluxes against fluxes derived from field data within a fen wetland, and assessed the performance of a new parameterization for canopy resistance from tundra dominated by non-vascular plant species. The comparison showed that cumulative fluxes of net radiation and evapotranspiration were well represented by CLASS for the fen wetland within the Deer River watershed. A recommendation is that the comparison be expanded to test model performance (hourly) against measured fluxes for critical periods within seasonal sub-episodes. The simulated cumulative totals of net long-wave radiation, sensible heat flux and the ground heat flux did not compare well against field-derived measurements. The work shows that the parameterization of the long-wave radiation flux can be significantly improved by adopting a different parameterization than currently exists in CLASS.

1.2.7 Discussion and Conclusions

1) Riverine influence on Hudson Bay

Hudson Bay is the downstream reservoir of a vast watershed that delivers large freshwater volumes to the marine system. Given this level of connectivity between the terrestrial/aquatic and marine systems, it is incumbent on the science community to understand the existing coupling mechanisms and to be able to anticipate the effect of climate change on watershed processes, including the downstream effects on the bay's major estuaries. These issues were embodied in the overarching objective of this project. Considerable effort went into creating a monitoring

network that provided the necessary information to: (a) better understand the tundra systems' hydrometeorological processes with linkages to the cycling of the major nutrients and GHG, and associated dependencies to system habitat; (b) critically examine the parameterization of the major hydrological, climatological and biochemical processes in physically-based numerical models; and (c) validate model performance.

Further attention is warranted in the river and estuarine environments of the region because the results suggest that the rivers could be atypical in their carbon dynamics relative to published results from boreal systems (Stainton, unpublished). Boreal streams and rivers are typically considered to be heterotrophic, whereas our data suggest that the rivers entering the bay are autotrophic, at least for much of the summer season. Remote sensing is a powerful tool for scaling observations in space and time. Satellite technology was used to produce regional CO_2 and CO_2 flux estimates for the Bay, yet the robustness of the parameterizations still remains to be tested.

Observations indicated that river discharge and associated terrestrial carbon input is responsible for pCO_2 patterns observed in estuaries and along coastal Hudson Bay (Else et al. 2008a,b). Relatively low off-shore rates of CO_2 uptake relative to other Arctic shelf environments likely result from lower than expected primary productivity for an Arctic shelf sea, and a larger than expected outgassing region due to high river discharge. This emphasizes the importance of collecting field data in the coastal regions. The relationship between marine carbon exchange dynamics to river discharge and associated load underpinned the importance of integrated system science and demonstrated quite clearly that the impacts on coastal watersheds associated with climate change must be considered in Arctic marine sensitivity studies.

Rainfall interception loss, controls on tundra evapotranspiration, and tundra-aquatic water delivery and storage constitute major knowledge gaps in the understanding of watershed hydrology. The current treatment of these processes represents a major impediment to model performance; however, this project provided significant contributions to improve model parameterizations of critical hydrological processes.

The attention to tundra ponds, and their role in regional water balances and water routing in particular was significant since: (i) these features have largely been ignored in the literature and do represent upwards of 40% of the land coverage; (ii) their coverage is expected to increase with regional warming; (iii) their role is anticipated as an important flood attenuator should higher summer precipitation become the norm.

2) Greenhouse Gases and Long-Term Fate of Carbon Stores

Contemporary carbon budgets for the peat-dominated tundra systems are still not known, because while the land portions appear to be net emitters of CO_2, ponds appear to be net CO_2 sequesters. Regional differences will depend greatly on the proportion of the landscape made up of land or water, and the nature of the land surface. The fen environments appear to be growing sinks of atmospheric CO_2. The total carbon budget also depends on the methane flux, yet a representative flux is still very much in question. Methane is of great interest because its greenhouse warming potential is approximately 23 times greater than that of CO_2, and studies have shown Subarctic and boreal ecosystems to emit CH_4 in significant amounts. Nitrous oxide (N_2O) is another powerful GHG and its warming potential is 300 times that of CO_2. This work showed that anaerobic habitats (wet) with high plant productivity (sedges) had high emissions of CH_4 and low rates of N_2O consumption (Churchill 2007). Conversely, aerobic environments (dry) characteristic of lichen mats and some mosses had low consumption rates of CH_4 and emission of N_2O. The importance of N_2O consumption in peatlands and wetlands may be considerable for the HBL and coastal areas. If concentrations of N_2O in the atmosphere continue to increase, there will be potential for a greater N_2O consumption gradient resulting in N_2O more readily diffusing into the soil. Because strong relationships were observed between GHG emission characteristics and plant community types, plant community types could be used to predict GHG emissions in similar environments (Churchill 2007). These findings imply that climate change induced alteration of plant communities. Increased soil moisture, water levels and active layer depths in the landscape will increase GHG emissions and potentially contribute to further GHG emissions and climate change feedback.

3) Hydrologic Modelling

Results indicate that two popular physically-based hydrological models (SLURP and WATFLOOD) do not reproduce identical summertime discharge, with SLURP overestimating and WATFLOOD underestimating discharge. Preliminary assessments (Jing, unpublished) indicate that the differences are largely related to parameterizations for evapotranspiration and snowmelt. Attention should focus, in particular, on the parameterization of these processes.

1.2.8 Acknowledgements

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1.3 Climate Variability/Change and Marine Ecosystem Resources in Hudson Bay (Project 3.3)

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1.3.1 Abstract

The main objective of the project was to assess how climate-induced variability and change in sea temperature, sea ice cover dynamics and the timing and intensity of river freshet affect marine biological productivity, fish stocks and marine mammals in Hudson Bay. This chapter summarizes the scientific activities conducted from icebreakers and land-based laboratories and observations from space. Large spatial and temporal variability was observed in the physical, chemical, and biological data. River plumes influence primary production, phytoplankton taxonomic composition, zooplankton dynamics and the feeding success and survival of fish larvae in Hudson Bay's immense estuarine system.

1.3.2 Key Messages

- Hudson Bay is characterized by relatively low primary production at the end of the summer, due to the strong stratification of the water column, which reduces the input of nutrients from depth.
- Phytoplankton, zooplankton and fish are in denser concentrations in the coastal zone and towards Hudson Strait to the north.
- Beluga whales make use of Hudson Bay during winter.
- Environmental and biological data are missing for the ice melt period in late spring-early summer.
- Continuous monitoring (physical data collection, remote sensing and marine autonomous observatory) is needed to detect changes in the ecosystem.

1.3.3 Objectives

The overarching objective of this project was to assess how climate-induced variability and change in sea temperature, sea ice cover dynamics and the timing, intensity and composition of the river freshet affect marine biological productivity, fish stocks and marine mammals in Hudson Bay. The hypothesis was that increasing sea surface temperature (SST) and changes in river discharge and decreasing seasonal sea ice duration would change biological productivity in Hudson Bay, with associated changes in species assemblages, migration patterns, distribution, and abundance of exploited and exploitable species. The specific objectives were to:

- Document and anticipate present and future availability of marine renewable resources to communities of Hudson Bay;
- Propose management strategies for sustainable exploitation.

1.3.4 Introduction

The Hudson Bay system (Hudson Bay, Hudson Strait, Foxe Basin) represents one of the largest drainage basins of the North American continent. Water mass characteristics and circulation in the Hudson Bay system are driven by freshwater dynamics, *i.e.,* fluvial input from the large drainage basin and sea ice formation and melt, and by inflows of Arctic and Atlantic waters in the northern region of Hudson Bay and in Hudson Strait (Ingram and Prinsenberg 1998, Jones et al. 2003). Seawater in Hudson Bay appears to be primarily of Pacific origin, transiting from the western Arctic (Beaufort Sea) through the Arctic Archipelago and reaching the Hudson Bay system through the narrow Fury and Hecla Strait to the north of Foxe Basin (Ingram and Prinsenberg 1998). This strong influence of Arctic (Pacific origin) water, in addition to Atlantic water that mainly affects the Hudson Strait region, and the important freshwater inputs make the Hudson Bay system a distinct Arctic environment exhibiting deeper water mainly of Arctic origin overlain by a thin freshwater (brackish) layer (Ingram and Prinsenberg 1998). The composition of the fauna appears to reflect these various water origins, with a dominance of Arctic zooplankton and fish (*e.g.*, Arctic cod) species that are mixed with estuarine and Atlantic species in the coastal regions of Hudson Bay and Hudson Strait (Grainger 1965, Rochet and Grainger 1988, Fortier et al. 1996). Moreover, the marine mammal community (seals, belugas, and polar bears) inhabiting the region is typical of the eastern Canadian Arctic, which demonstrates the Arctic nature of the Hudson Bay system (Stirling et al. 1999). Because of these multiple environmental forcings, a high biodiversity is expected for this region. This is why the Canadian Arctic Resources Committee identified the Hudson Bay system as an Arctic 'hot spot' for marine conservation (Beckmann 1994).

Significant physical and biological shifts have occurred in most polar environments (Overland et al. 2004), with mounting evidence of their impacts on the ecosystem and local communities (Grebmeier et al. 2006). The Hudson Bay system is no exception and has also been singled out as one of the most sensitive regions affected by climate change and variability (IPCC 2001; Heide-Jørgensen and Laidre 2004). The expected changes in physical forcing in the Hudson Bay system could also have a potential impact on the renewable resources in this marine ecosystem by altering the phytoplankton bloom dynamics and the associated food web structure, as well as distribution and abundance of marine fishes and mammals, and polar bears (see Gaston et al. 2003, 2005; Ferguson et al. 2005). Approximately half of the Inuit population of Nunavut and Nunavik lives in the Hudson Bay system. These physical and biological changes will have profound impacts on their hunting and fishing activities, on their ability to transport supplies and goods and on their economic development in general. Both of these regions' communities and others further south will have to face the significant consequences of these changes by developing adaptive strategies based on the knowledge of their environment. The ability to detect future climate-driven changes in the Hudson Bay system therefore strongly depends on the basic knowledge and understanding of the evolution of key oceanographic variables and of various components of the Hudson Bay ecosystem from lower to upper trophic levels. Unfortunately, this information is still fragmentary or missing (Dunbar 1970, Fortier et al. 1996, Harvey et al. 2006, Cusson et al. 2007).

Hudson Bay's marine ecosystem is expected to be influenced through changes associated with climate warming and through riverine input, which connects the Bay's system to human land-use practices, including agriculture, forestry, mining and hydroelectric development far to the south (south into northern USA and west to east from the Rocky Mountains to Québec, respectively). The ultimate goal of this project was to predict how the Hudson Bay marine ecosystem will respond to these potential changes, and therefore to provide better information to the stakeholders of Hudson Bay. The first steps toward this goal involved the collection of appropriate physical, chemical and biological data to add to the very limited historical dataset of Hudson Bay (*e.g.,* Martini 1986).

1.3.5 Activities

During 2004, project researchers participated in the Fisheries and Oceans Canada – Maurice Lamontagne Institute led MERICA Expedition (Harvey et al. 2006), which provided an excellent opportunity for this scientific project to study optics, ice algae/ phytoplankton, zoo- and ichthyo-plankton dynamics and vertical fluxes. Sampling was conducted in the Hudson Bay system aboard the CCGS *Pierre Radisson* from 1 to 15 August 2004. A project to analyze seven years of SeaWiFS (satellite ocean color) data to establish a baseline of surface phytoplankton biomass and to map the influence of riverine freshwater was commenced (see Figure 1). A community sampling program was initiated to determine stock and age composition of the beluga whale harvest around the northern Quebec coast, which included community visits to Salluit and Ivujivik to encourage their participation in the project and to provide feedback on beluga research in the northern Quebec area. Project members also completed the first ever aerial survey to determine beluga abundance in Hudson and James Bays. Furthermore, satellite telemetry transmitters, used to monitor movement patterns and diving behaviour of beluga and measure some important oceanographic parameters, were deployed on beluga captured at Petite Rivière de la Baleine (Nunavik).

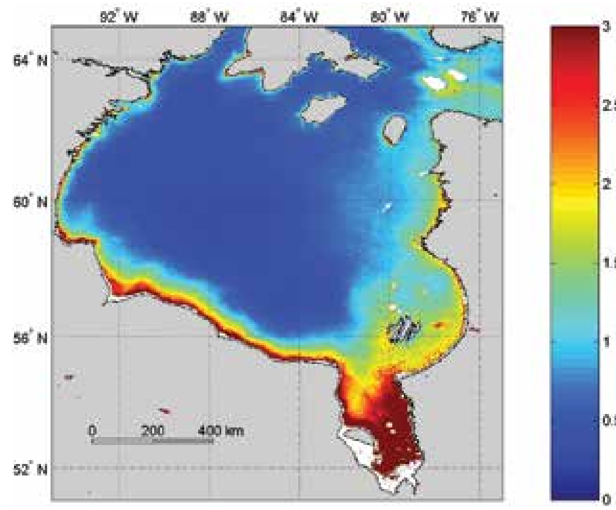

Figure 1. *SeaWiFS-derived surface chlorophyll a concentration for Hudson Bay averaged over 1998-2004. High values near coastal regions are an artefact of river water laden with coloured dissolved organic matter (CDOM) and therefore represent a proxy for the extent of river plumes.*

In the spring of 2005, in collaboration with projects on Ocean-Atmosphere-Ice Coupling and Climate Variability (see section 1.1) and on Carbon and Contaminant Cycling in the Coastal Environment (see section 1.4), project members participated in a sea ice study near Churchill, Manitoba, where temporal variation of bottom ice and surface water algae, contrasting an estuarine *versus* marine site, were sampled. Involvement in MERICA and the satellite work proved invaluable during the planning meeting for the 2005 ArcticNet cruise track. The end result was a very successful scientific expedition, which represented the most comprehensive coverage of physical and biological parameters collected in Hudson Bay over a single time period. Aboard the CCGS *Amundsen* from 15 September to 26 October 2005, researchers collected continuous acoustic surveys to remotely monitor the distribution of zooplankton and fish and sampled for optical properties, nutrients, phytoplankton, zooplankton and fish and short-term flux of particulate matter at discrete stations. The beluga study was also advanced through analysis of the telemetry data and the addition of a graduate student who examined the differences/similarities between telemetry data and Traditional Ecological Knowledge (TEK). These different datasets are known to provide complementary information, yet they suffer from weaknesses that need to be recognized when applied to resource management issues.

The processing and analysis of data from the 2005 ArcticNet cruise began between 2005 and 2006. Furthermore, project team members participated in the MERICA 2005 and 2006 expeditions, enhancing the temporal and spatial coverage of physical, chemical and biological data collected in the bay. During this time period, project members also collaborated with the project on Carbon and Contaminant Cycling, Makivik Corporation and local fishermen and communities to examine fish harvested by communities surrounding Hudson Bay for the determination of basic biological characteristics (*e.g.*, growth, feeding) of various fish species found in Hudson Bay. The pilot project in 2005-2006 included the communities of Rankin Inlet, Sanikiluaq, Inukjuaq, Puvirnituk and Ivujiviq. This project also fed into a preliminary community-based monitoring program targeting Arctic cod and capelin in collaboration with the project on People and Environmental Change: Linking Traditional and Scientific Knowledge (see section 1.6), which began in October 2006, and involved the communities of Umiujaq and Churchill.

Another important aspect of data collection in the bay was the deployment and recuperation of oceanographic moorings during both the ArcticNet and MERICA expeditions. In addition to monitoring physical parameters over an annual period, some of these moorings were equipped with biological sampling equipment, including sediment traps to measure vertical flux of organic matter and hydrophones to passively monitor the presence of marine mammals.

During 2007, researchers saw advancement in data analysis of the datasets mentioned above, as well as a continuation and improvement of the community monitoring programs. Furthermore, researchers were involved in the 2007 ArcticNet cruise aboard the CCGS *Amundsen* from 3-17 August, allowing for an additional year expansion of the Hudson Bay dataset.

1.3.6 Results

The dataset collected as part of ArcticNet and related studies in Hudson Bay was immense. Presented below are just a few selections from these data to illustrate the key findings.

Results from the analysis of the seven years of SeaWiFS data indicated that most of the bay is characterized by a low phytoplankton biomass with a relatively small seasonal cycle (Figure 1). Higher SeaWiFS-derived chlorophyll concentrations were detected near the coast of Hudson Bay and in James Bay but the analysis proved that this was an artefact caused by the presence of freshwater plumes extending far away along the southwestern and southeastern coast. Interannual variability was also highest along the coastal areas, depicting Hudson Bay's link to interannual variability of the river freshet. For the autumn period, Granskog et al. (2007) showed that the input of dissolved organic carbon (DOC) from rivers is largely confined to coastal areas of the bay as inferred from the distribution of coloured dissolved organic matter (Figure 2).

In Hudson Bay, the coastal zone is covered by landfast first-year ice from December to May-June (Saucier et al. 2004). During early spring, large river plumes are formed under complete landfast ice (Li and Ingram 2007). Observations of the ice algae community near Churchill showed a remarkable difference in algal species composition between a brackish (average salinity of 12) and a marine (average salinity of 32) site, with a strong contribution of

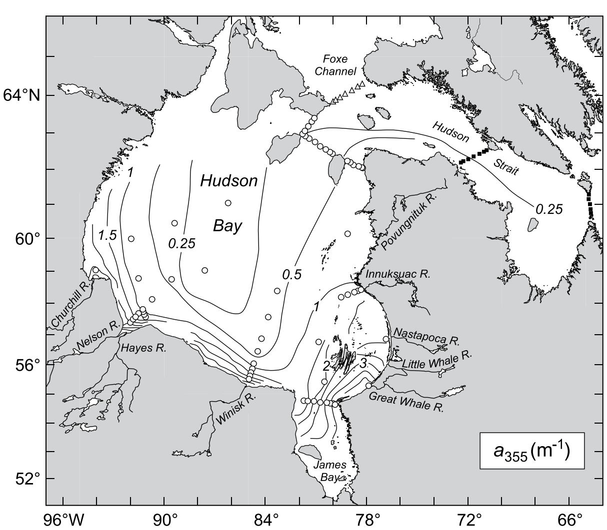

Figure 2. *Distribution of CDOM in the surface mixed layer of Hudson Bay and Hudson Strait during fall 2005. The absorption coefficient of CDOM (m^{-1}) was measured on filtered samples at 355 nm (adapted from Granskog et al. 2007).*

the pennate diatoms *Pauliella taeniata* and *Nitzschia* spp. at the brackish station and of flagellates at the marine site. In addition, a strong relationship between phosphate (PO_4^{3-}) concentrations and surface salinity showed that river water contains very low concentrations of PO_4^{3-} (Figure 3).

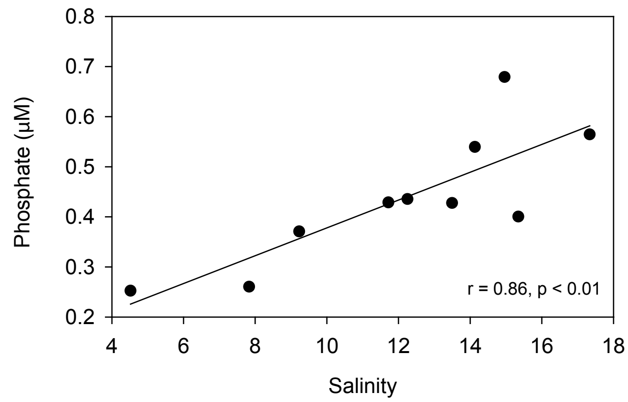

Figure 3. *Linear regression between surface water phosphate concentrations and salinity at a brackish (estuarine) station in southwestern Hudson Bay, spring 2005.*

The distribution of nutrients in the bay was highly heterogeneous, and the spatial patterns differed among nutrients (Figure 4). Concentrations of nitrate were generally highest in the west and particularly low along the northeastern portion of the bay. Local peaks in concentration were observed in Foxe Basin and the mouth of James Bay. The latter sector exhibited the highest concentrations of silicate by far. In contrast with nitrate, silicate was not systematically elevated in the western half of the bay and showed a wedge of very low concentrations in the northern part of the survey area. This wedge was associated with the highest concentrations of phosphate in the bay. The lowest concentrations of phosphate were observed in the western portion of the bay, near the coast.

In August-September, phytoplankton production in Hudson Bay and Hudson Strait varied from 50 to 1200 mg C m^{-2} d^{-1} and from 670 to 2700 mg C m^{-2} d^{-1}, respectively (Figure 5). In general, the main primary producers were large phytoplankton (> 5 µm) in the strait and small phytoplankton (0.7-5 µm) in the bay. In this system, total phytoplankton production was inversely correlated with the strength of stratification in the upper 80 m of the water column (Figure 5). This suggested that vertical mixing of the water column controlled primary production by governing the availability of nutrients in the euphotic zone (see Drinkwater and Jones 1987). Interestingly, large and

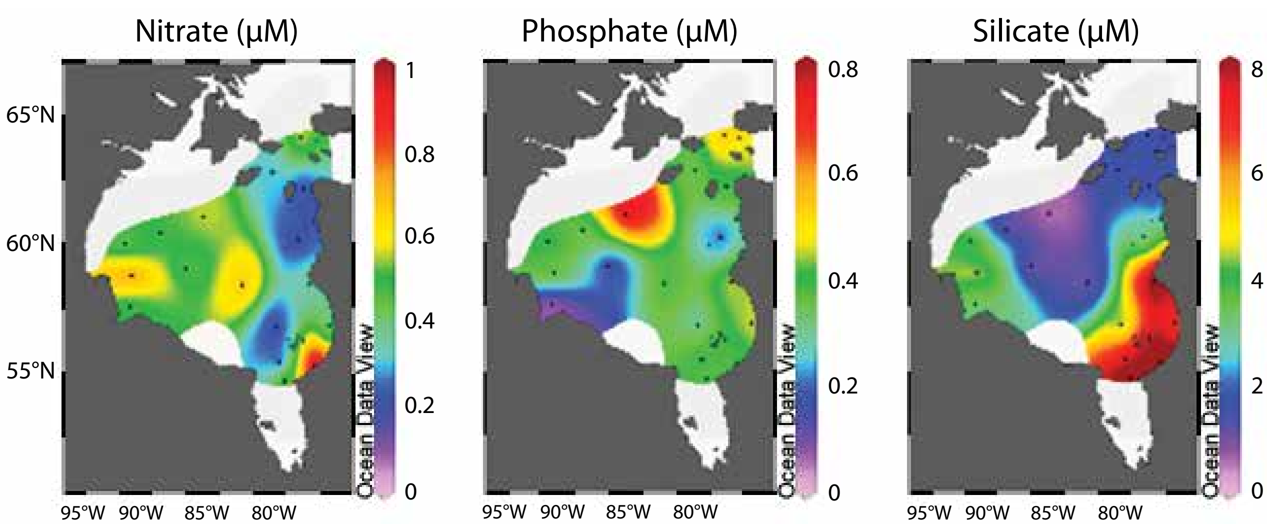

Figure 4. *Contour plots of the concentrations of nitrate, phosphate and silicate in the surface waters of Hudson Bay during fall 2005. This figure was produced with the Ocean-Data-View software (R. Schlitzer, http://www.odv.awi.de).*

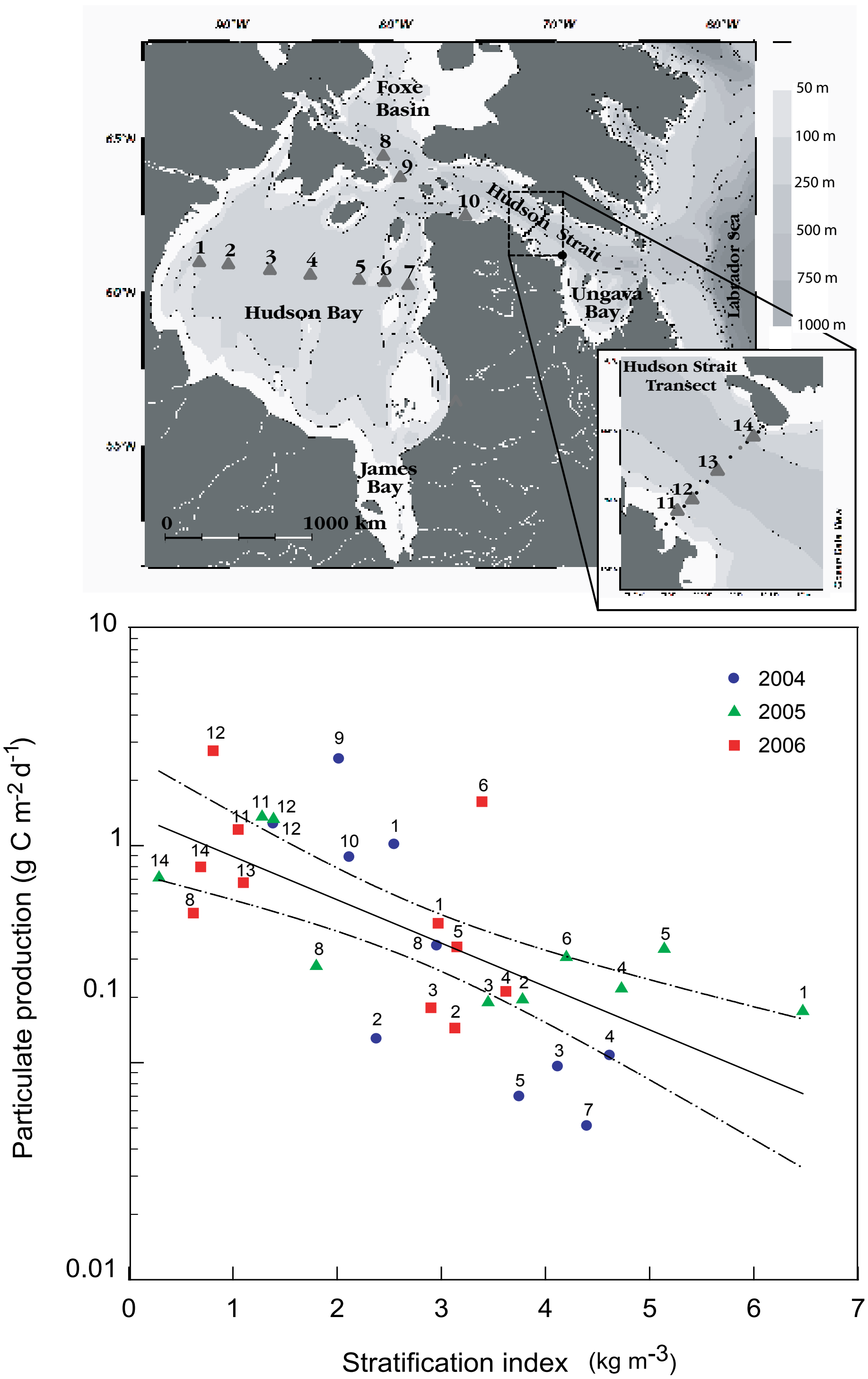

Figure 5. *Relationship between particulate phytoplankton production and the stratification index of the water column (i.e., difference in sigma-t between 80 and 5 m) in Hudson Bay during the 2004, 2005 and 2006 MLI-DFO led MERICA expeditions.*

small phytoplankton cells in the Hudson Bay system showed an unequal contribution to total production versus total chlorophyll *a* biomass. The results suggested that large algal cells accumulated in the euphotic zone, whereas small algal cells were grazed intensively by microzooplankton.

During the three sampling years (2004-2006), phytoplankton production increased towards Hudson Strait where the strength of stratification decreased. A similar tendency was observed in vertical fluxes of pigments (chlorophyll *a* and pheopigments), biogenic silica and particulate organic carbon (POC) at 50 m. POC sinking flux ranged from ca. 50 to 77 mg C m^{-2} d^{-1} at 25-50 m in the fall of 2005.

Continuous acoustic data were collected by the CCGS *Amundsen* to monitor large zooplankton and fish along tracks in the Hudson Bay system. Higher abundances were observed towards Hudson Strait (Figure 6). The center of the bay had very low abundances of zooplankton and fish that were restricted to a layer near the pycnocline. Near coastal areas, both zooplankton and fish became denser with the formation of an aggregated layer of zooplankton near the bottom.

The hydrophones were used to passively monitor marine mammals by their specific vocalizations. In southeastern Hudson Bay, the annual ArcticNet mooring provided a year-long record of these vocalizations and revealed the frequentation of this area by

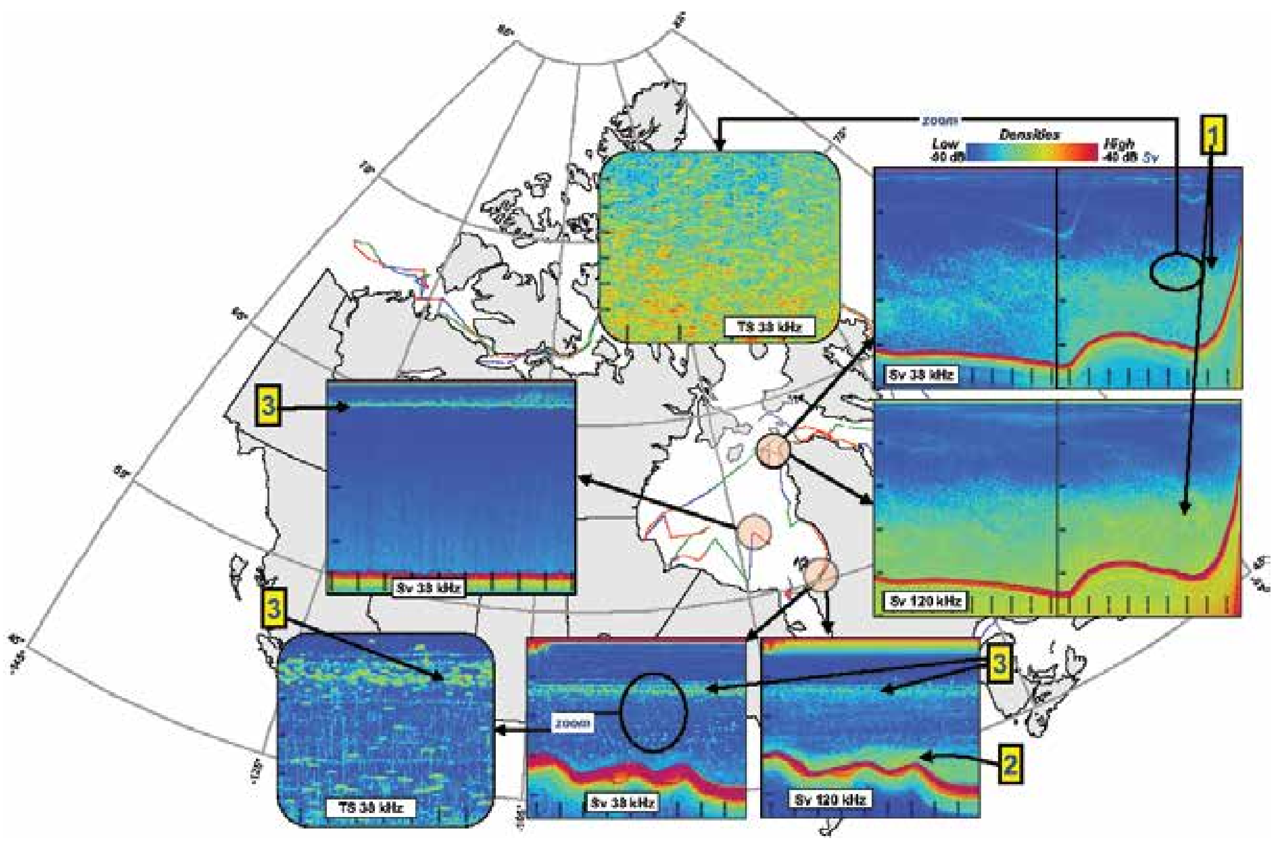

Figure 6. *Examples of dense fish and zooplankton biomass layers detected by the multifrequency acoustic system of the CCGS Amundsen demonstrating: (1) > 200 m thick layer of zooplankton/fish at the entrance of Hudson Bay, (2) zooplankton demersal aggregation along the coast, and (3) zooplankton and fish aggregation at the pycnocline.*

whales. Another finding was that beluga were present in recurrent polynyas in mid-winter. The TEK study has shown that the area between the Belcher Islands and the mainland is a common overwintering site for belugas. However, all belugas monitored via telemetry left the bay between September through November to overwinter off the Labrador coast.

1.3.7 Discussion and Conclusions

Hudson Bay hosts a complex interaction of marine, terrestrial and atmospheric processes that are extremely vulnerable to environmental changes and anthropogenic stressors such as regulation of the discharge from rivers and global warming (Gough et al. 2004, Déry and Wood 2005, Déry et al. 2005, Gagnon and Gough 2005). In particular, the future expected changes in inputs of freshwater and constituents (dissolved organic and inorganic nutrients and sediments) from major Hudson Bay rivers and nutrient-rich Arctic waters, as well as the decrease in duration and thickness of ice cover, have the potential to fundamentally alter the physical and chemical environment (circulation, stratification, light conditions, nutrients), and subsequently change the timing, amount, composition and fate of primary production, food web structure and function, which underpins ecosystem and renewable resources.

Hudson Bay is a "Mediterranean Sea" connected to Hudson Strait and Foxe Basin via narrow and relatively shallow channels that limit exchange of water between Hudson Bay and adjacent oceans (Pett and Roff 1982, Prinsenberg 1986a). River input (ca. 30% of Canada's total river discharge) and a near equal contribution of freshwater from sea ice melt govern the strong summer stratification observed in the bay and limit vertical mixing in the winter to < 100 m (Prinsenberg 1986b). The results showed that stratification controls primary production in the bay by limiting access to nutrients found at depth. This demonstrated the importance of studying the distribution of nutrients in the Hudson Bay system.

When interpreted collectively, the seemingly disjointed patterns in the surface concentrations of the different nutrients provided useful insights into the influence of rivers and external oceanic forcing on the bay. Firstly, phosphate was generally the limiting nutrient in rivers, whereas nitrogen was the limiting nutrient in oceanic water. This difference is due to the relatively intense fixation of atmospheric nitrogen in terrestrial ecosystems and, in the Arctic, is amplified by denitrification over shallow shelves (*e.g.*, Devol et al. 1997). Consistent with this paradigm, Figure 4 indicates that the lowest concentrations of phosphate were observed in the plume of the Nelson River, where they likely limited micro-algal production. The high concentrations of this nutrient in the northeastern sector of the bay and in Foxe Basin presumably represented the influx of Pacific-derived waters from the High Arctic. The low concentrations of silicate at these sites suggested that diatoms, which have a unique absolute requirement for silica, consumed the entire surface inventory as waters transited from the High Arctic to Hudson Bay. North American rivers typically discharge considerable amounts of silicate into the ocean, due to rock weathering on the continent. This was clearly the case at the junction of James Bay and Hudson Bay in the south and, to a lesser extent, off the Nelson River. The relatively high concentrations of silicate on the eastern side of the bay were consistent with its proximity to exposed portions of the Canadian Shield.

In late summer, phytoplankton production in the bay is limited by nutrient supply. Rates of primary production in the Hudson Bay are similar to those measured in the Canadian Beaufort Sea during the 2005 ArcticNet expedition. However, the higher production rates in Hudson Strait were within the range of values estimated in northern Baffin Bay (Klein et al. 2002). In late summer, a large part of the phytoplankton production in the bay is probably processed through the microbial food web, whereas in the Strait it is probably processed through the herbivorous food web.

The results supported a general geographic distribution of marine resources with increasing production towards Hudson Strait and near coastal areas influenced by rivers. This general distribution agreed with previous observations (*e.g.*, Anderson and Roff 1980a,b; Roff and Legendre 1986).

Observations from both TEK and acoustic data showed that whales make use of Hudson Bay as an overwintering ground. These observations raised the question as to whether more mild winters associated with climate warming increase the overwintering use of the bay by marine mammals. Furthermore, the connection of biological production to stratification and river input raised the question if longer ice-free periods will result in lower stratification strength within the bay and therefore increase production, or if a change in river discharge and chemical composition will override the influence of stratification to cause an unpredictable change to the ecosystem.

Results obtained through the sampling and analysis of chemistry and biology accomplished within this project were used to provide information on compartment sizes and trophic fluxes needed to model the response of the ecosystem to environmental change. For this purpose, a Nutrient-Phytoplankton/ice algae-Zooplankton-Detritus (NPZD) model of the Hudson Bay system was developed as part of a PhD thesis under the MERICA program. However, monitoring of the Hudson Bay ecosystem needs to be continued to better characterize inter-annual variability and to detect future change. Furthermore, although ArcticNet and collaborating studies have greatly increased the knowledge and data reservoir of Hudson Bay, data gaps still exist. Of particular note is the complete lack of historical data on surface waters during the late spring/early summer period when sea ice melt is rapid and a surface phytoplankton bloom can occur, as indicated by SeaWiFS data. Additionally, this research has highlighted areas of rich biological production in Hudson Bay where researchers stand to gain considerable information. To this end, project researchers suggested attempting an earlier expedition into Hudson Bay to characterize its early summer state and to continually monitor specific regions, or hotspots, within Hudson Bay. These hotspots include (1) coastal areas where major Rivers enter the bay, such as the Great Whale, Nelson and Churchill Rivers, near the mouth of James Bay and between the Belcher Islands and the mainland, (2) to the west of the Belcher Islands, and (3) between Southampton, Coats and Mansel Islands and the mainland where exchange of water and weakening of water column stratification occurs. This project also identified other objectives to be pursued, such as to (1) identify and review data sources on the present exploitation of marine resources, (2) identify the expectations of Inuit stakeholders regarding new accessible resources in the context of a longer ice-free season and potential access to offshore regions, (3) engage Inuit experts and trainees in the design and implementation of the inventories of marine resources and ecological hotspots of the Hudson Bay system, and (4) engage Hydro Manitoba/ Hydro-Québec in the monitoring of marine mammal vocalisations.

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1.4 Carbon and Contaminant Cycling in the Coastal Environment (Project 3.4)

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1.4.1 Abstract

An assessment of mercury (Hg) fluxes and speciation throughout the Hudson Bay system was completed during field studies from 2004 to 2007 as part of ArcticNet Theme 3. Total Hg (THg), monomethyl Hg (MeHg), dimethyl Hg (DMHg) and atmospheric species (Gaseous Elemental Hg (GEM), Particulate Gaseous Hg (PHg) and Reactive Gaseous Hg (RGM)) were measured in the major environmental fluxes and aquatic reservoirs directly related to Hudson Bay. These data were collected for the purpose of identifying the major sources of Hg to Hudson Bay and evaluating their relative magnitudes. Concentrations of THg and GEM in seawater were low throughout the system, but marine stations influenced by Arctic Ocean waters displayed lower levels of THg than coastal regions and those influenced by river inputs. Marine MeHg and DMHg concentrations were very low in surface waters, but increased with depth and appeared near a 1:1 ratio suggesting a relationship in production. Rivers delivered approximately 1.9 tonnes THg per year directly to Hudson Bay, which is comparable to atmospheric inputs (1.5 tonnes/year), and their delivery of ~31 kg MeHg per year to the marine system. River MeHg delivery was not directly related to THg concentration but was linked to wetland prevalence in the watershed. Atmospheric Mercury Depletion Events (AMDEs) spiked snow pack Hg concentrations to 67.8 ± 97.7 ng/L during spring, but Hg levels returned to background values near 4.25 ± 1.85 ng/L within days. Net springtime loading of Hg to Hudson Bay from AMDEs was estimated at 2.1 ± 1.7 mg/ha which, for an area of 1.23×10^8 ha, is ~0.26 tonnes to Hudson Bay. Marine surface sediment concentrations ranged between 18 - 57 ng/g, and core profiles suggest that Hg capture by the system is both spatially and temporally heterogeneous. Superimposed upon the biogeochemical studies of Hg cycling was an investigation of the trophic structure of the pelagic food web in the Hudson Bay system. Select species of zooplankton and higher trophic level fish demonstrated significantly different $\delta^{15}N$ signatures in Hudson Strait compared to Hudson Bay (*Calanus* spp.) and in western compared to eastern Hudson Bay (*Gadidae* spp.). This project identified regionally specific trophic structure and proposed that the pelagic food web in western Hudson Bay is approximately one trophic level longer than in eastern Hudson Bay, and that this is due to increased consumption of pelagic fish by top level species in the western Hudson Bay region.

1.4.2 Key Messages

- Hg levels were generally very low throughout the Hudson Bay marine ecosystem, yet relatively high concentrations of MeHg and DMHg were found in deeper waters.
- Overall, rivers contributed a minor proportion of the total Hg entering Hudson Bay, but major rivers draining wetland areas contribute significant loads of MeHg to coastal regions.
- AMDEs provided little net deposition of inorganic Hg (Hg(II)) to marine ecosystems but atmospheric deposition remained a major source of Hg to the entire physical system.

- The trophic structure of the pelagic food web differed between western and southeastern Hudson Bay, which was reflected in higher MeHg burdens in western Hudson Bay top trophic level fish species.
- The net Hg flux into the Hudson Bay system (including Foxe Basin and Hudson Strait) was near steady state (~0.1 tonnes/year) and only 1% was estimated to reside in the biota. Atmospheric, riverine and sedimentary fluxes have increased since preindustrial times.

1.4.3 Objectives

The primary objectives of this project were to:

- Determine the sources of MeHg that bioaccumulate through Hudson Bay food webs;
- Determine historical and current Hg regimes in the Hudson Bay marine ecosystem;
- Determine the influence of trophic structure in Hudson Bay food webs on Hg burdens in fish and marine mammals;
- Model the internal/external transport mechanisms of Hg and estimate the annual net Hg budget in Hudson Bay.

Within these goals, the following sub-objectives were defined:

- To quantify Hg and MeHg fluxes to and from Hudson Bay;
- To quantify *in situ* methylation of Hg(II) in the marine water column;
- To quantify regional CO_2 exchange characteristics within Hudson Bay;
- To investigate the impact of hydro-electric development on Hg delivery to Hudson Bay.

1.4.4 Introduction

Organisms at the top of high and Subarctic marine food webs often contain elevated concentrations of MeHg, a toxic and bioaccumulative form of Hg. These high Hg concentrations in top predators are primarily explained by the natural tendency of MeHg to accumulate in living tissue and pass from one organism to another (biomagnification), concentrating in top level consumers. Marine mammals and fishes containing high concentrations of this neurotoxin are frequently observed throughout the global Arctic (Ariya et al. 2004), exposing northern peoples to serious health risks. The source of MeHg in high and Subarctic food webs remains unclear because well known sources in southern environments, such as wetland sediments, are limited in their productivity and connectivity with Arctic marine systems. Arctic ecosystems are subject to a variety of Hg fluxes, and their relative importance to biological Hg concentrations varies with magnitude and associated environmental parameters such as residence time and rates of conversion to other Hg species. Investigations of Hg fluxes and their relative importance to Hg and MeHg cycling in Arctic marine ecosystems provide insights required for determining the mechanisms responsible for high MeHg concentrations in Arctic biota and how projected alterations in hydrology or climate might affect the behaviour of Hg in Hudson Bay.

The geographic scope of this study was the Hudson Bay marine ecosystem, which includes Foxe Basin, James and Hudson Bays and Hudson Strait. Rivers directly entering Hudson Bay, as well as atmospheric and marine exchanges, were also included. Upstream regions from the extensive Hudson Bay watershed were excluded with the exception of the Churchill/Nelson River system, which represented a model study area to examine the influence of both wetlands and hydro-electric development on Hudson Bay.

The main focus of this project was to produce a mass balance model of Hg in the Hudson Bay marine ecosystem that described the distribution of Hg and evaluated the relative importance of Hg fluxes. It also aimed to investigate the sources of MeHg to high and Subarctic biota by comparing the relative importance of atmospheric deposition, delivery from the watershed by rivers and *in situ* production of MeHg in the marine system of Hudson Bay. This research aimed to provide the basis to determine potential impacts that changing environmental processes, such as those influenced by human development and climate, may have on the Hg budget within Hudson Bay. Evidence of changing climate in high Arctic and Subarctic regions suggests that major environmental processes like carbon cycling, the hydrologic cycle and atmospheric exchange with oceans can significantly affect the speciation and behaviour of Hg in marine systems. Since Hg is environmentally present in a variety of interchangeable forms, investigation of both the fluxes and conversion (production) of the biologically relevant Hg species was necessary to estimate impacts of environmental changes.

1.4.5 Activities

2004

Beginning in 2004, researchers from this project studied the springtime cycling of Hg between air and snow packs near Churchill, Manitoba (MB) (Figure 1), for two consecutive spring seasons to determine the net input of Hg to Hudson Bay from AMDEs. From March to June 2004, the frequency and intensity of AMDEs along the west coast of Hudson Bay was quantified using an automated Tekran Hg air speciation unit stationed at the Churchill Northern Studies Centre. Atmospheric concentrations of GEM, PHg and RGM were monitored while measuring concentrations of THg in surface snow collected over the sea ice on Hudson Bay. Samples collected from the Churchill and Nelson Rivers (Figure 1) were taken to determine concentrations of MeHg and THg (and additional chemical parameters) and thereby estimate Hg exports to Hudson Bay. Samples were collected on the Nelson River at the Limestone Generating Station every two weeks year-round. On the Churchill River, samples were collected both at the mouth of the Churchill River upstream of the weir at Churchill, and at Missi Falls at the northern outflow of South Indian Lake, approximately 250 km southwest of Churchill, MB. The sampling at Missi Falls was conducted in an effort to determine if the Hudson Bay lowland wetlands contributed significantly to the high concentrations of MeHg found in Churchill River water.

A coastal flux station was deployed during the spring of 2004 at Cape Churchill on Hudson Bay to monitor the near-shore exchange characteristics of CO_2. The resulting time series of CO_2 fluxes was a big step towards improving the understanding of the intertidal zone's air-surface carbon gas exchange characteristics.

During the MERICA cruise in 2004, a collection program for zooplankton and larval fish was initiated onboard the CCGS *Pierre Radisson* for the purpose of characterizing the Hudson Bay pelagic food web and determining the predator-prey relationships and their effect on MeHg burdens. Oblique (d = 1 m^2, 500 µm), vertical quadrupole (d = 1 m^2, 2 x 200 µm, 2 x 500 µm), and rectangular mid-water trawl (RMT, d = 9 m^2, 1600 µm) nets were used in 'live-catch' zooplankton tows to collect biota. Following retrieval, live zooplankton were sorted by genera and frozen immediately for transport. Zooplankton and larval fish were collected in Hudson Bay, Foxe Basin, and Hudson Strait (Figure 1).

2005

A sampling program was also initiated in the Northwest (NW) Passage and Hudson Bay onboard the CCGS *Amundsen* during the 2005 ArcticNet cruise. Concentrations of four Hg species (MeHg, DMHg, THg and dissolved GEM) were measured in seawater collected at the surface, middle and bottom layers of the water column. Preliminary Hg(II) methylation experiments were also conducted at numerous sites

Figure 1. *Map of Hudson Bay. Communities in which samples were collected are in bold text; water bodies in which samples were collected are in italicized text. (Modified from the Atlas of Canada, Natural Resources Canada; www.nrcan.gc.ca).*

using novel Hg stable isotope techniques. At each site, three bottle replicates of surface and bottom seawater were obtained and $^{198}Hg(II)$ and $MM^{199}Hg$ were added to all six samples. By adding both Hg(II) and MeHg isotopes, the research determined, for the first time, whether methylation and/or demethylation were occurring in the ocean water column by examining both the production of $Me^{198}Hg$ from $^{198}Hg(II)$ and the loss of $Me^{199}Hg$. Sampling also continued on the Churchill and Nelson Rivers as described for 2004.

During the 2005 cruise, researchers also began an intensive program for Hg and carbon measurement in Hudson Bay which consisted of three main aspects:

(1) Marine water mass measurements for Hg (THg and MeHg) were collected in each major water mass at all stations throughout the NW Passage and Hudson Bay regions. Water masses were determined from salinity and temperature profiles. $\delta^{18}O$ and trace metal samples were also obtained to provide ancillary water mass and chemistry information. Additional constraints on the aquatic flux of Hg to Hudson Bay were produced by focusing on river samples for dissolved and particulate THg, MeHg and trace metals. Such sampling was conducted at the furthest downstream freshwater site in nine major rivers directly entering Hudson Bay (Puvirnituq, Inuksuak, Nastapoka, Petite Baleine, Grande Baleine, Winisk, Hayes, Nelson and Churchill Rivers) (Figure 1).

(2) To determine sedimentary parameters of the Hudson Bay system, marine sediments were collected with box corers at 15 locations during the cruise, 13 within the Hudson Bay system and two within the NW Passage to be used for reference. Box cores were collected at major ship stations where supplementary water parameters were measured. Each box core was sub-sectioned at 1 cm intervals for the upper 10 cm, followed by 2 cm intervals for the next 10 cm, and 5 cm intervals for the remaining 25 cm. Each layer was further sub-sectioned for analysis of Hg, redox elements, polychlorinated biphenyls (PCBs), ^{210}Pb (for dating purposes), and carbon parameters (% OC, lignins).

(3) Throughout the cruise, zooplankton and larval fish were collected from each station as described for 2004. Additional fieldwork in the Hudson Bay system occurred during the spring and summer of 2005, with project members participating in ArcticNet-led field camps on the Hudson Bay coast from February to May and July. During this time, Hg, zooplankton, carbon, and water mass parameters were measured extensively in the coastal and estuarine regions of the Churchill, Nelson and Hayes rivers. Data from these spring and summer field camps complemented the seasonal data determined from the CCGS *Amundsen* September/October cruise.

Measurements documenting the surface water pCO_2, ΔpCO_2, and the air-surface flux of CO_2 across Hudson Bay were completed during the 2005 cruise.

In 2005, atmospheric Hg measurements were initiated in the Churchill region using an automated Tekran Hg air monitoring unit (Tekran 2573A) to measure GEM concentrations in a multi-year program.

2006

During the 2006 CCGS *Amundsen* voyage to the North Water (NOW) polynya and through the NW Passage, concentrations of four species of Hg (MeHg, DMHg, THg and dissolved GEM) in seawater collected at the surface, middle and bottom layers of the water column were measured. Primary research goals were to expand the preliminary Hg(II) methylation experiments begun in 2005. Again, using novel Hg stable isotope incubation experiments, rates of production of $Me^{198}Hg(II)$, $DM^{198}Hg(II)$ and $^{198}Hg(0)$ from the addition of $^{198}Hg(II)$ to seawater were determined. Furthermore, adding $Me^{199}Hg$ to water samples allowed for the examination of the production of $DM^{199}Hg$ from $Me^{199}Hg$, as well as rates of demethylation in the water column of polar oceans. Sampling also continued on the Churchill and Nelson Rivers as described for 2004. However, in 2006, the North Saskatchewan River upstream of Edmonton was also sampled as a reference site.

During the NW Passage and Hudson Bay sections of the CCGS *Amundsen* cruise, THg and MeHg were again measured in water, zooplankton, larval fish, sediments and rivers. During this cruise, it was also possible to collect samples in Fury and Hecla Strait and Foxe Basin (Figure 1) to complement those collected in Hudson Strait in 2005 and provide information on the exchange of Hg between the Arctic Ocean and Hudson Bay. Additional box cores of marine sediments were collected to supplement those from 2005 and to improve the geographical resolution.

A successful fish collection program was initiated in five northern coastal communities on Hudson Bay for the purpose of measuring THg, MeHg and trophic level parameters. Data was used to construct a model of Hg/trophic level relationships in Hudson Bay biota. Researchers also participated in field camps at both the Churchill and Nelson River estuaries and continued sampling in the Churchill, Nelson and Hayes River estuaries as described for 2005.

Continued GEM measurements in the Churchill area from March to October added pHg and RGM measurements to the atmospheric Hg sampling program with two additional air monitoring units (Tekran 1130/1135).

Work in the Churchill region throughout the summer of 2006 aimed at determining changes in surface water Hg concentrations after rainfall events. The focus was on the peat ponds of the coastal regions of Hudson Bay, which dominate the landscape in many regions of the Hudson Plains ecozones that comprise the coastal regions of Manitoba and Ontario. Sampling was undertaken in conjunction with members of the Hudson Bay Coastal Zone in a Changing Climate System project (see section 1.2). An additional wet deposition monitoring program was initiated by researchers from the Geological Survey of Canada to quantify the contribution of Hg in wet deposition (all forms of precipitation) to atmosphere/ocean exchanges by directly collecting precipitation from the coastal region near Churchill.

Also in the Churchill region, fieldwork studies of the permafrost were initiated with late winter fieldwork focusing on collecting permafrost cores representing different sub-environments of the coastal plains. The purpose was to investigate geological parameters of the coastal permafrost region and to quantify the contribution of Hg to Hudson Bay associated with permafrost melt and coastal erosion.

2007

Incubation experiments were completed in the NOW polynya during Leg 3 of the CCGS *Amundsen* program. The Hudson Bay Hg program with THg and MeHg sampling was continued during Leg 1 at stations of major water mass exchange (Hudson Strait North and South, James Bay East and West), as well as rivers directly entering Hudson Bay (Puvirnituq, Kogaluc, Grande Baleine, Winisk, Hayes, Nelson). The air sampling program in Churchill continued through May 2007, at which time the equipment was transferred to the CCGS *Amundsen* for a similar program during the ArcticNet and International Polar Year (IPY)-related Circumpolar Flaw Lead (CFL) project in the Beaufort Sea.

The team conducted a supplementary field trip to the Northwest region of Hudson Bay to measure Hg parameters (dissolved and particulate THg, MeHg) and ancillary parameters (trace metals, carbon parameters) in water and sediments at the outflow of Baker Lake, a region visited for the first time by the CCGS *Amundsen*. The outflow of Baker Lake represented the second largest direct input (after the Nelson River) of watershed runoff to Hudson Bay.

Work in the Churchill region was expanded to include sampling of a series of tributaries of the Churchill River for Hg parameters in an effort to measure the response of additional Subarctic systems to water level changes and rainfall events. Specifically, upstream regions of the Churchill River watershed (Mile 470, Goose Creek and Deer River) were included in 2007. Concentrations of contaminants were converted to fluxes with river discharge information. The temporal scope of the seasonal study was also expanded to include the freshet period in early spring.

1.4.6 Results

1) Atmospheric Hg Measurements

Year-round measurements of GEM in the Churchill region from May 2005 to May 2007 demonstrated average ambient GEM concentrations of 1.2 ng/m^3. However, GEM concentrations demonstrated seasonal characteristics throughout the year with increased fluctuations in the spring and summer months and increased stability during the early winter. While summer fluctuations tended to increase GEM levels frequently to > 3 ng/m^3, concentrations decreased to < 0.3 ng/m3 during the Arctic marine springtime, a phenomenon characterized as an AMDE.

AMDEs result from the oxidation of GEM in the Arctic atmosphere to RGM and PHg, both of which fall out of the atmosphere to snow packs (Kirk 2006, Kirk et al. 2006, Dommergue et al. 2003). During numerous springtime AMDEs measured near Churchill (MB), concentrations of THg in surface snow increased often to over 60 ng/L, demonstrating that AMDEs resulted in deposition of oxidized Hg (Hg(II)) to snow packs. However, immediately following the AMDEs, average concentrations of THg in snow declined drastically from 67.8 ± 97.7 ng/L to only 4.25 ± 1.85 ng/L four or more days afterwards (Kirk et al. 2006). In 2003, prior to the beginning of ArcticNet, THg was measured in surface snow collected daily over the sea ice and total gaseous Hg (TGM) concentrations were measured in the interstitial airspaces of snow packs. When concentrations of THg in the surface snow decreased, concentrations of TGM in interstitial airspaces of the snow pack increased sharply from between ~1.4-3.4 ng/m^3 to between ~20-150 ng/m^3, suggesting a reduction of deposited Hg(II) to GEM, which then diffused out of snow packs. At snowmelt in both 2003 and 2004, average concentrations of THg in meltwater collected over Hudson Bay were only 4.04 ± 2.01 ng/L. Using concentrations of THg in meltwater and snow water equivalent, the estimated net springtime loading of Hg to Hudson Bay from AMDEs is only 2.1 ± 1.7 mg/ha, indicating that only a small portion of the Hg(II) deposited during AMDEs enters Hudson Bay each spring (Kirk et al. 2006).

2) Hg in river waters

The average concentration of THg in unfiltered water from the Churchill River (1.71 ± 0.66 ng/L) was approximately two times higher than in the Nelson River (0.84 ± 0.36 ng/L). The average concentration of MeHg in water from the Churchill River (0.21 ± 0.11 ng/L), however, was approximately 3.9 times higher than in the Nelson River (0.05 ± 0.04 ng/L). Concentrations of MeHg in both the Nelson and Churchill Rivers were on average higher in 2005 and 2006 than in the previous two years. In the Nelson River, 54% of the THg was bound to particles > 0.45 µm in size, whereas only 11% of the THg was bound to particles in the Churchill River. Particles in the Nelson River were likely silt mobilized from bank erosion in numerous hydro-electric reservoirs along the river. Interestingly, dissolved THg concentrations remained fairly constant in the Nelson River throughout the year, whereas concentrations of particulate-bound Hg increased during the summer.

River water THg concentrations entering Hudson Bay were distinctly higher than those measured at marine stations, with few exceptions. Mean whole water THg concentrations in rivers ranged from 0.72 - 3.47 ng/L and dissolved Hg from 1.05 - 3.34 ng/L. Highest THg concentrations were found in either southern or high volume rivers with the exception of Baker Lake (0.72 ng/L), a large volume drainage with low THg. In rivers where whole water and dissolved THg were measured, dissolved Hg was the

greatest component of THg. In rivers sampled during high and low flow periods, high flow periods demonstrated greater THg concentrations than low flow periods. Based on the measured THg concentrations in rivers representing 26% of the total riverine discharge directly to Hudson Bay, it was estimated that rivers deliver 1.9 tonnes of Hg annually to this system (Hare et al. 2008). MeHg in rivers ranged from 0.061 ng/L to 0.157 ng/L and dissolved MeHg from below the detection limit (0.02 ng/L) to 0.10 ng/L. It was estimated that rivers deliver ~31 kg of MeHg annually to this system.

3) Seawater Measurements

Details of the measured concentrations of Hg species are reported in Kirk et al. (2008) and are summarized here. In 2005, seawater THg concentrations were low at all sites and all depths sampled, averaging 390 ± 470 pg/L. Concentrations of GEM were also low at all sites and all depths, averaging 24 ± 21 pg/L. Concentrations of gaseous DMHg, however, were extremely high at depths below 100 m at most sites (averaging 80 ± 37 pg/L) but were often very low at the surface (averaging 2 ± 1 pg/L). Concentrations of MeHg were also high in deep waters (on average 98 ± 34 pg/L) but were often barely detectable at the surface (on average 23 ± 11 pg/L). DMHg and MeHg were always present in a near 1:1 ratio suggesting that similar processes produce these two Hg species, or that one is produced from the other. In 2006, measurements of THg in seawater were completed in the northern region of the Hudson Bay system that included the Foxe Basin and Fury and Hecla Strait. Foxe Basin is a large shallow bay that provides a direct pathway for Arctic Ocean water to enter Hudson Bay. Similar to the studies in 2005, Foxe Basin exhibited low THg concentrations in the water column (overall mean of stations = 0.52 ng/L, standard deviation (sd) 0.2 ng/L).

The dissolved phase of Hg was undistinguishable from THg (overall mean of stations = 0.52 ng/L, sd 0.24 ng/L), indicating the dominance of dissolved-phase Hg and extremely low levels of particulate-bound Hg. In Hudson Strait, the only other pathway for marine water mass exchange between the global oceans and the Hudson Bay system, outflowing water column THg levels were equal to the system average at 0.52 ng/L (sd 0.04 ng/L, n = 9) while the inflowing Baffin Current on the northeast side had even lower THg concentrations of 0.19 ng/L (sd 0.04 ng/L, n = 7). Since the bathymetry of the Hudson Bay system limits the penetration and mixing of the inflowing Arctic Ocean and Atlantic Ocean currents to regional basins within the system, determining any impact of differing Hg levels in source waters is not straightforward. However, using the available models for marine water mass exchange between the global oceans and the Hudson Bay system, it was estimated that 1 tonne of Hg enters the region annually from Fury and Hecla Strait, while approximately 1.7 tonnes of Hg exit through the Hudson Strait (Hare et al. 2008).

4) Marine Biota

Hg and $\delta^{15}N$ measured along the food webs of both the southeastern and western Hudson Bay, including planktivorous zooplankton, insectivorous zooplankton, larval fish, piscivorous fish, Greenland cod and beluga, revealed the western Hudson Bay food web to be longer (Figure 2). Whereas $\delta^{15}N$ in planktivorous zooplankton was approximately equal in both food webs (8 ‰ ^{15}N), maximal $\delta^{15}N$ in the southeastern Hudson Bay reached only 15.2 ‰, 2.3 ‰ less than the maximal $\delta^{15}N$ measured in the western Hudson Bay food web (17.5 ‰ ^{15}N).

Zooplankton in the Hudson Bay system displayed noticeable differences in trophic levels and corresponding THg and MeHg burdens. Carnivorous zooplankton species such as *Cliona* spp. and *Euchaeta* spp. demonstrated THg and MeHg levels up to 142 ng/g (dry weight, dw), while solely planktivorous taxa *Thysanoessa* spp. and *Calanus* spp. contained maximum THg levels of 36.9 ng/g (dw). Correspondingly, *Cliona* and *Euchaeta* spp. contained up to 34.6 ng/g MeHg (dw), while *Thysanoessa* spp. and *Calanus* spp. contained maximum MeHg concentrations of 17.3 ng/g (dw). Similar results were

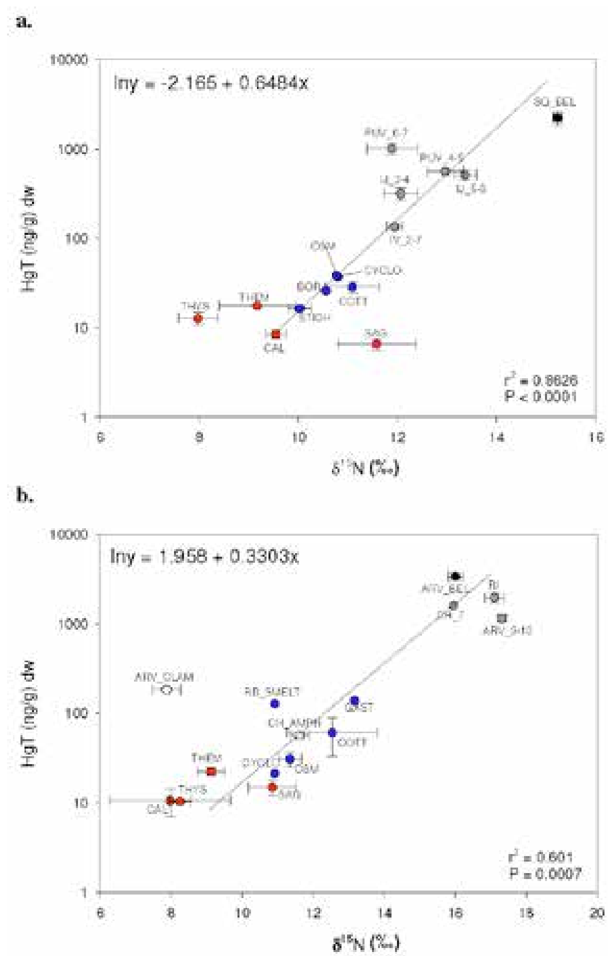


Figure 2. *Food web HgT (logarithmic) as a function of $\delta^{15}N$ in (a) Southeast Hudson Bay and (b) West Hudson Bay. CAL = Calanus spp., THYS = Thysanoessa spp., THEM = Themisto spp., SAG = Sagitta spp., BOR = BoreoGadidae spp., OSM = Osmeridae, STICH = Stichaeidae, COTT = Cottidae, CYCLO = Cyclopteridae, GAST = Gasterosteidae, RB_SMELT = rainbow smelt, ARV_CLAM = unknown Arviat clam species, AMPH = Anonyx spp. Adult Gadidae from: CH = Churchill, ARV = Arviat, RI = Ranking Inlet, PUV = Puvirnituq, IV = Ivujivik, IJ = Inukjuak. Green points = POM; red points = zooplankton; blue points = larval fish; grey points = Delphinapterus spp. from ARV = Arviat, SQ = Sanikiluaq; white points = miscellaneous food web members (Pazerniuk 2007).*

observed in *Themisto* spp. when separated into size classes; smaller *Themisto* spp., feeding lower on the food chain (according to $\delta^{15}N$ measurements), contained lower levels of Hg than larger *Themisto* spp. which fed at higher trophic levels. Biomagnification factors (BMFs; Fisk et al. 2001) for the zooplankton studies fell between < 1 and 19.8 and appeared to be regionally specific within genera. The lowest BMFs were observed in zooplankton from eastern Hudson Bay with the sole exception of *Calanus* spp., while the highest BMFs were generally recorded in Foxe Basin or southern Hudson Strait.

Investigations of THg and MeHg in high trophic level species (Greenland Cod, *Gadidae* spp.) in the Hudson Bay system demonstrated expected relationships between MeHg and age and size. However, they also demonstrated strong geographical influences. For example, while a significant correlation of THg with overall cod length was observed in all locations, results also displayed a consistent trend of higher THg levels in *Gadidae* from western Hudson Bay compared to *Gadidae* collected from eastern Hudson Bay communities. For instance, six year old *Gadidae* showed higher mean THg levels in Arviat (278 ng/g dw, n = 11) compared to six year old fish from Puvirnituq (221 ng/g dw, n = 3), Ivujivik (< 100 ng/g dw, n = 2) and Inukjuak (126 ng/g dw, n = 6). The overall observed THg trend in decreasing order followed Rankin Inlet = Arviat (NT) > Puvirnituq > Inukjuak > Ivujivik (Nunavik). THg was also correlated with age. For example, a seven year old *Gadidae* caught in Churchill had a THg level of 369 ng/g dw, which was higher than levels of seven year old *Gadidae* from the eastern Hudson Bay communities.

5) Marine Sediments

Surface sediment concentrations of Hg were low throughout the Hudson Bay system but varied up to three-fold between sampled locations. Surface sediment THg ranged from 18 - 57 ng/g dw, with the majority of cores displaying surface Hg concentrations in the range of 25 - 35 ng/g dw. Although previous investigations of Hg in Hudson Bay surface sediments are limited, a similar range of ~17.5 - 33 ng/g dw (n = 3) was reported in Stewart and Lockhart (2005).

Comparison of upper (younger) and lower (older) layers of the sediments commonly revealed that lower layers consistently contained equal or lower THg concentrations than surface layers. In some cores, peak concentrations were observed within the upper layers of the sediment core. No cores displayed Hg peaks within the deeper layers. The relationship between THg and the percent organic carbon (% OC) showed a positive correlation in all cores analyzed to date.

Sedimentary Hg deposition rates were calculated based on sediment accumulation rates and measured surface THg concentrations. Cores in southeastern (0502-06) and central (0502-10) Hudson Bay demonstrated low Hg accumulation rates of 2.6 and 2.7 $ng/cm^2/yr$, respectively.

6) Mass model of Hg

The team's research provided Hg data for the atmosphere, rivers, seawater and sediment for the first ever mass budget calculation of Hg for the Hudson Bay system (Figure 3). Both a preindustrial and a contemporary model were created (Figure 3), for which the full details are documented in Hare et al. (2008). In the contemporary model, the three largest influxes to the system were rivers (1.9 tonnes/year), resuspension from the seafloor (1.7 tonnes/year) and atmospheric deposition (1.5 tonnes/year). The largest efflux mechanism in the Hudson Bay system was sedimentation (4.5 tonnes/year), followed by outflow to the Atlantic Ocean (1.7 tonnes/year). Overall, the net inventory of Hg was found to be 98 tonnes with only 1% estimated to exist in the ecosystem's biota. The contemporary model showed that Hg fluxes were near equilibrium in Hudson Bay with a net influx estimated at 0.1 tonnes/year. However, net Hg has been slowly increasing in the system over time according to the preindustrial mass Hg model.

Several differences were apparent between the preindustrial and the contemporary mass models of Hg (Figure 3). There was a change in atmospheric deposition, increasing by 1.4 tonnes/year over time. Riverine input also increased from preindustrial to modern times, which may be related to the increased atmospheric deposition in Hudson Bay's watershed. Finally, sedimentation of Hg has increased over time by 2.4 tonnes/year.

7) Carbon Flux Characteristics

A strong relationship was identified between dissolved CO_2 in sea water (fugacity of CO_2 , fCO_{2sw}) and river discharge, with low-salinity coastal waters observed to be supersaturated with respect to the atmosphere, and offshore waters found to be undersaturated. Relationships of fCO_{2sw} with salinity, sea surface temperature (SST), and coloured dissolved organic matter (CDOM) suggest that thermodynamic effects and the oxidation of riverine carbon are driving supersaturation in the coastal zone. Instantaneous fluxes of CO_2 were calculated using ship-based tower measurements and were found to range from +14.8 mmol m^{-2} day^{-1} in James Bay to -22.3 mmol m^{-2} day^{-1} in Foxe Basin (Else et al. 2008).

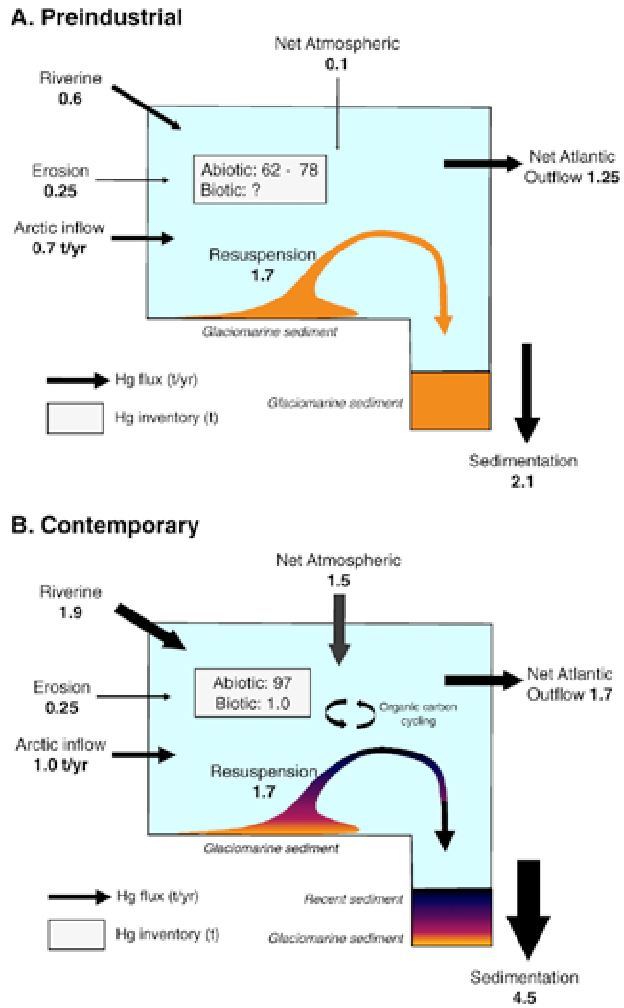


Figure 3. *Mass balance model for Hg in the Hudson Bay marine system for A) preindustrial and B) contemporary times (Hare et al. 2008).*

1.4.7 Discussion and Conclusions

1) Atmospheric Hg and Depletion Events

Although evidence of AMDEs in southern regions of Hudson Bay has been reported previously (Dommergue et al. 2003), investigations of AMDEs in the Churchill (MB) region were the first to continually monitor Hg species for an entire spring season in both the atmosphere and the snow pack surface and interstitial air. These measurements facilitated the first direct estimate of Hg deposition to Hudson Bay from the atmosphere via AMDEs. Based on the observed cycling of GEM and RGM within the snow pack, it appears that the vast majority of Hg deposited to Hudson Bay during AMDEs does not remain within the snow for very long. Therefore, despite frequent high levels of THg on the snow pack surface, Hg does not accumulate in snow packs and AMDEs contribute only 260 ± 200 kg of Hg to Hudson Bay annually (Kirk et al. 2006).

2) Influence of Rivers to Hudson Bay

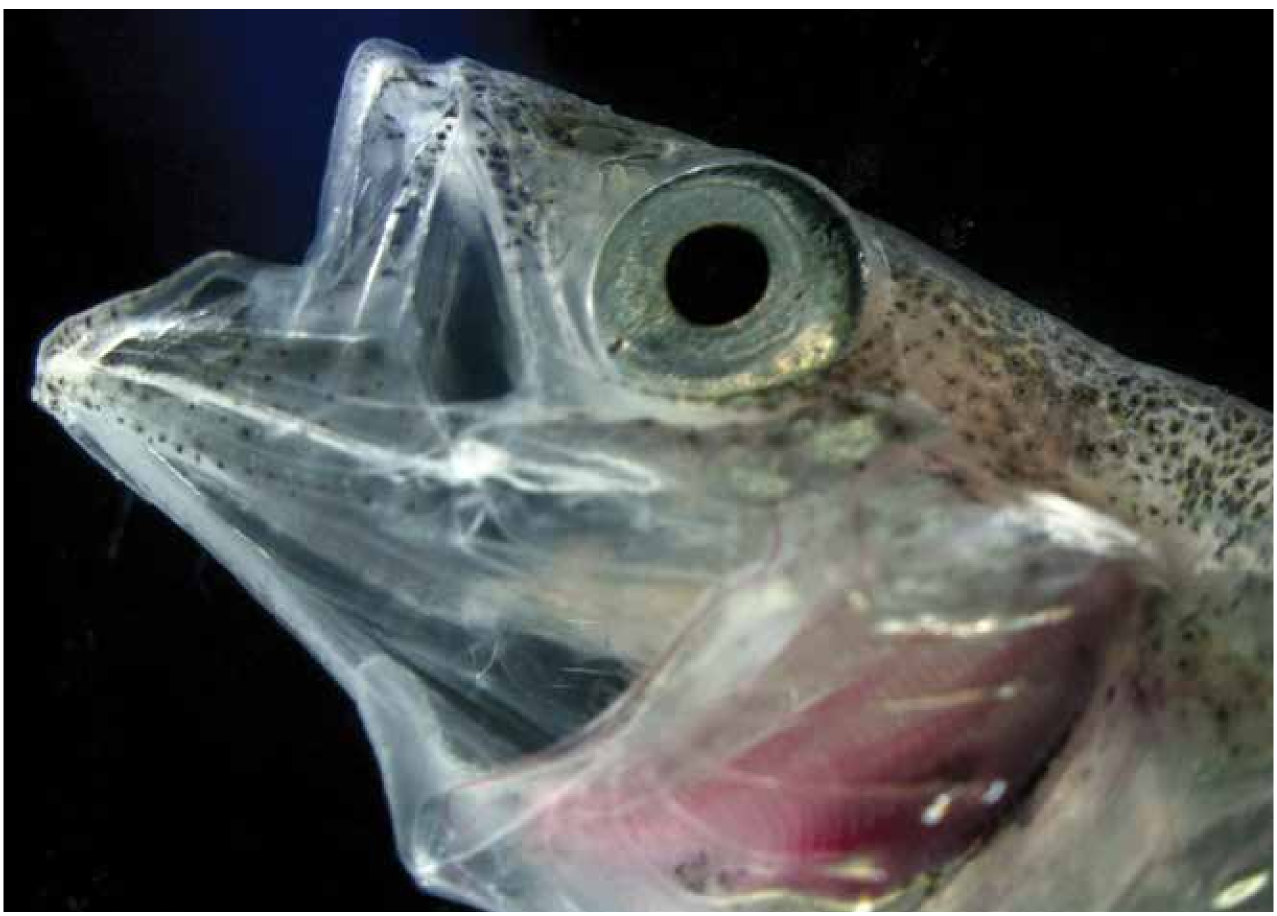
Hudson Bay is the downstream reservoir of a vast watershed that delivers large freshwater volumes to the marine system. Despite the heavy development in southern regions of the watershed, researchers observed low THg concentrations in rivers flowing into

the system. These low concentrations are reflected in the relatively low THg inputs from rivers compared to other sources (*e.g.*, atmosphere and ocean). It is estimated that roughly 1.9 tonnes of THg enter the system from rivers, of which ~31 kg is in the form of MeHg (Hare et al. 2008). This compares to an estimate of nearly 9 tonnes delivered from annual atmospheric deposition (Ariya et al. 2004). Nevertheless, neither the atmosphere nor the global oceans are considered significant sources of MeHg and therefore rivers likely play an important role in delivering MeHg to the Hudson Bay system, especially to coastal regions.

Although concentrations of MeHg in the Nelson River were relatively low, concentrations of MeHg in the Churchill River were quite high (especially in the warm summer season) and characteristic of those observed in wetlands, which are important natural sites of microbial MeHg production by sulphate-reducing bacteria. Both high concentrations of MeHg and a high percentage of the THg methylated in aquatic ecosystems often indicate sites of elevated net methylation. Approximately 12% of the THg was methylated in the Churchill River, whereas only 6% of the THg was methylated in the Nelson River. MeHg data collected from a limited sample size at Missi Falls, where water originally enters the Churchill River, suggest there are high rates of natural Hg(II) methylation in wetlands of the Hudson Bay Lowlands and that this is contributing significant amounts of MeHg to the Churchill River. MeHg concentrations at Missi Falls were only 0.023 ± 0.006 ng L^{-1} compared to 0.205 ± 0.109 ng L^{-1} entering Hudson Bay after the river passed through the wetlands. While levels of MeHg in the Churchill River were much higher than in the Nelson River, the Churchill River typically discharges much less water into western Hudson Bay than the Nelson River. As a result, the total export of MeHg from the two rivers into Hudson Bay may be approximately equivalent.

3) Seawater of Hudson Bay

Measurements of THg in seawater throughout Hudson Bay and surrounding inland waters (Foxe Basin, Hudson Strait) showed low levels of THg and MeHg, much below river and atmospheric concentrations. This indicated that the marine system is subject to Hg additions from the adjoining environments. However, the impact of the surrounding system on the marine ecosystem is likely very small or regionally confined because of the vast size and volume of Hudson Bay and the removal mechanisms present (*e.g.*, evasion, sedimentation). THg levels in seawater remained well below 1 ng/L in coastal and offshore regions and both DMHg and MeHg remained a fraction of this value, even at depth (Kirk et al. 2008). However, DMHg levels were very high relative to previous studies (*e.g.*, Cossa et al. 1994; Mason et al. 1998) and roughly equivalent to MeHg concentrations in a 1:1 ratio. Although results from experiments using stable Hg isotope tracers were still in the initial stages of interpretation at the time of this report, the general consensus was that methylation of Hg(II) to MeHg occurs in deep regions of the water column at some sites, though the rate of methylation is quite low as predicted. However, once MeHg is produced, it is likely rapidly converted to DMHg. The production of GEM from inorganic Hg(II) throughout the water column has also been observed.



4) Marine Biota and Diversity of Trophic Structure

Overall levels of MeHg and THg in biota of Hudson Bay were lower compared to the Beaufort and Chukchi seas (Stern and Macdonald 2005). Results indicated that MeHg biomagnification occurred exponentially up the pelagic food chain (Figure 2). Hg concentrations in biota were predominantly explained by trophic level (via $\delta^{15}N$) and by geographic distribution. The trophic level structure for both zooplankton and fish assemblages varied within the Hudson Bay system. In particular, $\delta^{15}N$ measurements in *Calanus* spp. differed between Hudson Strait and Hudson Bay, and similarly the $\delta^{15}N$ values from Greenland cod (*Gadus* spp.) were spatially distinct between the western and eastern Hudson Bay. *Gadidae* from western Hudson Bay were enriched in $\delta^{15}N$ (and had higher MeHg levels) compared to eastern Hudson Bay *Gadidae* and *Delphinapterus* spp., indicating increased consumption of higher trophic level species (Pazerniuk 2007). Western *Gadidae* stomach contents complemented these findings as their diet consisted of more fish compared to eastern Hudson Bay *Gadidae*. The shorter pelagic food web in southeastern Hudson Bay, with a trophic transfer from zooplankton to top predator of 7.2 ‰ in comparison to 9.8 ‰ in western Hudson Bay, may have resulted from similar feeding niches ($\delta^{15}N$) between larval fish and insectivorous zooplankton, whereas in western Hudson Bay larval fish had higher $\delta^{15}N$ and THg than zooplankton (Figure 2). Additionally, differences in Hg input from riverine discharge between the two regions may have contributed to higher MeHg in fish analyzed from western Hudson Bay stations. Annual THg input was reported to be higher from rivers discharging into western Hudson Bay, particularly the Nelson River, in contrast to Hudson Bay's southeastern rivers (Hare et al. 2008). Anthropogenic activities (*i.e.*, agriculture, hydro-electric power development) in the western Hudson Bay watershed could also have been a source of MeHg to the western Hudson Bay via river deposition.

5) Marine Sediments

The Hg results from the marine sediments revealed spatial and temporal patterns that were different between regions and dichotomous relationships with organic carbon. The Hg profiles/data from the sediment cores also provided convincing evidence for significant diversity between temporal periods, suggesting that Hg deposition and/or capture in this system changed over the last century.

6) Mass model of Hg

Hg fluxes from the atmosphere, rivers and sedimentation have increased 15, 3, and 2-fold, respectively, from preindustrial to modern times in the Hudson Bay system (Figure 3). Although Hg deposition from the atmosphere has increased substantially between the two time periods, researchers believe that the system's internal sedimentation processes can compensate this input due to the resuspension of uncontaminated glacigenic sediments (Hare et al. 2008). These 'clean' resuspended sediments have the capacity to adsorb Hg out of the seawater prior to burial on the seafloor. Accounting for all influx and efflux mechanisms, the net influx of Hg into the system was only ~0.1 tonnes/year, nearly at steady state.

With the amplification of climate warming in Hudson Bay, a couple of predictions were made with respect to the model's Hg fluxes in the mass model: (1) rivers and coastal erosion may increasingly contribute to influxes of Hg; (2) resuspension of Hg-bound particles may also increase due to a shorter duration of sea ice cover, increased temperatures and larger nutrient inputs. However, sedimentation rates may also increase as a result (Hare et al. 2008).

7) Carbon Flux Characteristics

To extend the temporal frame of the carbon measurements, long-term fluxes were calculated using National Centers for Environmental Prediction (NCEP) reanalysis wind speed climatologies (Else et al. 2008). From these fluxes, the project team estimated a 3.1 TgC sink for Hudson Bay during the open water season, which is substantially lower in comparison to other Arctic shelves. Further field measurements are necessary to constrain fluxes for other seasons and over an annual cycle.

1.4.8 Acknowledgements

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1.5 Persistent Organic Pollutants and Human Health (Project 3.5)

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1.5.1 Abstract

Persistent organic pollutants (POPs) have been targeted globally for environmental regulation because of their characteristics of accumulation, persistence, toxicity and potential for long-range movement. The classic examples of POPs are polychlorinated biphenyls (PCBs) and dichloro-diphenyl-trichloroethanes (DDTs). However, brominated diphenyl ethers (BDEs) and perfluorinated compounds (PFCs) have emerged as the next generation of pollutants, particularly in the Arctic ecosystem. BDEs, which are used as flame-retardants in various commercial products, have been shown to occur in both environmental and biotic media in the Arctic. PFCs have been widely used in cosmetics, fire fighting foams, and water and grease repellent coatings for fabrics and food packaging. These compounds (mainly perfluorooctanesulfonate (PFOS) and perfluorooctanoate (PFOA)) have been detected in biota in the Arctic.

This project focused on health effects on humans and wildlife species that have possibly resulted from exposure to these compounds and other POPs in the Arctic, including methylmercury. The first subproject aimed at assessing exposure of Inuit communities to old and emergent POPs through the consumption of wild foods. The estimated uptake of the new POPs including BDEs and PFCs is low and poses minimal risks to the Inuit population. Classic POPs from traditional food have decreased particularly among Inuit from Kivallik and Baffin. More data for mercury in caribou and ringed seal meat, narwhal and beluga fat (muktuk), as well as lake trout are needed for more reliable Hg exposure estimates. The second subproject aimed at identifying possible health effects on the Inuit population as a result of exposure to food contaminants. Biomarkers of neurotoxicity, genotoxicity and cardiovascular effects were measured in adults participating in the Inuit Health Survey in Nunavik (northern Québec). Results indicated that mercury exposure has a negative influence on the nervous system (inhibition of monoamine oxidase activity in platelets) and the cardiovascular system (inhibition of paraoxonase 1 activity in serum), but is not related to DNA damage in blood lymphocytes. Neurotoxicity and cardiovascular markers were also measured in participants in the second phase of the Inuit Health Survey completed in Nunavut.

1.5.2 Key Messages

POPs in traditional foods and dietary exposure

- Intake of brominated flame retardants and perfluorinated surface treatment chemicals was low and poses minimal risks to Inuit health.
- Updated estimates of the intake of POPs in Kivallik and Baffin were lower than those previously obtained in early 2000.
- More data on caribou and ringed seal meat, narwhal and beluga muktuk, as well as lake trout are needed for more accurate Hg exposure estimates.

Toxicity of POPs

- PBDEs had minimal effect on muscarinic receptors (mAChr) and monoamine oxidase (MAO) *in vitro* and *in vivo* using mink as a model.
- MAO in platelet can be used as an indicator for mercury toxicity.
- There was a negative association between body burden of Hg and MAO activities in platelet samples of Nunavik Inuit.
- There was a negative association between body burden of Hg and paraoxonase (PON1) activity in serum samples of Nunavik Inuit.
- DNA damage measured in lymphocytes of Nunavik Inuit was not linked to environmental contaminants but rather to alcohol consumption.

- Exposure to dioxin-like compounds was strongly associated with PCB exposure in Nunavik Inuit.

1.5.3 Objectives

POPs in traditional foods and dietary exposure

- Obtain comprehensive exposure information and risk assessment parameters on POPs for Inuit by analysis of country foods.

Toxicity of POPs

- Develop biomarkers for early indices of neurotoxicity in human and wildlife populations in the Arctic;
- Examine the possible relation between exposure to methylmercury and biomarkers of DNA damage and cardiovascular diseases in the Inuit population;
- Assess the body burden of dioxin-like compounds in the Inuit population.

1.5.4 Activities

POPs in traditional foods and dietary exposure

Project participants collaborated with Environment Canada to analyze 120 organic extracts from samples of country foods already collected between 1997-1999 from the Northwest Territories (NWT) and Nunavut and that were previously analyzed for PCBs and other organochlorine pesticides, and for brominated flame retardants, *i.e.,* polybrominated diphenyl ethers (PBDEs), as well as hexabromocyclododecane (HBCDD).

A collaboration with Health Canada allowed for measurement of PFOS, perfluorinated carboxylates (C_7-C_{11}) and fluorotelomer unsaturated carboxylic acids (6:2, 8:2 and 10:2 FTUCAs) in 68 archived traditional food samples.

Collaborations with Fisheries and Oceans Canada, Environment Canada and other ArcticNet researchers allowed for collection of data in wildlife and fish gathered in different Inuit regions. Using food sample contaminant data and food use statistics collected in 1997-1999, researchers were able to estimate earlier dietary exposure to contaminants in the food supply.

Toxicity of POPs

During ArcticNet Phase 1, project members participated in health surveys and performed multiple analyses to:

- Develop and validate sensitive and robust analytical methods to measure animal brain tissues and human blood samples collected in both laboratory and field studies;
- Study inter-species differences in neurotoxicological responses to contaminant exposure;
- Study effects of POPs versus mercury in brain extracts of marine mammals;
- Develop surrogate neurochemical biomarkers in blood (MAO in platelets and mAChr in lymphocytes) to evaluate neurochemical changes in humans;
- Study the relationship between neurochemical biomarkers and body burden of contaminants in Inuit populations;
- Measure paraoxonase activity in 900 Inuit adults from Nunavik;
- Measure dioxin-like compounds using the DR-CALUX bioassay in 500 Inuit adults from Nunavik;
- Measure DNA strand breaks in blood lymphocytes of 300 Inuit adults using the alkaline Comet assay;

- Examine factors influencing biomarkers, such as lifestyle habits and body burden of contaminants.

1.5.5 Results

POPs in traditional foods and dietary exposure

PBDEs were detectable in all 120 samples. The highest concentration was found in an Arctic cisco egg sample (36.36 ng/g). In general, marine mammal samples had higher concentrations than those found in fish and land mammals. Participants from the Baffin area had the highest intake, as they consumed the highest amount of traditional food. Even though caribou had low concentrations of PBDE (most parts contained less than 10 ng/g), it is the major contributor to PBDE in all five regions. In Labrador, caribou contributes almost 90% of the total PDBE intake. PBDE intake in Baffin was the highest at approximately 1µg per day. The top three sources were caribou, narwhal, and ringed seals.

Elevated concentrations of PFCs were found in caribou liver (6.2 ± 5.5 ng/g), ringed seal liver (7.7 ± 10.2 ng/g), polar bear meat (7.0 ng/g), and beluga meat (7.0 ± 5.8 ng/g). Mean daily dietary exposure was estimated to be 210 to 610 ng/person with the highest estimated exposure occurring in men between the ages of 41 and 60 years. Traditional foods contributed a higher percentage of PFC intake than market foods in all age and gender groups. In general, caribou meat, Arctic char meat and cookies contributed the most to dietary exposure of Inuit, with caribou flesh contributing 43 to 75 percent of daily PFC dietary exposure. Caribou meat and Arctic char contributed the most to PFC dietary exposure in Inuit men and women of all age groups.

Through a collaboration with Fisheries and Oceans Canada, researchers obtained data for concentrations of chlordane, toxaphene and PCBs from 221 beluga whales collected between 1992 and 2005 in eight communities (Sanikiluaq, Arviat, Husky Lakes, Hendrickson Lake, Repulse Bay, Igloolik, Iqaluit and Pangnirtung), blubber data from 33 walrus collected from two communities (Hall Beach and Igloolik) between 1992 and 2004, and narwhal blubber from 77 animals collected from four communities (Arctic Bay, Pond Inlet, Grise Fiord and Clyde River) between 1987 and 2004.

Data were obtained from Environment Canada for chlordane, toxaphene, PCBs and mercury (Hg) in 42 fish, seven fish from each of these six communities (Paulatuk, Holman, Cambridge Bay, Gjoa Haven, Iqaluit, Pangnirtung). Data were also obtained for concentrations of chlordane, toxaphene, PCBs and mercury in ringed seal blubber and ringed seal liver. The data for mercury were available from 307 seals collected from 12 communities (Arctic Bay, Arviat, Gjoa Haven, Nain, Pond Inlet, Qikiqtarjuaq, Resolute Bay, Sachs Harbour, Pangnirtung, Holman, Grise Fiord and Inukjuak) collected between 2001 and 2006; the data for the organochlorines were available for 86 seals collected from 11 communities (Arctic Bay, Gjoa Haven, Arviat, Resolute Bay, Sachs Harbour, Nain, Qikiqtarjuaq, Grise Fiord, Inukjuak, Holman and Pangnirtung) between 2001 and 2004. Because ringed seal meat is a major component of the diet and there was no contaminant data available, it was decided to use a ratio of 0.03 to convert mercury concentrations in seal liver to seal meat.

Overall, the updated contaminant concentrations appeared to be similar to the previously reported concentrations or generally lower. The updated POP concentrations in walrus blubber that decreased by a factor of 10 also suggest that the POP concentrations in walrus blubber can vary in a wide range. In the two regions of Kivallik and Baffin where consumption of marine mammals was more common and residents had a higher intake of POPs, a decrease of organochlorines (OC) intake was observed.

The five food types with updated POP concentrations accounted for over 80% of total POP intake.

Therefore, the new estimates for OC intakes can be considered updated assuming the traditional food intake patterns remain similar. Data for POPs in narwhal muktuk and polar bear meat were required to complete the database for similar estimates. For mercury, however, no updated data were available for some main contributors. Moreover, no data were available on ringed seal meat, which accounts for 22.6% of Hg intake. The results based on conversion from data on ringed seal liver may have an intrinsic error. More data are needed on caribou and ringed seal meat, narwhal and beluga muktuk, as well as lake trout to generate updated and meaningful levels of exposure to Hg.

Toxicity of POPs

Sensitive methods and sample preparation procotols were developed to measure biochemical markers for neurotoxicity in wildlife and humans (Stamler et al. 2005, 2006a). Effects of mercury on neurotransmitter systems were studied by conducting *in vitro* toxicity tests showing that both inorganic and organic mercury can inhibit the formation of muscarinic acetylcholine receptor bindings in the cerebral cortex and cerebellum of humans, rats, mice, mink, and river otters (Basu et al. 2005). However, there was a difference in susceptibility across species, river otters being the most sensitive and humans being the most resistant (Basu et al. 2005). The effects appear to be quite specific for mercury, as other ubiquitous environmental neurotoxicants such as organochlorines (*e.g.*, toxaphene, chlordane, DDT and PCB) did not show similar inhibition effects (Basu et al. 2006). The brominated fire retardant mixture also showed little neurotoxicity in a mink model (Bull et al. 2007).

Because mercury affects MAO activities in blood platelet as well as in the brain, it has been demonstrated that platelet MAO activities can be used as a surrogate biomarker for mercury neurotoxicity in a human population (Stamler et al. 2006b). MAO activities were found to be associated with subtle health effects, such as loss in acquired colour vision (Stamler et al. 2006c). Similar negative relationships between MAO activities and Hg in blood levels in over 400 Inuit participants in the Nunavik survey in 2004 were also observed (Stamler et al., unpublished). The determination of POP concentrations in the blood samples has been completed. Blood samples were collected to further study this relation in the Inuit Health Survey that was conducted in Nunavut where a total of 2000 samples were collected and analyzed.

Exposure to food chain contaminants such as methylmercury and PCBs can induce oxidative stress and DNA damage, which is a primary event in the carcinogenic process. Inuit people are exposed to unusually high doses of these food chain contaminants through their traditional diet that comprises large amounts of predator species from the marine food web. The Comet assay was used to determine DNA damage in peripheral blood mononuclear cells of 298 Inuit adults (131 men and 167 women) who were recruited in the course of the Inuit Health Survey and examined with respect to relations between this damage and lifestyle, nutritional and environmental factors. Questionnaires were administered to participants to document dietary and lifestyle habits. Blood samples were collected to measure concentrations of environmental contaminants (heavy metals, OC, brominated flame retardants, halogenated phenolic compounds, PFOS), nutrients (selenium, omega-3 fatty acids) and biological markers of oxidative stress. Peripheral blood mononuclear cells were isolated by the Ficoll Hypaque technique and stored frozen in liquid nitrogen until the Comet assay was performed. The alkaline version of the Comet assay was conducted using a modification of the protocol elaborated by McNamee et al. (2000), and Comet parameters were scored on 100 cells per participant using the LAI Comet Assay Analysis System (Loats Associates Inc., Westminster, MD). The mean DNA damage expressed as the percentage of DNA (% DNA) in the tail of the comet was 4.0 (SD = 1.9), with values ranging from 0.3 to 9.5. Percent DNA values were similar in men and women. However, a negative correlation was observed between age and

% DNA (Pearson's $r = -0.16$; $p = 0.007$). Simple correlation analyses did not reveal any statistically significant association between DNA damage and concentrations of mercury, lead and cadmium in blood. DNA damage was also not related to dietary intakes of traditional foods as calculated from the food frequency questionnaire data. Smoking was without effect on DNA damage, while the consumption of alcohol was associated with greater DNA damage (drinkers: mean % DNA = 4.2 (SD = 1.9) vs abstainers: mean % DNA = 3.4 (1.7); $p = 0.002$) (Laidaoui et al., unpublished).

MeHg has been shown to inhibit PON1 activity *in vitro* and therefore researchers hypothesized that blood mercury levels may be linked to decreased serum PON1 activity in Inuit people who are exposed to methylmercury through their seafood-based diet. Serum PON1 activity and blood concentrations of mercury and other metals were measured in 900 Inuit adults who participated in a health survey conducted during fall 2004 in Nunavik. Univariate analyses indicated that PON1 activities were positively correlated to blood selenium (Pearson's $r = 0.12$; $p < 0.001$) and blood mercury levels ($r = 0.10$, $p = 0.004$). However, in a multiple regression model adjusted for age of participants, alcohol consumption, blood high-density lipoprotein (HDL) levels and eicosapentaenoic content of erythrocyte membranes, blood selenium concentrations remained positively associated with PON1 activities (standardized beta = 0.13, $p = 0.007$), whereas blood mercury concentrations were negatively associated with PON1 activities (standardized beta = -0.14, $p = 0.013$) (Carrier et al., unpublished).

Polyhalogenated aromatic hydrocarbons that share structural similarities with 2,3,7,8-tetrachlorodibenzo-p-dioxin, which are referred to as dioxin-like compounds (DLCs), bind the aryl hydrocarbon receptor and can have a wide range of toxic effects. Inuit people living in Nunavik are exposed to DLCs and other POPs through their traditional diet that comprises large amounts of sea mammal fat. Plasma samples obtained from 482 Inuit adults from Nunavik were analysed for DLCs using the dioxin-receptor chemically activated luciferase expression (DR-CALUX) bioassay. This bioassay is cheaper and requires a smaller volume of sample than the conventional analytical chemistry method and is therefore well suited for epidemiological studies. The mean plasma DLC concentration in participants was 89 pg TEQ/L (median = 65 pg TEQ/L), with values ranging from < 30 to 533 pg TEQ/L. Age, body mass index and marine mammal fat consumption were correlated to plasma DLC concentrations ($p < 0.001$). Plasma concentrations of PCB congeners nos. 105, 118, 153 and 156 were determined by high-resolution gas chromatography-mass spectrometry and were found to be correlated (Pearson's $r = 0.61$-0.63, $p < 0.001$) to DLC concentrations (Medehouenou et al., unpublished). This cohort study allowed for examination of associations between exposure to DLCs and the risk of chronic diseases in the Inuit population.

1.5.6 Discussion and Conclusions

POPs in traditional foods and dietary exposure

The estimated uptake of the new POPs including BDEs and PFCs was low and poses minimal risks to the Inuit population. Classic POPs from traditional foods have decreased among Inuit, particularly in Kivallik and Baffin. More data for Hg in caribou and ringed seal meat, narwhal and beluga muktuk, and lake trout are needed for more reliable Hg exposure estimates. Our results will facilitate decision-making for sampling in future exposure assessment studies.

Toxicity of POPs

The combination of laboratory-based experiments, field studies and the use of multiple species as study models allowed for the development and validation of several markers for neurotoxicity. Through multiple collaborations, whole brain samples were obtained from 50 beluga (ArcticNet and Fisheries and Oceans Canada), 50 polar bears (Makivik Research

Centre) and 50 ringed seals (Environment Canada) from across the Canadian Arctic. The association of the biochemical markers with concentrations of Hg and POPs in different regions of the brain was examined which provided information on contaminant effects on key species of marine mammals in the Arctic. The measurement of surrogate neurochemical biomarkers in blood samples also offered an ethical way to evaluate neurochemical changes in humans.

The capacity of mercury to inhibit the activity of PON1 in serum, which could be related to an increased risk of atherosclerosis, was also investigated. Results suggested that mercury exposure has a slight inhibitory effect on PON1 activity, which seems to be offset by selenium intake. The association between mercury and PON1 activity was further re-examined with data collected from the Nunavut leg of the Inuit Health Survey.

Results did not support the hypothesis that methylmercury increases DNA damage in blood lymphocytes of participants in the Inuit Health Survey. Alcohol consumption, rather than exposure to environmental contaminants, induced DNA strand breaks as revealed by the Comet assay. The project failed to demonstrate a link between exposure to environmental contaminants and chromosomal damage as evaluated by the micronucleus test in 68 women participating in this survey (Al-Sabti et al., unpublished).

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1.6 People and Environmental Change: Linking Traditional and Scientific Knowledge (Project 3.6)

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1.6.1 Abstract

The changes observed in the northern landscape and environment have implications on all aspects of natural and human systems in the Arctic. This project aimed to determine and document the effects of environmental change on people in the Hudson Bay coastal communities, wildlife, and physical environment of the region. The main goal was to identify and model the linkages between traditional knowledge and 'western' science regarding environmental change. This project focused on a variety of aspects related to environmental change which included gaps in scientists' understanding of the impact and opportunities that climate change will have on economic well-being, quality of life, lifestyles, climate change indicators or triggers, knowledge transfer, policy development, and understanding of relationships between Inuit and other northern Aboriginals and marine ecosystems. Quantitative and qualitative methods used included interviews, workshops, 'Town Hall' meetings, and community-based monitoring. Some of the major project conclusions were a) effective environmental monitoring is best achieved by building on local Inuit and other northern Aboriginal priorities and expert observations to establish a monitoring program and complementing it with 'western' monitoring systems; b) Inuit and other northern Aboriginals are fully aware that environmental and climate change are having an impact on their lifestyles and they recommended working together to develop locally-based adaptation strategies; c) mentoring youth is one of the communities' top priorities and an essential step in northern environmental education.

1.6.2 Key Messages

- Changes in sea ice conditions and climate have affected the frequency, timing, duration, and safety of subsistence activities.
- Changes in sea ice conditions and climate have significantly affected the distribution and abundance of some wildlife species.
- Combining Inuit and other northern Aboriginal-based and 'western'-based monitoring and knowledge systems provides invaluable information for optimizing adaptation strategies.

1.6.3 Objectives

The main objectives of this project were to:

- Identify the human dimension of environmental change using traditional and 'western' science;
- Determine linkages between traditional knowledge and 'western' science to improve research outcomes;
- Contribute to an environmental assessment for the Hudson Bay region, which includes recommendations for minimizing potential ecological problems and exploring potential benefits based on the insights gained by understanding the linkage between traditional knowledge and 'western' science.

1.6.4 Introduction

For years it has been obvious from general circulation model outputs that climate change will have greater impacts in the Arctic (Barber 2006, Yackel and Barber 2001, Riedlinger 2001). Observational data, which these models are based upon, often lack sufficient temporal measurements. However, Inuit and other northern Aboriginal observations based on multi-generational use and knowledge of the northern environment provide another way of identifying key factors related to climate change (Arnold et al. 2006, Berkes et al. 2006, Riewe and Oakes 1994). Arctic science typically focuses on either traditional or scientific knowledge (Simpson 1999). The general agreement is that understanding the linkages between these two conceptual frameworks helps provide the models needed to better integrate the expertise of local experts and scientists (Huntington 2000; Mallory et al. 2006a,b; Riewe and Oakes 2006). Due to the unique social and physical geography of the Sanikiluaq, Churchill, Repulse Bay and Kuujjuarapik areas, the research team focused on the human dimension of specific Arctic science systems directly relevant to sea ice in the Hudson Bay. Through community collaboration, building on local environmental assessment initiatives for the Hudson Bay, as well as collaboration with other scientists, this project aimed at identifying linkages between scientific data and traditional/local knowledge in order to (1) apply those linkages by developing monitoring and mentoring programs supported by both local communities and scientists, and (2) contribute to a Hudson Bay environmental assessment as described by Usher (2000).

1.6.5 Activities

1) Inuit and other Northern Aboriginal-Graduate Student Collaborations

Twelve Masters students and three Doctoral students were trained to conduct community-based interdisciplinary research with Inuit and other northern Aboriginal field workers, guides, advisors, and interpreters. Project researchers examined the implications of climate change on wildlife (beluga, eiders, narwhal, polar bears, peregrine falcons), youth (environmental education, perspectives), transportation (access to hunting territories), social well-being indicators (hunter's perspectives, impacts of sea ice changes, marine subsistence), and other factors affecting the human ecosystem (*i.e.,* post-diversion use of Churchill River for subsistence hunting and fishing).

Northern students developed local methods to learn about the environment from their elders and scientists, contributed to academic posters and publications, and attended conferences and forums. Research results were presented orally to Peter Pitseolak School (Cape Dorset), Qiqirtak Ilihakvik (Gjoa Haven), Kugluktuk School (Kugluktuk), Nuiyak School (Sanikiluaq), Duke of Marlborough School (Churchill), Tusarvik (Repulse Bay), Umiujaq School (Umiujaq), Kuujjuarapik School (Kuujjuarapik), Chesterfield Inlet School (Chesterfield Inlet), and Coral Harbour School (Coral Harbour). Research posters were also disseminated weekly to almost every school in Hudson Bay coastal communities.

2) Community-based Monitoring

A community-based monitoring (CBM) program was an integral part of this project. It helped train local monitors and set up equipment in Churchill and Sanikiluaq. Data has been analyzed, combined with 26 years of data from the Ocean-Ice-Atmosphere Coupling project (see section 1.1), and presented to the community of Sanikiluaq at a workshop held to discuss further developments in CBM. This CBM was developed in collaboration with several people to establish a marine component, linking traditional and scientific knowledge on fish (capelin and cod), establish moorings needed to collect measurements, and to coordinate the development of Inuit and other northern Aboriginal observations.

3) Dissemination of Research

Several communities worked with researchers to create community books summarizing the research results and some researchers produced a one-page pamphlet and provided multiple copies to the local *café* for those interested. Researchers solicited 1-page research summaries and/or posters from northern scientists for inclusion in a compendium of research conducted in the Hudson Bay region. Project members participated in numerous academic conferences for which approximately 24 posters and abstracts were produced. Several project students participated in the 'Ant-Arctique' project, where they fostered communications between local high school students and polar researchers on research vessels (CCGS *Amundsen* in the Arctic, and the Sedna IV in the Antarctic). Several students visited school classrooms to further encourage a classroom approach to polar research. Project students also attended weekly University of Manitoba seminars, hosted workshops, including "Climate Change: The Next Step" (November 2005, Churchill), "Integrating Arctic Science" (March 2007, Winnipeg, with the ArcticNet Student Association), "Research Forum on Science Teaching and Learning" (February 2007, Faculty of Education, NSERC Manitoba Centre for Research in Youth, Science Teaching and Learning (CRYSTAL)), and Sanikiluaq Community Environmental Monitoring System Workshop (January 2007). Community presentations and broadcasts taught the ecology of eiders in sea ice habitats, as well as ongoing research and monitoring activities and objectives. A video "Arctic Eider" and a television documentary were produced by J. Heath.

1.6.6 Results

Following the philosophy of the decolonizing methodology (Smith 1999), Hudson Bay coastal communities discussed possible research topics with scientists in local meetings, workshops, conferences, and youth forums (*i.e*., Churchill 2005, Churchill Northern Studies Centre/University of Winnipeg 2006, Arctic Youth Forum 2006, Sanikiluaq Community Environmental Monitoring System Workshop 2007), as well as through one-on-one discussions with federal and territorial officials, local experts and scientists. As a result of these discussions, the purpose of this project shifted from modeling linkages between traditional or local knowledge and 'western' science regarding environmental change in Hudson Bay coastal communities, to laying a foundation for the social health perspectives of a Hudson Bay environmental assessment, including people-centered perspectives on social impacts, environmental health, wildlife populations, and community-based monitoring. Individual research projects within this project linked directly with scientific research conducted by other ArcticNet projects, while meeting current needs of monitoring local observations in selected communities. Community members played a lead role in setting research objectives, planning fieldwork activities, information exchange, collecting scientific field data, and dealing with logistical challenges. For instance, following mass wildlife mortality events associated with sea ice conditions, community member concerns initiated the following sub-projects:

- Impacts and opportunities of changes in environmental conditions on seasonal travel routes in Churchill and Sanikiluaq;

- Inuit-based monitoring and scientific monitoring in Churchill, Sanikiluaq, Kuujjuarapik, Akulivik, Repulse Bay and Wager Bay;

- Issues or opportunities regarding environmental change on people's food and hunting, lifestyles, and health.

Northerners are required to cope with a variety of significant environmental changes, including changes in access to hunting territories, changes in wildlife distribution, and a shift in reliability of traditional or local knowledge due to the unpredictable nature of changes. There is also a need for youth environmental education with elders and scientist mentors, as well as for more methodical and coordinated environmental monitoring and impact assessments. Research results showed that Inuit and other northern Aboriginal perceptions of health and well-being were very different from those of Southerners, with environmental change likely to have profound implications for the well-being of Northerners. The importance of maintaining hunting-based subsistence to Inuit culture, identity, health and social well-being was underlined (Blakney 2006, Gislason 2007, Gilligan 2007, Edye-Rowntree 2007). Collaborations with other northern scientists (*e.g.,* Tyrell 2007) were established within this project. Indicators of change included changes in Lower Churchill River usage, traditional knowledge information exchange between elders and youth, forms of transportation and lack of winter roads, rate of sea ice formation, inter-annual differences in the extent and location of sea ice and polynyas, sea ice conditions needed for travel, as well as movements, health, numbers, and density of certain species near the shores and offshore.

Other work focused on incorporating surveys and knowledge of northern hunters about the timing and variability of sea ice formation across a range of specific habitats, and relationships with transportation, polar bears, beluga, fish, contaminants, and eider abundance-distribution patterns (*i.e.,* Gilchrist et al. 2006). Long-term monitoring of these patterns is essential in updating IRIS evaluations. Aerial surveys, workshops, interviews and local ecological knowledge were integrated to evaluate distribution and abundance patterns of wildlife – particularly eiders and polar bears – associated with sea ice habitats such as polynyas, floe edges, leads and pack ice.

Training and Mentoring

Youth were involved in the research process to facilitate mentoring and to inspire northern youth to attend university or college. Youth from local high schools and the ArcticNet Schools on Board Program worked as research assistants and assistant monitors, collecting local observations. In Churchill, youth chose to present their own perspectives on environmental change, in addition to working with elders and scientists to learn other ways of observing, analyzing, and interpreting change (Arnold et al. 2006). Presentations and discussions with youth and scientists were used in all communities to facilitate knowledge exchange and mentoring. Local experts were trained in recognizing diseases in wildlife, collecting tissue samples, conducting interviews and workshops, writing reports, preparing posters, producing a video, and analyzing local expert monitoring. Inuit and other northern Aboriginals provided research advice, logistical support and guiding services, as well as teaching traditional skills, analysis and interpretation which was essential to the development and completion of this research.

Project members met with Sanikiluaq Environmental Committee representatives to explore potentials for collaboration and exchange of information at an environmental monitoring system planning meeting. Team members worked with the local Hunters and Trappers Organization (HTO) and Environmental Committee to develop a systematic community-based environmental monitoring program, to start in Sanikiluaq and Churchill and to expand to each community in the Hudson Bay region. This proposed program was designed to meet Inuit and other northern Aboriginal needs for monitoring (*e.g.*, ocean, snow and ice, marine fish, birds, and mammals) and build on the physical monitoring conducted by ArcticNet.

In 2007-08, project team members increased their involvement with Northerners in a meaningful integration of traditional and western approaches to science by incorporating community-based sub-projects. Demographic links to perceptions of environmental change were examined in the coastal communities of Hudson Bay, involving youth, elders, hunters, trappers, teachers, tour operators, and other Northerners in Churchill, Sanikiluaq, Kuujjuarapik, Umiujak, Coral Harbour, Chesterfield Inlet, Repulse Bay and Foxe Basin communities (Hall Beach, Igloolik, Cape Dorset, Kimmirut). To collect the information needed to analyze the human perspective of a Hudson Bay environmental assessment, a systematic community-based monitoring (CBM) system linking traditional and scientific knowledge was established. Community members involved in the CBM deployed monitoring projects at sites of ecological and local importance, providing a consistent method for inter- and intra-annual monitoring of wildlife and sea ice. Taking quantitative measurements at sites was important to local residents, with elders providing long-term information.

1.6.7 Discussion and Conclusions

During Phase I, this project built community research relationships in Churchill, Kuujjuarapik, Sanikiluaq, Chesterfield Inlet, Coral Harbour, and Repulse Bay through community consultation, collaboration and social science fieldwork. Gaps in the scientific understanding of the impact and opportunities of climate change on economic well-being, quality of life, lifestyles, and mental health (travelling on the land and waterways, hunting and fishing practices, recreation, wildlife management), climate change indicators or triggers (monitoring, beluga, narwhal, polar bear, eider duck, capelin, cod, and meteorological indicators), knowledge transfer (formal and informal environmental education and awareness, inter-generational information exchange), and policy development (co-management, curriculum) were explored by graduate students in collaboration with community field guides/advisors and youth. Research was strategically coordinated with the Foxe Basin polar bear study (Repulse Bay) and Umiujaq community to fill in some of the missing information relating to the understanding of the marine ecosystem (polar bear, narwhal and beluga hunters). Local youth, harvesters, elders and other members of the community became actively engaged in the project by initiating, co-developing and co-implementing community-based research, as well as through involvement as field guides/advisors or participating youth.

Several models were developed to illustrate integration between physical, social and health knowledge on climate change (Gilligan et al. 2006) and integration within sub-projects (Figure 1). Gilligan (2007) focused on how changes in the environment are altering the way harvesters travel "out on the land", Edye-Rowntree (2007) focused on how local residents adapted to dramatic environmental changes created by the Manitoba Hydro diversion. Both projects are located on the outer ring (Project 3.6 sub-projects) and both linked to the 'River' portion of the 'Physical' ring, which represents the physical environment, as well as the 'Fish' and 'Humans' portions of the 'Biology' ring. On the 'Social Aspects' ring, both projects link to 'Mixed Economy', 'Recreation', 'Traditional Resource Use' and 'Contemporary Resource Use'. On the fifth ring called 'Stakeholders', both projects link to 'Locals', 'Fishers', 'Hunters' and 'Trappers'. Both projects link to the 'Resource Management' and 'Adaptation and Mitigation' portions of the 'Policy' ring. Similar relationships exist with the work of all other project members. Finally, each of the sub-projects was integrated into many other ArcticNet Phase 1 projects.

1.6.8 Acknowledgements

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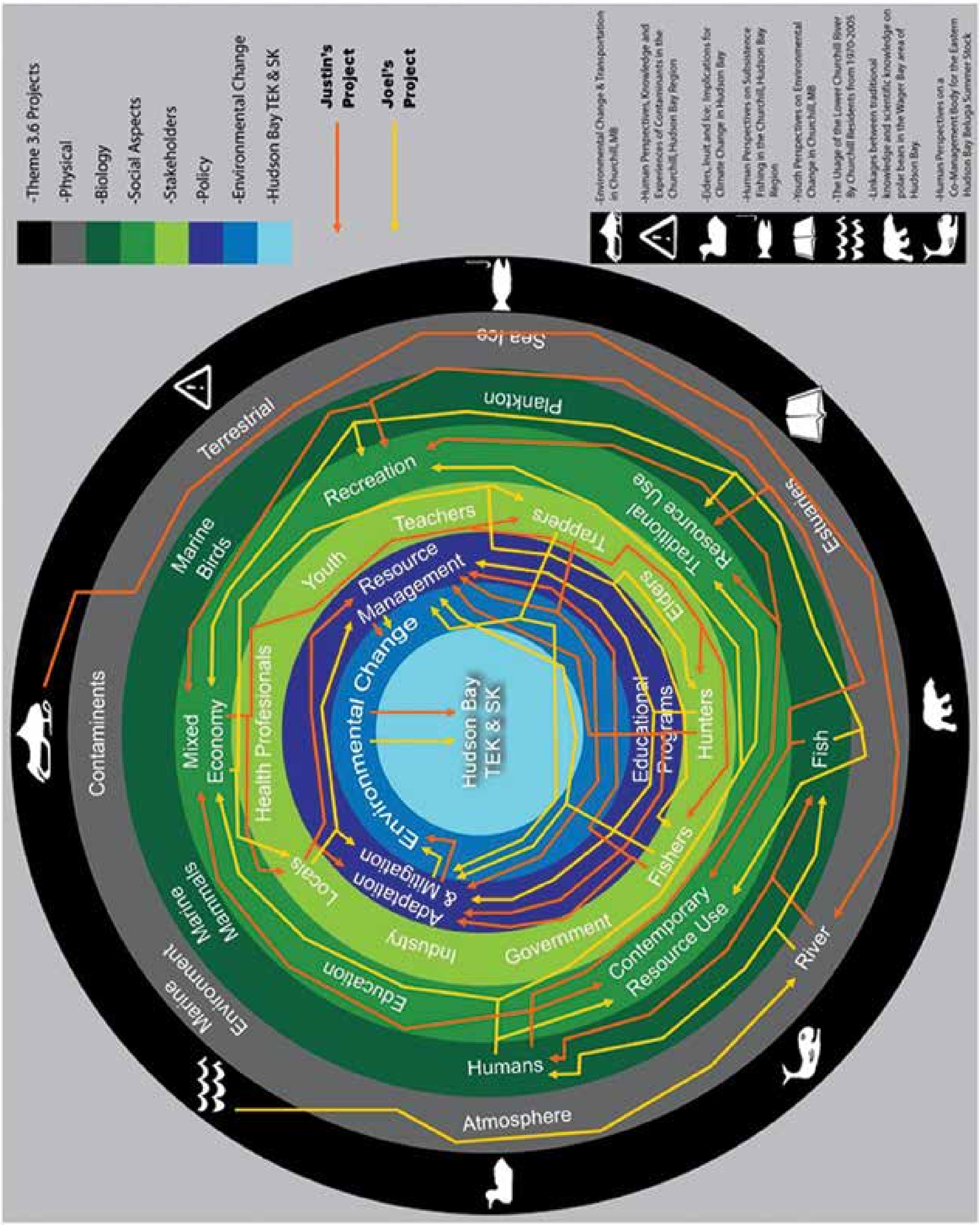

Figure 1. *Project 3.6 integration diagram.*

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1.7 Nunatsiavut Nuluak: Baseline Inventory and Comparative Assessment of Three Northern Labrador Fiord-based Marine Ecosystems (Project 3.7)

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1.7.1 Abstract

In partnership with the Nunatsiavut Government, the Royal Military College, Parks Canada, the Department of National Defence, Environment Canada, the Department of Fisheries and Oceans, and Voisey's Bay Nickel Company Ltd., this project conducted a baseline inventory and comparative assessment of three northern Labrador fiord marine ecosystems. The purpose of the project was to address Inuit concerns regarding the ecological integrity of the marine environment in northern Labrador by acquiring a better understanding of the effects of climate change, modernization and contaminants. An integrated regional approach has been implemented to address concerns from all stakeholders, including those of major industrial and governmental organizations. The three coastal marine ecosystems studied were Anaktalak Bay in the South (the shipping route to the Voisey's Bay nickel mine), Saglek Bay (affected by a historical source of PCB contamination) and Nachvak Fiord in the North (a pristine ecosystem adjacent to the Torngat Mountains National Park Reserve). These studies complemented each other and, with the addition of northern Labrador to the ArcticNet program, provided relevant comparative data for other systems investigated by ArcticNet. The study facilitated the participation of Inuit and integrated Inuit knowledge throughout the entire process including selection of indicators, analysis and interpretation of data and conducting field research, and helped build capacity among Inuit in Labrador and strengthened partnerships (through collaboration).

1.7.2 Key messages

- Nachvak Fiord and Anaktalak Bay are relatively pristine environments, with contaminant levels in biota and sediments that are representative of long-range transport effects only.

- Ecosystem recovery from a local historical source of polychlorinated biphenyls (PCBs) in Saglek Fiord is slowly occurring.
- More pelagic and wider ranging species such as Arctic char are not affected by the local source of PCB contamination in Saglek Bay; however, there is still a high degree of biomagnification in the local benthic-based food chain.
- Some ringed seal from Saglek Fiord have higher levels of PCBs than seals typically affected by long-range transport of contaminants in the Arctic.
- The Voisey's Bay Nickel Company (VBNC) has developed a nickel-copper-cobalt mine and mill in the area around Voisey's Bay, near Nain NL, which discharges treated effluent to the head of Anaktalak Bay and uses the fiord as its main shipping route. Local Inuit are concerned about the potential impacts of mining activities on the Anaktalak Bay ecosystem, but results suggest that there are no contaminant issues.
- Environmental stressors due to climate change and modernization in the Anaktalak Bay ecosystem often act synergistically when combined.
- There is a need to monitor ecosystem changes and environmental effects to ensure that Inuit are able to mitigate negative changes and adapt when mitigation is not possible.

1.7.3 Objectives

The central aim of this project was to determine the effects of climate change and modernization in three marine fiord ecosystems.

The general objectives guiding this project were to:

- Establish a cooperative partnership in northern Labrador for the long-term marine monitoring program that integrates Inuit people and Inuit knowledge throughout all phases;
- Establish baseline inventories of three marine ecosystems and determine the feasibility and potential components of a longer management program;
- Provide more and better opportunities for Inuit to contribute to marine monitoring in a learning environment and to develop skills with which to conduct future monitoring programs.

The specific objectives of this project were to:

- Determine the local impacts of contamination and the extent of ecosystem recovery in Saglek Fiord from a local source of PCB contamination;
- Determine the spatial variability of phytoplankton production and biomass in the coastal zone, and compare the variability across latitudinal (*i.e.*, between fiords) and longitudinal (*i.e.*, mouth versus head) gradients within each fiord;
- Determine the spatial variability of zooplankton production and biomass in the coastal zone, and compare the variability across latitudinal (*i.e.*, between fiords) and longitudinal (*i.e.*, mouth versus head) gradients within each fiord;
- Determine the spatial variability in nutrient production rates within and between each fiord;
- Determine the influence/impact of environmental conditions on phytoplankton and zooplankton dynamics;
- Compare seasonal differences in the fiords (*i.e.*, July 2007 conditions versus fall 2006);
- Determine oceanographic conditions using vertical profiles with a Conductivity-Temperature-Dissolved Oxygen (CTD) probe;
- Determine the concentrations of inorganic nutrients (NO_3, NO_2, PO_4, and $Si(OH)_4$) within the fiords;
- Use the microfossil (mainly remains of dinoflagellate cysts and siliceous diatoms) record preserved in sedimentary deposits to determine

background (baseline) environmental conditions that prevailed prior to the beginning of military, mining and shipping activities;

- Assess the ecological and environmental disturbances brought about by the above-mentioned activities;
- Develop a classification of substrate and habitat types and map the results using multibeam acoustic data;
- Determine the changes in seabed conditions over time in ecologically sensitive areas of the fiords;
- Increase the holistic understanding of the marine ecosystem in Anaktalak Bay by seeking Inuit knowledge of individual components of the ecosystem and the relationships between these components;
- Compare the information gathered on the current state of the Anaktalak Bay ecosystem with historical perspectives and identify reasons for change.

1.7.4 Introduction

Labrador Inuit depend on the sea and sea ice for their harvesting and traveling activities, and for maintaining their lifestyle in general. They are concerned about the ecological integrity of the marine environment of northern Labrador especially in terms of the effects of climate change, industrialization (modernization) and contaminants. This project was designed to address the prevailing concerns of local Inuit identified through the work of the Nunatsiavut Inuit Research Advisor (funded by Nasivvik and ArcticNet).

Limited baseline information existed on the structure and composition of marine ecosystems in northern Labrador. Nachvak Fiord, located adjacent to the recently established Torngat Mountains National Park Reserve, provided an important reference site for the collection of baseline data in pristine Labrador fiords (Figure 1). A marine monitoring initiative was developed by Parks Canada (Parks Canada 2005a,b), and the collection of an appropriate set of indicators from Nachvak Fiord allowed researchers to carry out a feasibility study for the long-term marine monitoring in this region. Saglek Bay, which is part of Saglek Fiord, forms the southern boundary of the Torngat Mountains National Park Reserve. In excess of 10 km^2 of sediments in Saglek Bay have been contaminated with PCBs due to the erosion of soils from an adjacent military site (Greggor et al. 2003). While more offshore (pelagic) and wider ranging species were not affected, there was a high degree of biomagnification in the local benthic-based food chain (Kuzyk et al. 2005a,b). Upon removal of the shore-based source of PCBs, there was a need to develop a long-term monitoring program for Saglek in order to develop sound harvesting advisories based on meaningful data. Anaktalak Bay (a fiord) is used extensively by Labrador Inuit for harvesting wildlife

Figure 1. *Map of northern Labrador showing the three fiords studied within Nunatsiavut Nuluak.*

(both from the water and adjacent shores) and travel by snowmobile and boat. The Voisey's Bay Nickel Company (VBNC) has developed a nickel-copper-cobalt mine and mill in the region, which discharges treated effluent to the head of Anaktalak Bay and uses the fiord as its main shipping route. Within this ArcticNet project, researchers filled identified gaps needed to understand the marine ecosystem of Anaktalak Bay, and collected baseline data to test the feasibility of the proposed monitoring program.

This project was formally recognized as "Nunatsiavut Nuluak", Nunatsiavut referring to both the people and the land to which the project is intimately tied and Nuluak being the Inuktitut translation of "net". This branding recognizes the vital role that the Nunatsiavut Government and the Inuit of northern Labrador played and continue to assume in the evolution of this project. Through Nunatsiavut Nuluak, researchers established a cooperative partnership in northern Labrador for a long-term marine monitoring program that integrates Inuit people and Inuit knowledge and builds on Inuit capacity to address the social, scientific, and economic concerns of Nunatsiavummiut in a meaningful way.

1.7.5 Activities

2006

A comprehensive work plan for northern Labrador fiords was first established in consultation with Inuit, government, industry, and university stakeholders during two meetings in St. John's, NL (June). The meetings were attended by representatives from the Nunatsiavut Government, Royal Military College, Memorial University, Queen's University, Parks Canada, Environment Canada (Canadian Wildlife Service), Department of National Defence, the Department of Fisheries and Oceans, Voisey's Bay Nickel Company, Sikumiut Environmental Management Ltd., and community members.

From July to August, researchers conducted five weeks of field work in Anaktalak, Saglek, and Nachvak fiords from Inuit-owned long-liner and small boats. The data collection project consisted of surface sediment sampling, habitat mapping through video transects and photography, water column profiles to examine baseline water chemistry, and biota sampling (ringed seal, Arctic char, shorthorn sculpin) to determine effects of modernization on the ecosystem. The participants were from the community of Nain, Parks Canada, Environmental Sciences Group, Nanuk Diving Inc., Sikumiut Environmental Management Ltd. and Memorial University.

In October and November, researchers conducted three full days of fieldwork (one day each in Nachvak, Saglek, and Anaktalak fiords) from the CCGS *Amundsen*. The fieldwork consisted of approximately 24 hours of continuous sampling in each fiord collecting CTD profile data, water samples for dissolved oxygen, contaminant, nutrient, and phytoplankton analyses using the rosette, zooplankton sampling using an oblique Tucker trawl and Hydrobios vertical tows, small box cores for sedimentary contaminant profiles, large box cores for palaeoceanographic work, as well as multibeam seabed mapping and sub-bottom profiling. During this mission, emphasis was placed on box coring and multibeam seabed mapping. Participants in this stage of the project included representatives from Environmental Sciences Group, the Western Newfoundland and Labrador Field Unit of Parks Canada, Torngat Mountains National Park, Memorial University, Université Laval, College of the North, OKalaKatiget Society and Sikumiut Environmental Management Ltd.

In December, researchers organized a workshop in Nain (NL) to further the understanding of environmental changes in Anaktalak Bay and their effects on local Inuit in order to prepare the development of a multi-partner monitoring (MPM) program for the area. Suggestions for future monitoring were discussed with fourteen local Inuit participants (10 men, 4 women).

2007

In April 2007, researchers conducted a community consultation with partners in Nain (NL). At the meeting, researchers requested community input on project directions, including results to date and future directions. A documentary produced by the OKalaKatiget Society on the coast of Labrador that was released on the Aboriginal Peoples Television Network (APTN) was also presented. Following the meeting, a comprehensive work plan for northern Labrador fiords was developed in consultation with Inuit, government, industry, and university stakeholders during two meetings in St. John's (NL, June). This meeting was attended by representatives from the Nunatsiavut Government, Royal Military College, Memorial University, Queen's University, Parks Canada, Environment Canada (Canadian Wildlife Service), Department of National Defence, the Department of Fisheries and Oceans, Sikumiut Environmental Management Ltd., and Nunatsiavut community members.

In July and August, researchers conducted seven weeks of fieldwork in Anaktalak, Saglek, and Nachvak fiords from an Inuit-owned long-liner and small boats. This research consisted of surface sediment sampling, habitat mapping through video transects and photography, water column profiles to examine baseline water chemistry, and biota sampling (ringed seal, Arctic char, shorthorn sculpin) to determine effects of modernization on the ecosystem. Participants came from the community of Nain, Parks Canada, Canadian Wildlife Service, Royal Military College of Canada, Environmental Sciences Group, Indian and Northern Affairs, Memorial University and the College of the North Atlantic.

During the annual voyage of the CCGS *Amundsen*, researchers conducted three days of field work (one in each of Nachvak, Saglek, and Anaktalak fiords) in July and August. This work consisted of approximately 12 hours of continuous sampling in each fiord collecting CTD profile data, water for nutrient and phytoplankton analysis using the rosette, zooplankton sampling using an oblique Tucker trawl and Hydrobios vertical tows, and box cores for sedimentary contaminant profiles. Participants came from the Royal Military College of Canada, the Torngat Mountains National Park Reserve, Environmental Sciences Group and the Nunatsiavut Government.

1.7.6 Results

Since the official start of this ArcticNet project in April 2006, much of the data gathered within Nunatsiavut Nuluak have been analyzed and synthesized. Data collection and analyses were completed for phytoplankton, zooplankton, oceanographic work, palaeoceanographic sediment cores, as well as seabed mapping. In addition, the specific results of the Anaktalak Bay workshop had to be verified and released to the community prior to their presentation elsewhere.

As part of the study of the effects of contamination on the ecosystems of Nachvak and Saglek fiords as well as Anaktalak Bay, concentrations of polychlorinated biphenyls (PCBs) were determined in sediments, Arctic char (*Salvelinus alpinus*), shorthorn sculpin (*Myoxocephalus scorpius*) and ringed seal (*Pusa hispida*). Concentrations of contaminants from Nachvak Fiord were low and reflective of an ecosystem that is only affected by global atmospheric transport (Figure 2). The Anaktalak Bay ecosystem was also relatively clean and reflective of global transport effects (Figure 2).

Results from Saglek Fiord indicated that wide-ranging pelagic species, such as Arctic char, were not affected by the PCB contamination in the fiord and were safe for human consumption (Figures 2 and 3). This was further supported by the similarities in total PCB concentrations of Arctic char tissues between Saglek and those from Nachvak and Anaktalak.

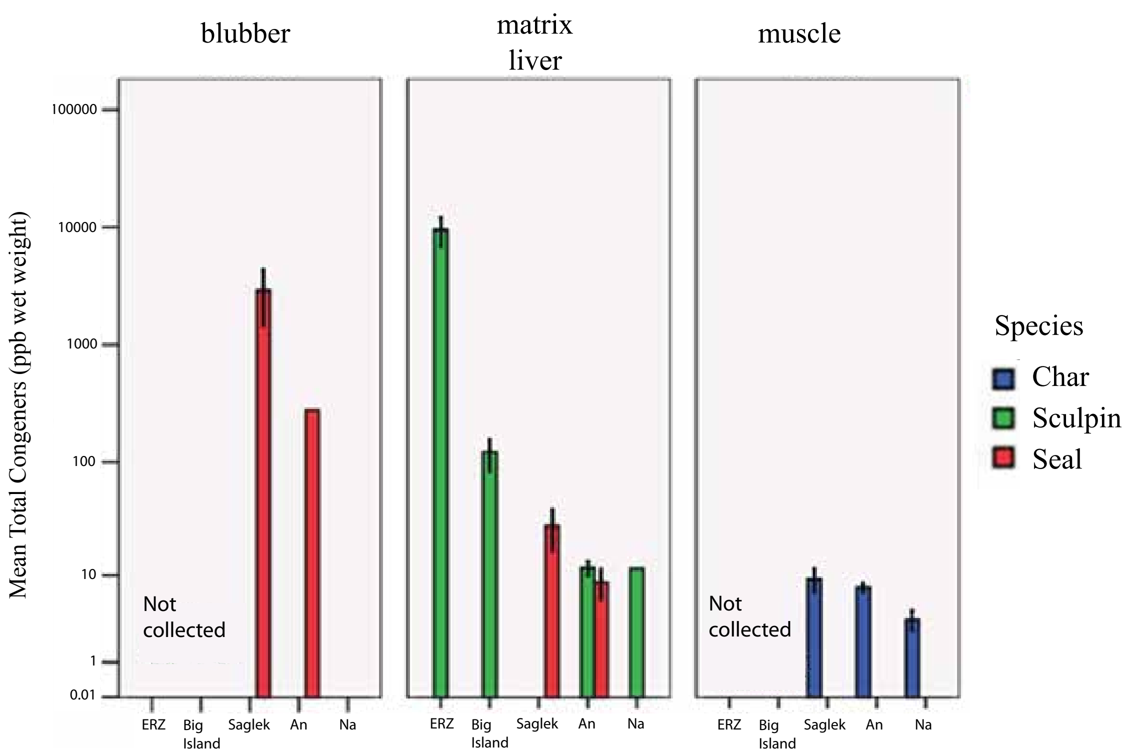

Figure 2. *PCB concentrations (*ppb*) in three important species from the northern Labrador coast. Note the logarithmic scale. Total congeners indicates the sum of all congeners. ERZ refers to the Ecological Risk Zone immediately adjacent to the contaminated beach area in Saglek Bay. Big Island is approximately 6 km from the contaminated beach. An: Anaktalak Bay; Na: Nachvak Fiord. Detection limits for PCB congeners were sample-specific and ranged from 0.01 to 1.0 ng/g (ppb).*

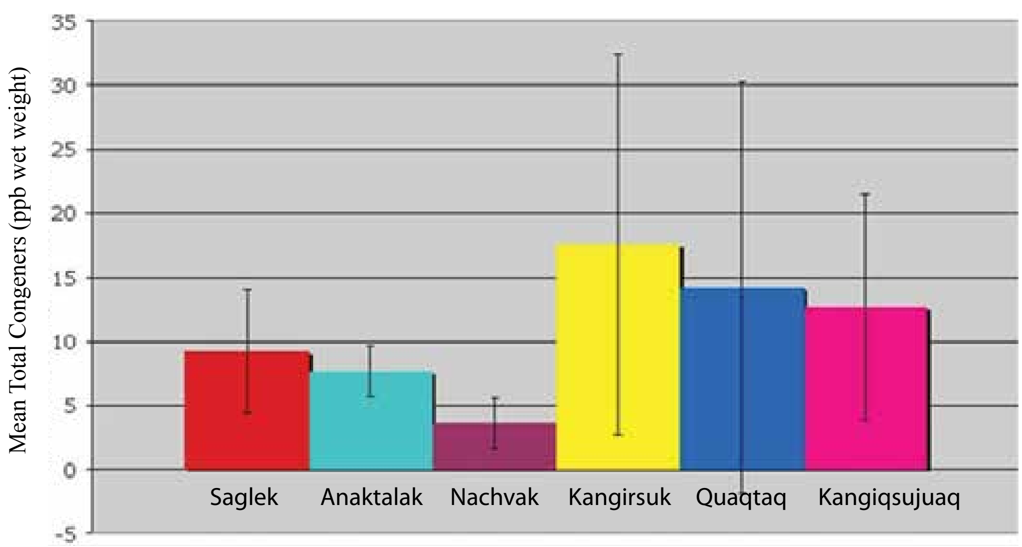

Figure 3. *PCB concentrations in Arctic char muscle tissue (ppb). Total congeners indicates the sum of all PCBs congeners. Data from outside northern Labrador (Kangirsuk, Quaqtaq and Kangiqsujuaq) are from Muir et al. (1999). Detection limits for PCB congeners were sample-specific and ranged from 0.01 to 1.0 ng/g (ppb).*

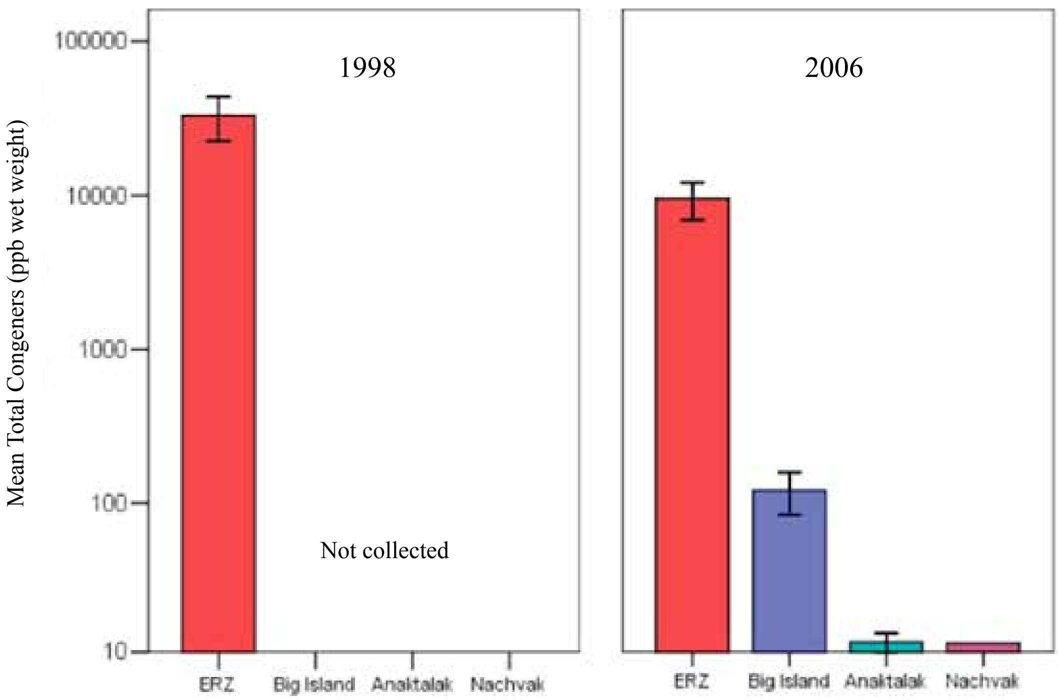

Figure 4. *A comparison of PCB concentrations in shorthorn sculpin liver samples from individuals in 1998 and 2006. Total PCBs indicates the sum of all congeners. Concentrations below the analytical detection limit were assigned a random value between the detection limit and zero. Detection limits for PCB congeners were sample-specific and ranged from 0.01 to 1.0 ng/g (ppb).*

On the other hand, local benthic species in Saglek Fiord, such as shorthorn sculpin, had high concentrations of PCBs, which decreased exponentially with distance from the remediated beach (Figures 2, 4). Shorthorn sculpin from the area closest to the formerly contaminated beach (*i.e.*, the "Ecological Risk Zone"- ERZ) had levels in excess of 10,000 µg/g wet weight. Shorthorn sculpin from Big Island, which is approximately 6 km from the remediated beach, had intermediate levels of PCBs while those from both Nachvak and Anaktalak fiords had concentrations comparable to those typical of long-range transport levels from the rest of the Arctic (Figure 4).

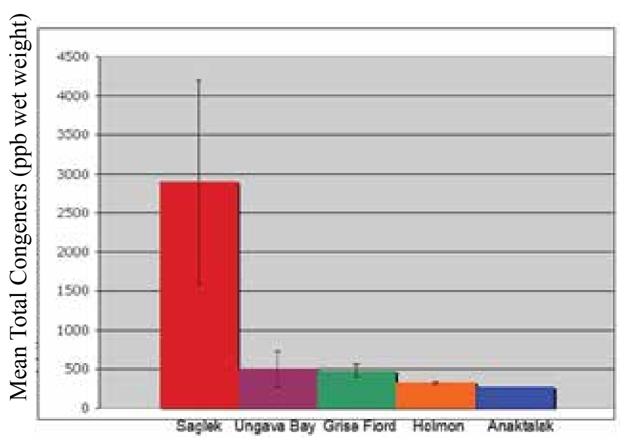

Figure 5. *Ringed seals PCB concentrations. Total PCBs indicates the sum of all congeners. Data from outside northern Labrador are from Muir et al. (1999; Ungava Bay and Holman) and Fisk et al. (2002; Grise Fiord). Concentrations below the analytical detection limit were assigned a random value between one-half of the detection limit and the detection limit. Detection limits for PCB congeners were sample-specific and ranged from 0.01 to 1.0 ng/g (ppb)*

Ringed seal from Saglek Fiord had PCB tissue concentrations that were elevated when compared with other eastern Arctic sites (Figure 5). However, results indicated that there were two divergent groups of seals: those with PCB concentrations that were significantly elevated (so-called "hot" seals) and

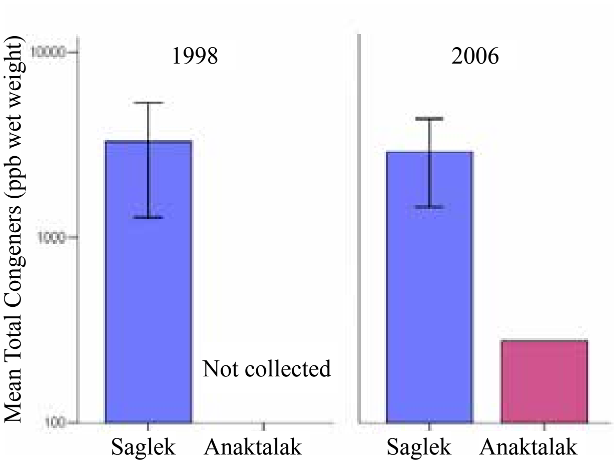

Figure 6. *A comparison of PCB concentrations in ringed seal adipose tissue samples from individuals in 1998 and 2006. Concentrations below the analytical detection limit were assigned a random value between one-half of the detection limit and the detection limit. Detection limits for PCB congeners were sample specific and ranged from 0.01 to 1.0 ng/g (ppb).*

those with PCB concentrations that were comparable to other eastern Arctic sites. PCB concentrations in seals collected from the Saglek Fiord area in 1998 and 2006 were statistically similar (Figure 6).

1.7.7 Discussion and Conclusions

Overall, project data suggest that the Nachvak Fiord and Anaktalak Bay ecosystems are relatively pristine. These fiords therefore provide important baseline and reference data for the monitoring of changes in northern Labrador ecosystems. Saglek Fiord, however, was still affected by the legacy of PCB contamination in the terrestrial and marine environment, despite the removal of the land-based sources of PCBs. Although PCB levels in shorthorn sculpin remain high in the area nearest to the formerly contaminated beach (the ERZ) in Saglek Fiord, our results show a statistically significant decrease in liver PCB concentrations from 1998 to 2006 (Figure 4). This suggests that, once the shore-based source of contamination was removed, uptake and consequently risk within the local benthic-based biota slowly decreased. Further studies are needed to verify these observations over longer timescales.

The divergent ringed seal groups in Saglek Fiord suggested that there may have been differences in behaviour and/or migration within ringed seal populations from the northern Labrador coast. In order to gain a better understanding of the ecosystem risks associated with these contaminant results, further studies of ringed seal movements as well as their trophic feeding status are warranted.

1.7.8 Acknowledgements

Nunatsiavut Nuluak would like to thank the local people of Labrador who contributed to the success of this project. In particular, the help of Chesley and Joe Webb and the crew of the Viola Dee is acknowledged here. We also thank Sid Pain of Nanuk Diving Inc. for his efforts. Eli and Jacko Merkuratsuk are a “fountain of wisdom” along the northern coast of Labrador and are instrumental to our program. The Torngat Mountains National Park Reserve has served as our base camp, which has become a second home for our project during the field season. Nunatsiavut Nuluak is funded by the Department of National Defence, the Nunatsiavut Government, Parks Canada, Environment Canada, Fisheries and Oceans Canada, ArcticNet, and INCO (Voisey’s Bay Nickel Company Ltd.). We thank all partners for their efforts in moving forward towards a better understanding of northern Labrador marine ecosystems.

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2. Science to Policy-Makers and People (Theme 4 Overview)

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Introduction

Communities throughout the Canadian Arctic are experiencing significant changes in environmental conditions. In the decades to come, the Arctic will continue to be a region of change. Individuals, communities and governments facing these changes need relevant information for the development of policies and strategies. In response to this need, the focus of Theme 4 is to provide relevant information to aid decision-makers with the development of policies and strategies to adapt to a changing Arctic environment. An open dialogue between researchers, policy and decision-makers and all those impacted or dealing with environmental change allowed for the identification and discussion of key issues, knowledge gaps and priorities related to adapting to climate changes in the coastal Canadian Arctic.

Study Area

The Theme 4 research programme encompassed the eastern and western Canadian Subarctic and Arctic, and was without a specific geographic focus as with Themes 1, 2 and 3. The eight projects that comprised Theme 4 spanned the natural, health and social sciences. In order to gain an understanding of the broad perspectives examined, fieldwork was conducted across all the regions – Inuvialuit, Nunavut, Nunavik, and Nunatsiavut (Figure 1). This being mentioned, certain projects focused on a specific region in a given year.

Research Projects and Objectives

Given the diversity of the region, there was a fundamental need to understand the pattern and impacts of climate change with emphasis on human activities and responses to regional environmental concerns. The range of aspects considered included modelling of climate and atmospheric hazards, the impacts of atmospheric hazards on local communities, how these hazards change with climate, food security and community health, vulnerability to climate change at the community level, economic, policy and legal frameworks in the North and their implications for adapting to climate change.

Inuit, largely from Nunavut, have been partners and collaborators in Theme 4 research projects, thereby incorporating Inuit Qaujimajatuqangit (IQ) in the research and in the understanding of strategies and policy development. Certain Theme 4 projects have developed strong partnerships with federal govern-

Figure 1. *The Theme 4 research area.*

ment departments (*e.g.*, Meteorological Service of Canada, Department of Foreign Affairs and International Trade Canada, Department of Fisheries and Oceans, Environment Canada, Indian and Northern Affairs Canada) and international organizations. These collaborations expanded the capacity of research to affect change.

Climate change issues addressed by the natural, human health and social sciences across eight different projects ultimately aimed to fill knowledge gaps, to anticipate the future coastal Canadian Arctic environment, and to provide assessments and advice to facilitate the formulation of policies and adaptation strategies.The topics covering the natural, health and social sciences and specific objectives of each project were as follows:

Project 4.1 – *Projecting into the Future: the Canadian Arctic Environment, Tomorrow to 2100* – aimed to verify climate models in order to make safe predictions of future weather and sea ice conditions by improving the credibility and utility of existing Arctic climate model results. Simulations of previous or current events were run to allow researchers to see how well models performed when compared to actual data.

Project 4.2 – *Reducing Human Vulnerability to Environmental Changes in the Canadian Arctic* – focused on human vulnerability and resilience studies in order to ascertain whether the nature and speed of some changes and stresses, including environmental change, may be approaching or exceeding the adaptive capacity thresholds of the Arctic people.

Project 4.3 – *Vulnerabilities and Adaptation to Meteorological and Related Hazards* – sought to identify some of the meteorological extremes occurring in the present climate, as determined from comparing the history of past weather elements (including averages and extremes in temperature, precipitation, wind) with local communities and meteorologists. Researchers aimed to understand what local communities consider to be an extreme event, versus what conditions have to be in place for an extreme event to be considered a hazard. Examples of extremes include blizzards, snow accumulation, blowing snow, strong winds, wind chill and reduced visibility.

Project 4.4 – *Climate Change, Key Traditional Food Species and Community Health in the Arctic* – addressed the impacts of climate change on traditional food security as associated with alterations in animal, fish and plant populations, as well as ice and snow conditions. The availability of, and access to traditional food has implications for community health and well-being, to the extent that adaptation plans are sought that address the effects of climate change on traditional food harvest in Inuit communities.

Project 4.5 – *Surveillance and Management of Climate Change Impacts in the North: Implications for Northern Public Health Policy and Infrastructure* – aimed to work with individuals, northern managers and organizations to plan and design Community Health and Environmental Surveillance (CHES) programs, that are sensitive to climate change impacts, in order to build capacity for each northern region.

Project 4.6 – *Conservation, Economic Development and Community Values: Legal, Policy and Ethical Perspectives* – aimed to examine the legal, policy, administrative and ethical framework within which sport hunting is practiced. Research involved a number of Inuit organizations in documenting and analyzing variations in the practice of conservation hunting in the Canadian Arctic.

Project 4.7 – *Science-Policy Interactions* – sought to understand the process by which research results are brought to the attention of policy- and decision-makers, and mechanisms by which governments and organizations communicate concerns, priorities and information needs to researchers, in order to help research conducted by ArcticNet scientists and their partners to trigger change. The project aimed to create an open dialogue between scientists and decision-makers.

Project 4.8 – *Strengthening Climate Cooperation, Compliance and Coherence* – conducted a legal and policy analysis of the impacts of climate change in the Canadian Arctic by studying the implications of a changing climate in governance, in interactions with Inuit land-claims organizations, in environmental protection and human rights, as well as in international sovereignty and diplomacy.

Project Integration within the ArcticNet Strategic Framework

The overlapping interests and complimentary research conducted by ArcticNet projects prompted the development of a strategic framework predicated on the formation of four Integrated Regional Impact Studies (IRIS), as a suitable approach to describe and understand the environmental impacts and socio-economic costs of climate warming in the Arctic. As Theme 4 aimed to provide information to aid decision-makers in the development of policies and strategies for adapting to a changing Arctic environment, project leaders, network investigators, researchers, Inuit and stakeholders were aware that their work would not only be informed by research projects under Themes 1 through 3, but would provide context for outcomes in all IRIS regions and the ArcticNet strategic framework in general. Theme 4 research can be divided into three subject areas, each contributing to a vision of IRIS: climate science scenarios, health science, and policy research. Each project involved one of these three approaches, notwithstanding interactions, impacts and implications among them. Together these projects described a story of integration, as changes, causes, consequences and responses to climate change were articulated and documented from the results of Theme 4.

Project Achievements

Significant environmental change is occurring in the Arctic. Scientific knowledge links these changes to global environmental problems – foremost among them being climate change – and to impacts on people and ecosystems, and approaches to reduce those impacts. In the Canadian Arctic, the coupling of climate change with economic strain, cultural transformation and other disruptive factors is causing a multitude of stressors on people and the ecosystem. During the first phase of ArcticNet, Theme 4 generated a substantial amount of research, mainly focused on the analyses and the elaboration of diagnoses. Yet the convergence of disciplines allowed Theme 4 scientists to produce insights into potentially broader impacts of climate change on northern lands, ecosystems and society, and provide essential input into the formulation of societal adaptation strategies and policy recommendations.

The main achievements and contributions of Theme 4 are presented according to their focus on natural, health and social sciences and note changes, causes, consequences and responses to climate change with implications for the four IRISes.

Sea Ice-Ocean Models

Predictions about future conditions were made through several modelling experiments, in an effort to verify and expand climate science knowledge and provide the ArcticNet community with access to model data that can reliably predict the future state of the Arctic landscape to 2050 and 2100. Regional models used to examine the sea ice-ocean climate of Hudson Bay revealed that most heat input to the waters of the bay was through surface fluxes with a minor influence from oceanic currents. Fall cooling arose during periods of strong cold winds with the main losses in November, though moderated by yearly climatological fluctuations. Runoff and precipitation caused small seasonal fluctuations in salinity as the main salt flux was controlled by ice formation and brine rejection. In the springtime, small diurnal fluctuations in salt flux were controlled by daytime melting.

For a 4°C climate change scenario, the model showed a large increase in the ice-free season in Hudson Bay, ranging latitudinally from 25 to 42 days. This has significant economic and environmental impacts, including a longer shipping season into the Port of Churchill, a significant stress on polar bear populations, human adaptation to a changing climate, and noticeable impact on the meteorology of northeastern Manitoba.

Models also revealed a steady decline in ice extent over the 1971-2000 interval and predicted amounts of less than 50% of the current low value in the 2041-2060 epoch. In the climate-forced future scenario, mid-century maximum ice concentrations were less than current minima. In light-ice years between 2041 and 2060, the Archipelago waters were nearly ice-free. In regional models, ice thickness declined and the duration of the ice-free period increased across the Arctic. Changes in Labrador were less distinct and more variable, probably because of the more southerly climatology at the site and the greater importance of snow cover in controlling ice growth. Within the Canadian Archipelago, ice thickness declined between 25 and 40 cm and the ice-free period increased by 22 to 49 days in the 2041-2060 period. In the interval 2081-2100, there was a further decline in ice thickness of between 44 and 65 cm, while the ice-free period increased by 37 to 84 days. The delay in freeze-up was greater than the advancement of break-up, and is thought to reflect the normal asymmetrical nature of the two processes. One significant finding was the change at Alert and Mould Bay to seasonal ice from multi-year ice by 2041-2060.

Atmospheric Hazard Studies

Strong and variable surface winds are considered to be among the most important weather hazards in the Arctic. The documenting of weather hazards in the Canadian Arctic by Theme 4 represents nearly 50% of journal articles in the Prairie and Northern Region component of the National Atmospheric Hazards Project of Environment Canada. Few comparisons with other studies have been possible due to this lack of information, but comparisons have now been initiated across other regions of the circumpolar Arctic including Norway.

Low-level Wind-fields

The evaluation of large scale and local atmospheric hazards (strong and variable surface winds, heavy snowfall, and freezing precipitation) over the eastern Arctic showed that some of the greatest impacts of regional strong storms and their effect at the community scale are linked with sustained periods of strong winds enhanced by topographic conditions. Persistent high wind situations are often linked with slowing of synoptic systems that become stronger over open water. Such winds at many locations are also associated with low-level jets having hazardous wind shear aloft for aviation. Extreme surface wind conditions in the Canadian and European Arctic revealed that where wind speed increases from the surface to the top of the troposphere, strong surface winds, associated with low-level jets, are larger than those of overlying flow. Strong surface winds are thus extreme flow conditions, often forced by orography and terrain features. Yet, trends in occurrence

and variability of hazardous strong wind events at various locations were generally inconclusive. Differences in hazardous conditions between Iqaluit airport and a nearby portable weather station showed variability in hazard strength down to small spatial scales.

Snow and Freezing Rain

Data analysis revealed that storms producing heavy snow and freezing precipitation in the eastern Canadian Arctic vary in origin, frontal structure, actual precipitation type and wind intensity. Surface upper-atmosphere and synoptic features of freezing rain indicated that freezing rain occurs in a variety of synoptic and vertical atmospheric conditions and is associated with stronger surface winds and a longer period of below 0°C temperatures after the freezing rain. The effects of freezing precipitation persist longer in the Arctic than in the South, and these events may increase in the future with greater likelihood of major disruptions when they occur in the Arctic.

Environmental Impacts on Traditional Country Foods

Many northern communities have witnessed variable changes in climate that are affecting the harvest of country/traditional foods (TF). Models were developed to link qualitative climate observations by members of northern communities to quantitative harvest, individual food use and nutrient intake data reflecting the impact of environmental changes on peoples' health.

The collection of qualitative research enabled detailed descriptions of the effects on traditional food availability due to changing environmental influences, such as warming temperatures, earlier ice break-up, higher winds and hazardous snow conditions, as verified by model data. A later freeze-up, thinner ice and lack of snow alters TF in terms of availability (distribution and animal numbers), accessibility (ability to reach hunting and fishing areas via land travel) and quality (wildlife health, fat content, perception of food safety issues). Key findings revealed new species and changes in migration of species affecting periods for fishing and hunting. For example, Arctic char appear up river earlier, snow geese stay longer in the fall, yet the closer presence of polar bears around shorelines restricts camping for long-term hunting and fishing. Collectively, the observations led to descriptions of changes in environmental conditions, and impacts on traditional/country food security and nutrient intake.

The comparison of traditional food consumption levels against benchmark nutrient requirements resulted in maps showing the key nutrients of concern in different regions of the Canadian North. Through knowledge exchange with wildlife biologists and Hunters and Trappers Organizations, adaptation management plans and programs were developed to inform communities for years to come. The ability of Inuit communities to cope and respond to these changes, mainly by adjusting subsistence activities, may not be a reliable indication of their ability to adapt in the future. The effectiveness of local adaptive strategies is uneven across the Arctic and knowledge gaps remain as to why some Arctic communities adapt remarkably well, while others are more vulnerable and exposed to drivers of change despite their use of similar resources and ecological settings. Further research into the integration of traditional ecological knowledge and scientific knowledge on the basis of different spatial and temporal scales is needed in order to understand the extent of change that can be accommodated by the existing ways of life of indigenous peoples.

Health Surveillance

In response to the limited capacity for disease surveillance in Inuit health systems that will be impacted by environmental changes, novel methods were developed to enhance and expand the capacity and adaptability of public health surveillance and environmental monitoring in the four Arctic regions of Nunavut, Nunatsiavut, Nunavik and Inuvialuit.

Of particular concern was the link between human health and gastrointestinal illness (*i.e.*, water quality and the impact of extreme weather events, and changes in season durations, on historically safe drinking water turbidity and total coliforms). Solid baselines were established for health, environmental and historic demographic information. Monitoring and surveillance capacity was enhanced through training and education within the health organizations and communities in order to further an understanding of risk management related to potential climate variability impacts on water quality and human health. Community participation provided a means for education and capacity building on the topic of weather, its relationship with water quality, and importance of water treatment to ensure a safe drinking water supply. Given the close relationship between the Inuit and their environment, it will be important for researchers to continue to work collaboratively with community members to develop proactive adaptive capacity. Results from various facets of current research on how quickly or how pervasively the warming of the climate will affect the environment are still emerging. Recent high quality data will feed into predictive models that will allow for the development and understanding of different regional scenarios and aspects of risk. These will ultimately help communities to be more flexible and resilient in response to challenges impacting their health and environment.

Within the formal health care infrastructure, case studies revealed that resource limitations were constraining data analysis and reiterative communication of data trends to health practitioners. For example, paper-based intake data collected for patient visits was transferred to an information management system that has been in use by provinces for several years. In Nunavik, a syndromic Palm-based surveillance system was compared against paper-based systems for visit records, through assessment of the impact on time spent on paperwork and manual data entry against data quality and access to medical information provided by the Palms. The evaluation of the innovative surveillance system is of great interest, particularly to health officials dealing with the challenges of providing quality service to remote communities.

Results of the case study identified a number of strengths and unique characteristics of the context within which health surveillance and monitoring activities operate in the four regions. As the public health system of Nunavik operates as part of the government of Québec, it benefits from the clarity of roles, responsibilities and programs determined by that province. This contrasts with the complex situations found in the three other Inuit regions where different layers of government are involved in the public health system and networks for environmental health monitoring and surveillance. Nunavik also has a more extensive and organized network of researchers in Québec working on these topics than in the other regions, but on the other hand was found to have less access to Federal programs focused on environmental monitoring initiatives, such as those for sea-level and permafrost melting. A comparison of the four regions using basic health status indicators revealed that Nunavik's population might in fact be more disadvantaged than any other Inuit population in Canada. The final case study findings for the other three regions will make possible detailed and comprehensive comparisons of challenges and advantages in the different public health systems.

Vulnerability in Arctic Communities

While climate change poses a risk to the sustainability of northern livelihoods, existing socio-economic pressures related to increasing integration into the southern wage-based economy are already challenging peoples' livelihoods. Research of vulnerabilities in seven northern communities revealed that climate does not act in isolation of other opportunities and constraints, and adaptation to changing environmental conditions has greater relevance if it addresses non-climatic conditions as well.

Vulnerability research looks at the role of relevant climate stresses in the context of other stresses. Relevant stresses or "exposures" that affect (positively or negatively) some components of the community's livelihood, health and safety are examined in community-based studies of vulnerability with respect to hunting behaviour, sea ice, food security, youth, infrastructure, and community planning. Systematic data collection methods and analytic frameworks allowed for comparison of findings among the case studies, and in the circumpolar context through the International Polar Year. Groundwork has been laid for long-term longitudinal case studies of human community vulnerability including opportunities for monitoring the results of practical adaptation strategies over time, beyond a snapshot of one or two years to long-term research relationships.

Much of the research revealed that climate and environmental changes impacting the community level were influenced not only by socio-economic factors, but by policies at the local and regional level, and by formal and information institutions. There is a need to "scale up" case studies to integrate with and inform regional policies and institutions, so that findings and results are mainstreamed in policy circles. The work was of direct relevance to decision-making and policy, as adaptation processes and initiatives are included in the research itself.

Science-Policy Interactions

Policy formulation is one mechanism employed by society to respond to change and its consequences. Current stressors in the Arctic, chiefly the coupling of climate change with economic strain and cultural transformation, have created an immediate need for public policy that reduces vulnerability and risk, facilitates adaptation, and fosters planning. In asking the research question: how does scientific knowledge about climate change affect public policy in the Arctic?, various theories were explored that enhance or restrict scientific knowledge from influencing policy decisions, including the actors involved in the science-policy dialogue, the type of scientific knowledge conveyed, the design mode of scientific assessments, and power relations between interested parties. Some common ground exists between these theories, including near universal agreement that scientific knowledge conveyed through scientific assessments will be more influential than primary scientific claims. As one of the objectives of ArcticNet has been to inform and perhaps influence policy deliberation and decision-making, the total body of ArcticNet findings to be conveyed through Regional Impact Assessments (RIAs) may increase the likelihood that policy influence will follow, though this outcome is by no means a certainty. It remains largely undetermined what type of scientific assessment or political institutional design is most likely to enable scientific policy influence.

Existing science-policy research was built upon in order to apply science-policy theories and findings

to the geographic area under study by ArcticNet. As much of the science-policy research to date has focused on international environmental agreements, the domestic approach adopted was innovative for its cross-scale analysis between global change and regional response. While firmly grounded in an accurate understanding of the institutional context, one aspect of science-policy research examined how institutional structures may act as conduits or barriers for science in the policy process. Another study examined the northern institutional context (*i.e.*, Nunavut) within the Canadian federation by undertaking a comparative study with Newfoundland, another Canadian jurisdiction whose economy and culture is significantly affected by ecological perturbations. The study is valuable for the lessons it conveys about adaptation policy planning in response to climate change. To situate Canada's policy for polar affairs, another study was conducted on the establishment and ten-year history of the Canadian Polar Commission. Other studies sought to better understand and articulate the roles played by specific institutions or processes at work in the northern policy cycle. A stronger grasp of the institutions of northern politics provides a necessary basis for further investigations into science-policy interactions in the Canadian North.

Further work could take research beyond an explicit institutional context to reconsider how existing theories of science-policy relationships may be confirmed, altered or rejected within this institutional setting. The dominant theories in the science-policy literature may be falsified or refined in light of factors such as consensus government, the codification of land claims, and/or the power of institutionalized indigenous knowledge.

Work was undertaken to apply science-policy theories to the development of practical and applicable methods for scientists and scientific bodies to convey research results and RIA recommendations to decision-makers. This applied research took on a decidedly communications-centred emphasis and stressed the importance of community participation and education. Senior researchers also continue to assume the role that science plays in international relations, specifically in the negotiation of the next phase of the UN Framework Convention on Climate Change and in the interplay of science and politics in the formulation of Canada's claim for a continental shelf extension in the Arctic beyond the 200-mile exclusive economic zone. Active engagement with the policy community and interdisciplinary collaboration has led to symposia, publications and speaking engagements and has added an additional important dimension to ArcticNet.

Conservation Hunting

Highly regulated polar bear conservation hunting programs in Canada require informed understanding by policy-makers, politicians, the scientific community and the media. In cooperation with northern partners, research in this area was informed by novel approaches developed in the policy science arena and applied to polar bear conservation and conservation hunting. New policy approaches to polar bear conservation and management in the Canadian Arctic sought a way forward for a management situation being challenged by recent changes affecting the Arctic, including inter alia, challenges to science-based wildlife management orthodoxy associated with growing Inuit political influence and the consequent new decision-making realities within existing co-management arrangements. The adoption of the polar bear as a symbol to draw public, political and media attention to the threatened northern environment/climate change by international campaigns may be considered a potent tool in their opposition to U.S. non-compliance with the Kyoto Protocol, but it also mobilized international opposition against hunting in general – which spilled over to negatively impact Canadian polar bear conservation hunting. Such campaigns, led by environmental organizations including Greenpeace and the Natural Resources Defence Council, while drawing attention to the deteriorating state of the Arctic sea ice environment, also added support to calls for international bans on trade in polar bear hides – an outcome that has posed a serious economic concern to both Inuit hunters and territorial governments.

Fieldwork in eleven Inuit communities demonstrated that research can be influenced by personal predilections – with some heavily constrained by particular authorities' interpretations of available evidence. Change requires discussion of differing understandings to grow in comprehension of the complex realities and emerge from defending rather than challenging known positions. 'Conventional wisdom' on the topic reinforces the need to remain open to alternative explanations and willingness to continually question whether an asserted 'conclusion' is any more than an untested hypothesis that either cannot be critically (*i.e.*, scientifically) tested, or is based on a circularity of reasoning or a number of questionable (*i.e.*, unproven) assumptions.

Model predictions of climate change impacts on polar bears and other species must be perceived in terms of inherent uncertainties associated with long-term climate change predictions and associated biological and societal impacts. Creative approaches to managing for uncertainty should be sought. The detailed yet largely undocumented understanding of past and present wildlife populations, and potential impact of environmental changes (including hunting pressure) on populations, is held by communities. Northern communities should be encouraged to develop an adaptive approach to local resource stewardship, in cooperation with neighbouring communities to form regionally applicable stewardship arrangements.

In pursuit of capacity-building on the topic of Arctic climate change impacts and international wildlife management and trade issues, enrichment/mentoring activities at Aurora College (environmental management diploma) and Nunavut Sivuniksavut (two-year certificate program) were created. A polar bear conservation hunting listserver has given attention to communication and outreach by posting research items accessed by hundreds of project-related and interested individuals.

In recognizing the need for improved cooperation between indigenous knowledge (IK) holders and wildlife researchers and managers, a widely acceptable/credible methodology for collecting and presenting Inuit knowledge was pursued with ArcticNet and northern partners, biologists and researchers to make IK a priority issue and to move the issue forward. Local-scale detailed indigenous knowledge has proved useful to environmental and wildlife/fishery scientists and has been combined with science to create a more culturally appropriate resource stewardship/co-management arrangement, as indigenous knowledge has shown to satisfy scientific requirements for addressing other research questions.

Exploration of new policy approaches to sustainable polar bear use, conservation and management in the Canadian Arctic is required. Research seeks a way forward for a management situation challenged by science-based wildlife management orthodoxy of a growing Inuit political influence and new decision-making realities within existing co-management arrangements.

Land Claim Agreements and Climate Change

Innovative approaches to research through integration between the natural and social sciences in the context of ArcticNet influenced links between law and policy issues surrounding climate change and the Arctic. It was concluded that a general set of assertions reflecting the disproportionate impacts of climate change on northern communities should gain legal recognition. As with the small island states, Inuit communities ought to have legal recognition for their claims within the Kyoto and post-Kyoto frameworks and domestic Canadian law. It is important to validate that the exposure stress and vulnerability of Inuit communities to climate change is in fact added stress to a complex and existing set of social pressures. It may seem that paying special attention to impacts on Arctic communities is a disproportionate response to direct climate change impacts on those communities. Yet, patterns of economic and social behaviour that have had adverse effects on Inuit and other indigenous communities for decades are perhaps some of the most overwhelming symptoms of climate change.

There is thus legitimacy to giving particular weight to the claims and concerns of indigenous communities, and Canada's absence of recognition for the Declaration of the Rights of Indigenous Peoples only serves to highlight the current legal vacuum. Should the courts and arbitration tribunals fail to recognize and take into consideration this perception, conflicts concerning land claim agreements will supersede climate change issues and delve into the larger cultural and legal divides that continue to separate Aboriginal Peoples and the Canadian nation state.

2.1 Projecting into the Future: the Canadian Arctic Environment, Tomorrow to 2100 (Project 4.1)

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2.1.1 Abstract

One of ArcticNet's overarching goals is to bring together Arctic researchers and expertise to conduct Integrated Regional Impact Studies (IRIS) of the consequences of climate change – especially of environmental and societal changes – and to provide decision-makers with the information needed to formulate adaptation strategies. One method of achieving scientific integration is to provide a framework in which dissimilar studies can meet and share to contribute to a holistic resolution of scientific questions; the framework allows for the linking of measurements and research conducted across various themes using numerical models that integrate the present state of knowledge and provide a window into the future.

This project has supported several modelling experiments. One of these was a regional ice-ocean model that explored the sea ice and ocean climate of Hudson Bay and examined the response of the region to an increase in temperatures caused by continued global warming. An ice algae model that reproduced the ice algae and plankton dynamics under seasonally ice-covered Subarctic conditions in Hudson Bay, Foxe Basin and Hudson Strait marine system was developed. Observations of deep-water subsurface currents to simulate deep-water renewal in Foxe Basin were merged and numerical simulations of the sea ice-ocean seasonal cycle in Hudson Bay were conducted. A 3-D coupled physics-CO_2 flux model was used to reproduce the coupling of the carbon cycle to the ice cover dynamics, freshwater discharges, and water circulation in the Hudson Bay system. Multi-year simulations of the coupled sea ice-ocean conditions in the Hudson Bay system were performed, for both current and projected climates. At the Bedford Institute of Oceanography, a coupled ocean-ice model was constructed, which focuses on Baffin Bay, the east coast of Labrador, and the Gulf of St-Lawrence. The ArcticNet IRIS Modelling Scenarios (AIMS) database was developed to provide access to archived data from Environment Canada's Global Environmental Multiscale (GEM) model and to provide a portal to the North American Regional Reanalysis data in Boulder, CO.

2.1.2 Key Messages

- Modelling activities within the ArcticNet community and particularly in this project, have the capacity to bring together disparate elements of the IRIS community and integrate individual research into a holistic description of ecosystems. Robust numerical models can fill in the spatial and temporal "gaps" that result from irregular sampling of the environment, and allow individual measurements to be placed in their seasonal and geographical context.
- Models of the state of physical aspects of the environment – the cryosphere, ocean, land, and atmosphere – can be projected into the future and used as a framework for the study of biological and social structures in years to come.
- Development of models, and access to model results and model datasets will become increasingly important as the ArcticNet programme matures into the IRIS framework.

2.1.3 Objectives

- To improve the credibility and utility of Arctic climate model results by:
  - * employing novel means of evaluating model performance over the ArcticNet focus regions;
  - * developing means to integrate the Arctic modelling community with process scientists, northern residents, and decision-makers at all governmental levels;
- To provide access to models, model data, and modellers for the ArcticNet community;

- To develop models that can reliably predict the future state of Arctic landscapes;
- To provide a standardized dataset which projects into the periods 2050 and 2100 so that all ArcticNet investigators use the same predicted forcing parameters of climate change.

2.1.4 Introduction

Model projections, the best means of estimating future weather and sea ice conditions, suggest that an ice-free Arctic can be expected at the summer minimum as early as 2050 (Flato and Boer 2001), should the present observed warming trend continue. Indeed, given the record extent of ice melt in 2007, this prediction may be optimistic. This project focused on four regional-scale models: Baffin Bay, Beaufort Sea, Canadian Archipelago, and Hudson Bay (Figure 1).

These models are high-resolution coupled ocean-sea ice-atmosphere models that examined marine and coastal processes to investigate how changes in the sea ice regime may affect people. Process science conducted within the ArcticNet framework can provide qualitative answers about the future direction of physical, chemical, biological and social aspects of a warming Arctic environment. However, a quantitative assessment requires the numerical guidance provided by models.

Moreover, computational models can often be used to identify environmental features that are less obvious, or that are not directly sampled with instrumentation. Models can be used to link disparate study elements (*e.g.*, biology to physics) with respect to questions concerning the impact on cod populations when sea ice thins, disappears earlier in the year, or lingers longer in the fall. Robust numerical models have the benefit of providing value both to the individual researcher, and to the IRIS consortium as

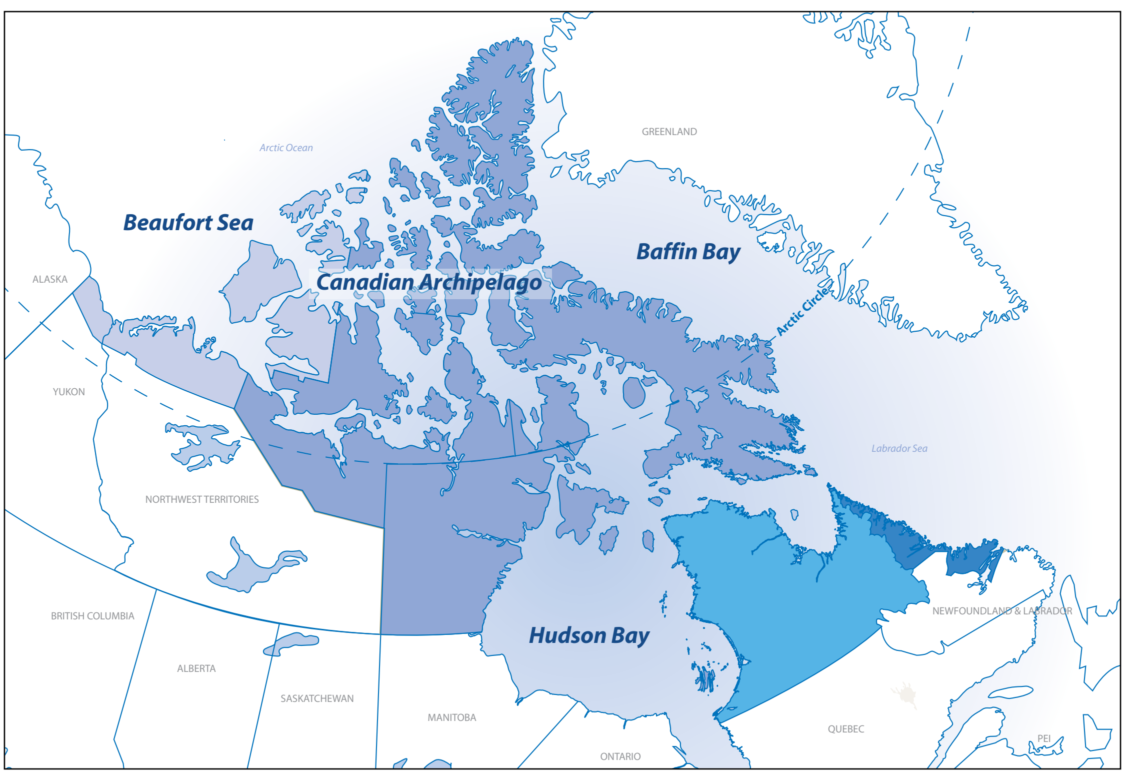


Figure 1. *Chart of the study areas in Baffin Bay, Beaufort Sea, Canadian Archipelago, and Hudson Bay.*

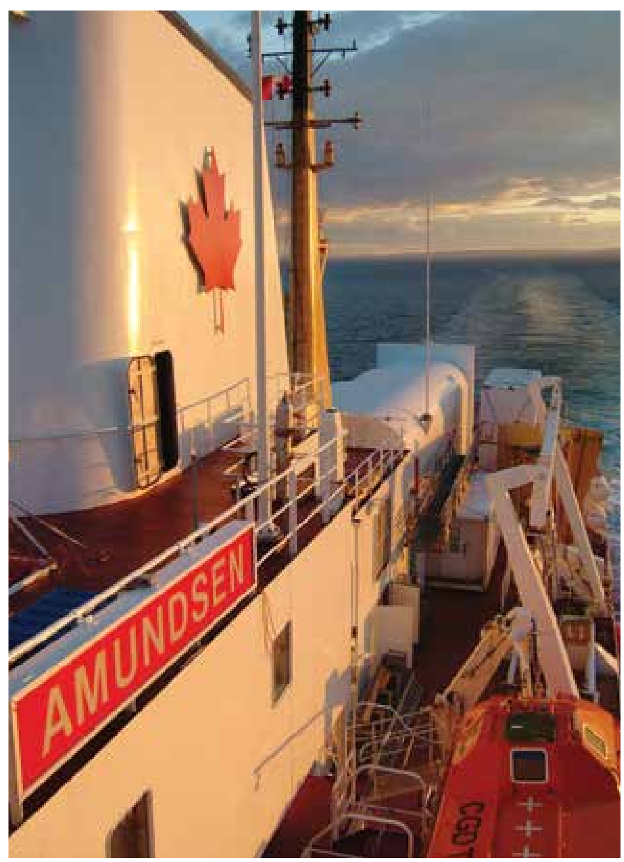
a whole. The goal of this project was to encourage modelling activities and to provide a framework in which the components of ArcticNet could be assembled into a coherent description of the present and future state of the Canadian Arctic. This project was an assembly point for the current direction of ArcticNet research and networking. Such assembly is critical if sound advice is to be passed on to decision-makers and the public throughout IRIS assessments.

2.1.5 Activities from 2004-2007

Research was conducted on cloud forcing of the snow/sea ice surface using a coupled one-dimensional radiative transfer model coupled to a snow/sea ice model. In support of this model, a study that examined how well clouds are resolved in MODIS satellite data relative to rawindsonde and ceilometer measurements collected *in situ* was completed (Jin et al. 2007a,b).

A "statistical downscaling" project was realized, whereby the Canadian General Circulation Model (GCM) was used to force a one-dimensional snow/sea ice model in the Canadian Arctic Archipelago (Dumas et al. 2006). This work predicted how fast ice would respond in the near future (*e.g.*, 50 years) when forced by climate conditions predicted by the GCM. A separate modelling project was also conducted to predict ice flows within the archipelago.

An ArcticNet IRIS Modelling Scenarios (AIMS) database was developed at the University of Manitoba and made available on-line. This project provided access to archived data from Environment Canada's GEM model and a portal to the North American Regional Reanalysis (NARR) data in Boulder, CO. The database archive was designed to make modelling results available to the larger ArcticNet community in a simple geocoded ASCII format so that results can be easily incorporated into GIS programs and additional studies. The AIMS database was designed around a Web portal that provides access to both archived numerical data and data held in other servers. In any numerical model, the volume of data available can be immense – commonly terabytes and petabytes – especially in models with high temporal and spatial resolution. AIMS archives are smaller datasets on a local server and provide a portal to access remote servers containing larger volumes of environmental data. The AIMS archive contains geocoded numerical data from Environment Canada's GEM model. The data are collected twice a day from the Environment Canada access point, converted to an ASCII format, geocoded, and archived on a CEOS server at the University of Manitoba. Access to the database is straightforward through the AIMS web site (reached by a link through the CEOS home page). Data are returned to the user as a zipped ASCII file. The archive has been running since July 2006, providing a meteorological framework for research data gathered during the CCGS *Amundsen* expeditions. AIMS also provides an easy-to-use portal into the



NARR (North American Regional Reanalysis) site, replacing arcane command strings with a simple set of menu choices on the web page. Access is provided to 87 of the 182 NARR parameters. NARR data is also delivered to the user in the form of a zip file, usually within a few seconds of making the request. The AIMS web portal can also link directly to other data sources, one of which is "WebTide", a site operated by the Department of Fisheries and Oceans. At WebTide, users can download a program to calculate tidal status at any site in Canada.

The regional ice-ocean model of Hudson Bay (Saucier et al. 2004) was used to examine the coastal sea ice and ocean climate. Systematic delta-type experiments for climate sensitivity and change were conducted. The results focused on the sea ice thermal sensitivity of the Hudson Bay marine system.

The STAR (Storm Studies in the Arctic) project, funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), investigated sea ice/atmosphere coupling. STAR was tied to this project through atmospheric modelling experiments with links to the marine system over the southern Baffin region on specific case studies (weather events) that occurred during ArcticNet Phase 1.

Multi-year simulations of the coupled sea ice were performed to assess ocean conditions in the Hudson Bay system, for both current and projected climates. The results were conveyed to northern communities for impact studies through Ouranos (an organization working on climate science and climate change adaptation) and Sanikiluaq workshops, where an attempt was made to build a sea-monitoring station on the Belcher Islands.

The mechanical energy budget of Hudson Bay and Foxe Basin was examined. A study of the freshwater cycles in the Hudson Bay system was also initiated. A field survey was undertaken during the summer of 2005 onboard the CCGS *Pierre Radisson* in Hudson Bay and Foxe Basin. The data has been merged with the profiles acquired by the ArcticNet program to examine freshwater cycles and for assimilation into regional climate models. The transport of freshwater through Hudson Strait was examined using both the regional climate model and data acquired throughout Hudson Strait (Straneo and Saucier 2007, 2008).

The coupling of a pelagic sea ice algae model to the regional climate model was investigated, as well as the renewal process of dense waters in Foxe Channel as it relates to sea ice production in the latent-heat polynyas in western Foxe Basin.

A coupled CO_2 chemistry and flux model was developed using the 3-D ice-ocean model of Saucier et al. (2004). The coupled model simulated CO_2 transport along with the ocean circulation and air-sea CO_2 flux in the Hudson Bay system under an abiotic environment (Dark Ocean Experiment) to explore the interaction between physical processes and the solubility of CO_2 and air-sea CO_2 exchange. This experiment was designed to understand the contribution of freshwater discharge to the carbon cycle of the Hudson Bay system, and its potential impact on the carbon cycle in the North Atlantic. A carbon-based biogeochemical model that includes nutrients, CO_2, primary production, zooplankton (two size classes) grazing, bacterial, detrital and dissolved organic matter has been developed.

Project team members have participated in MERICA (*e.g.*, Saucier et al. 2004) and ArcticNet cruises in Hudson Bay to acquire new key hydrographic information. Over 25 stations were sampled each year, including six moorings that have recorded continuous data over four years, resolving the whole range of tidal to interannual variability in key locations.

The development of a detailed regional climate model (Saucier et al. 2004) was pursued in order to examine the response of the sea ice-ocean conditions to climate warming. The capability was developed to couple this model with the Canadian Regional Climate Model and the Global Environmental Multiscale model (Qian et al. 2004, 2005, unpublished data).

A major snow blowing study was completed using field data (Huang et al. 2008). This project examined ways to improve predictions of blowing snow event characteristics and, in particular, the meteorological conditions responsible for extreme weather events that cause blowing.

The Canadian East Coast Ocean Model (CECOM) was developed to investigate ice thickness, concentration, velocity, sea surface elevation, freshwater and heat fluxes (Dunlap and Tang 2006). This model is used to forecast the movement and nature of sea ice along the west coast of Baffin Island and into Baffin Bay.

2.1.6 Results

When adding a mean air temperature increase of 4°C to the present climate conditions to simulate global warming, the regional ice-ocean model used by Saucier et al. (2004) revealed that a warmer atmosphere advanced the dates of sea ice melting from 25 days in Foxe Basin to six weeks in James Bay. The delay in freezing was more homogeneous among the sub-regions of the system, varying from three to four weeks. In this scenario, the sea ice cover season in James Bay was reduced to four months. This extended ice-free period allowed the water to store more heat in the mixed-layer. Sea-surface heating was then increased. Moreover, an ice-free surface around the summer solstice when solar radiation is maximal accelerated the melting rate and heating of the mixed-layer. The highest rises in summer surface water temperature were found along the southeast coast of Hudson Bay and in James Bay (Figure 2). Under the climate change scenario adopted for the model run, warming of the sea surface in James Bay exceeded 7°C whereas the added forcing in air temperature was only 4°C. Foxe Basin and the north shore of Hudson Strait were less affected by a general warming in air temperature.

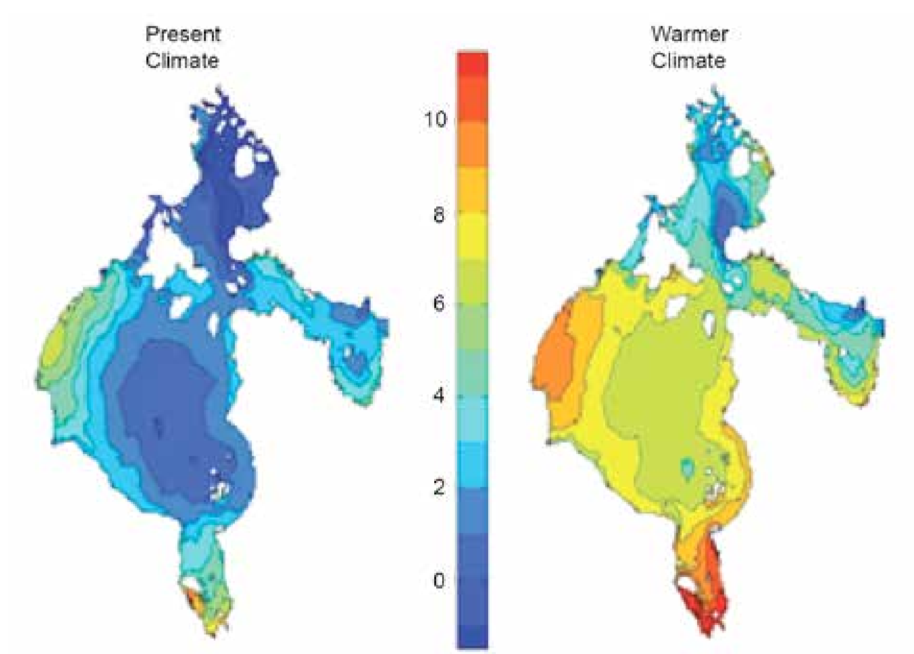


Figure 2. *Hudson Bay system climate change sensitivity experiment. Change in mean summer sea surface temperature (annual mean) due to a 4°C warmer air temperature.*

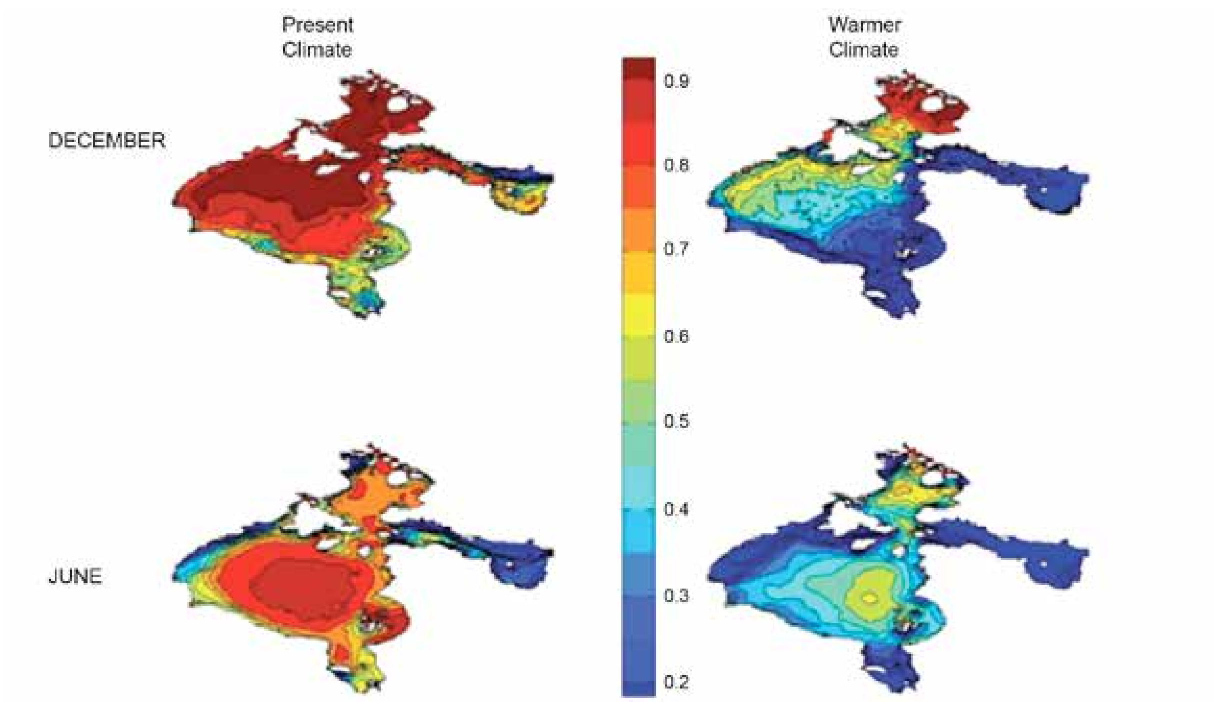


Figure 3. *Mean monthly sea ice concentration (months of June and December) for normal conditions (left) and 4°C warmer air temperature (right) in the Hudson Bay system (adapted from Joly et al. 2011).*

The additional heat stored in the mixed layer was released back to the atmosphere during autumn; this additional thermal energy took longer to extract, thus delaying freezing. An effect of this delayed freezing was a thinner sea ice cover. Sea ice thickness in southeastern Hudson Bay and James Bay was reduced by more than 35% over winter (Figure 3). Spatial variability in sea ice thickness was related directly to the predominance of mechanical growth and ridging over thermodynamic growth of sea ice in these regions. The deficit of sea ice production over a cryogenic cycle reaches 700 km^3 (- 30%) for the whole system (Figure 4). This reduction of sea ice generated a subsequent deficit of meltwaters in the spring, which in turn affected the related buoyancy-driven circulation and the freshwater outflow toward Hudson Strait and the Labrador Sea.

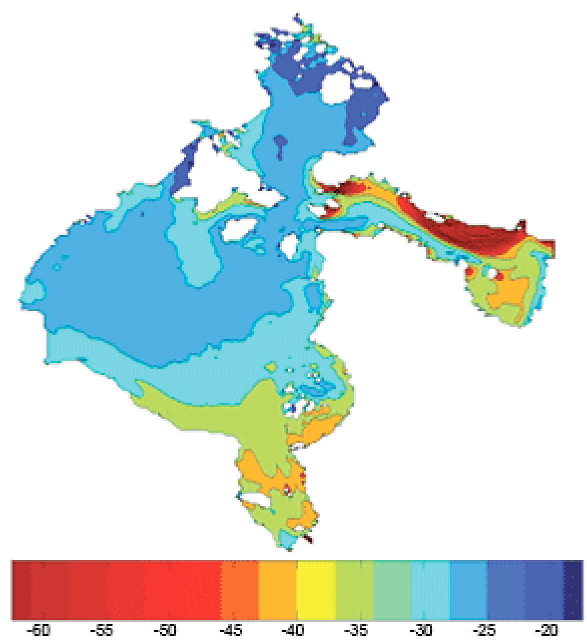


Figure 4. *Relative change (%) in maximum mean sea ice thickness with a 4°C increase in air temperature in the Hudson Bay system.*

The CECOM model (Dunlap and Tang, 2006) reproduced the northward-flowing West Greenland Current and revealed two cold southward flowing currents of Arctic water that entered Baffin Bay through

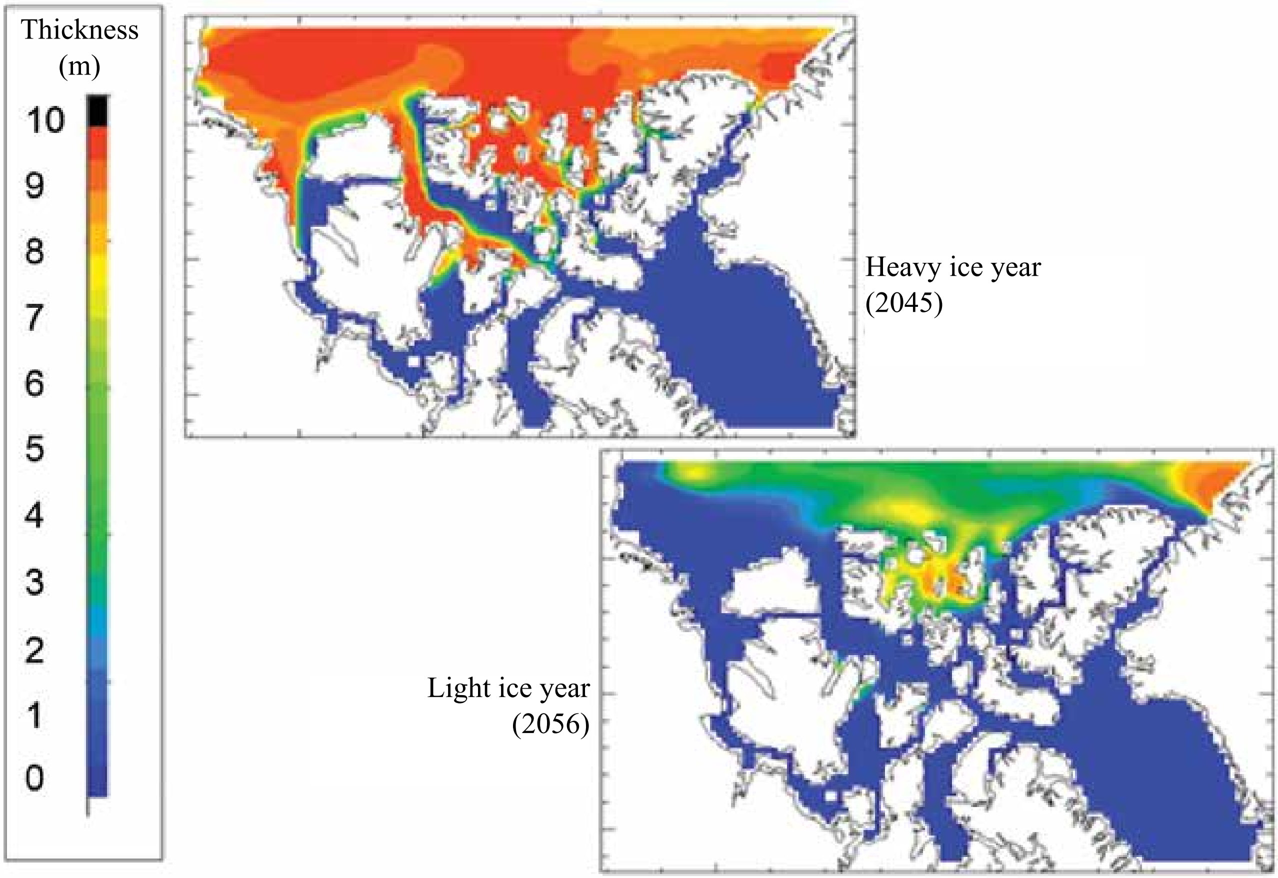


Figure 5. *Model predictions of future ice extent for years with heavy and light ice cover according to the model of Sou and Flato. Diagram courtesy of T. Sou.*

the northern sounds. The cold southerly flows were tied to the bottom topography of Baffin Bay: one flowed along the coast of Baffin Island, slowing and diffusing north of Davis Strait; the second originated in the central basin of the bay and flowed southward along the continental slope of Greenland, partly mixing with the West Greenland Current before exiting Davis Strait. Both of these currents were continuous at depth. The West Greenland Current exhibited a strong concentrated northward flow through Davis Strait, but then gradually diffused and slowed as it moved northward along the coast of Greenland. A velocity section across the bay through Davis Strait showed strong shears between the southward moving cold water and the northward flow of the Greenland Current, with the cores of the two flows separated by only 42 km at their narrowest point. These two flows could be traced from surface to bottom. A cross-section through the centre of Baffin Bay showed only weak representations of these two currents, and the flow at this latitude was dominated instead by a deep surface-based cold flow along the Baffin Island continental shelf.

Collaboration occurred on a separate project to study the flow and variability of ice in the Canadian Arctic Archipelago using a coupled ice-ocean model. This project used a high-resolution (0.2-degree) ice-ocean "Archipelago" model coupled with an Arctic Basin model (MOM 2.2). The Archipelago model made use of 11 "gates" to model ice flux through the Arctic islands. Flow was primarily from north to south, with ice exiting the islands into Baffin Bay. Model integration was conducted for two time periods: 1950-2000 with observed forcing and 2041-2060 with CGCM2 climate model forcing. The modelling exercise revealed a steady decline in ice extent over the 1971-2000 interval, and predicted amounts of less than 50% of the current low value in the 2040-2061 epoch (Figure 5). In the climate-forced future scenario, mid-century maximum ice concentrations were less than current minima. In light ice years between 2041 and 2060, the Archipelago waters were nearly ice-free.

A detailed, one-dimensional, land-fast ice model was used to simulate historical ice variation and to project future ice thickness and duration at ten communities in northern Canada (Dumas et al. 2006). The model was driven by observation-based forcing with a superimposed future climate change derived from the CCCMA global climate model (CGCM2). To extend the results to the future, 20-year mean anomalies were projected from the CGCM2 to the 1971-89 historical dataset (Dumas et al. 2006). Because this technique preserved the variance of the earlier time period, the authors also tested their predictions using the variability inherent in the CGCM2 model in a separate model run, with results similar to those based on the historical dataset.

2.1.7 Discussion and Conclusions

Several modelling experiments have been conducted to characterize the seasonal cycles in Hudson Bay and surrounding waters (Saucier et al. 2004) using a high-resolution 3-D coastal ice-ocean model with tidal, atmospheric, hydrologic and oceanic forcing. A multi-year hindcast simulation using GEM forcing was very precise and allowed the modelling group to compare results directly with data collected by ArcticNet and the MERICA programs.

The Hudson Bay Oceanographic Model (HBOM) revealed that most heat input to the waters of Hudson Bay is through surface fluxes with a minor component from tides. Autumn cooling came during periods of strong cold winds with the main heat losses in November, although this was moderated by yearly climatological fluctuations. Runoff and precipitation caused a seasonal fluctuation of about 2% in salinity as the main salt flux was controlled by ice formation and brine rejection. In the spring, small diurnal fluctuations in salt flux were controlled by daytime melting.

Water temperatures in Hudson Bay began to cool in September. Warmest temperatures were predicted for eastern and southern Hudson Bay – a pattern that remained throughout winter. Springtime warming came first in the northwest, north of Churchill and in James Bay, whereas the warming in the northeast was related to a persistent polynya in the region. East coast warming in spring was related to ice-free outflows from the rivers. Salinity was lowest in summer because of river plumes and ice melt. The flux of low salinity water made its way gradually toward Hudson Strait, which was reached in late fall. Winter salinity increased due to brine rejection and reduced runoff.

Autumn surface layer currents (to 60 m depth) were generally cyclonic and showed an affinity for shorelines, increasing in strength from the vicinity of Churchill, past the opening to James Bay, and northward along the Quebec shore. A strong current exited Hudson Bay along the south shore of Hudson Strait. Smaller and weaker gyres were evident in the model simulation: one in the western part of Hudson Bay opposite Churchill, another northwest of the Belcher Islands. Both were most evident in autumn in surface currents and more subdued at depth. Foxe Basin had a similar cyclonic circulation in autumn, but the strongest currents were in the northern part of that basin, rather than in the south and east as in Hudson Bay.

In spring, currents throughout Hudson Bay and Foxe Basin were much weaker, though a strong flow continued through Hudson Strait. The cyclonic flow around the shoreline all but disappeared, to be replaced by a weak mid-basin cyclonic gyre. The strong southerly east coast current had lost most of its autumn strength at the surface, and reversed to become a weak northerly flow at depths below 60 m. In winter, heat fluxes were maximal near Churchill, where losses were centred on regions of coastal divergence created by the prevailing winds. The same region had a high salt production rate in winter due to a persistent wind-created polynya.

The HBOM produced an accurate representation of sea ice concentration during freeze-up but an overestimate during spring melt. Sea ice volume was accurately modelled, throughout the ice season. In autumn, ice formed in open water and its thickness increased rapidly due to basal growth and ridging. By late December, basal growth had increased to 10 times the open-water growth rate. In March, ice concentration decreased from ridging and wind-driven leads, and melting began in May. The developing springtime circulation caused the remnant ice to accumulate in southern and southeastern Hudson Bay. Overall, the model successfully reproduced the pattern of ice formation, east-west gradient of thickness, the polynya in northwestern Hudson Bay, and the late melt in Foxe Basin and the south shore of Hudson Bay.

When run under a 4°C climate change scenario, the Saucier-group model showed a large increase in the ice-free season in Hudson Bay, ranging along a latitudinal gradient from 25 to 42 days. This could have significant economic and environmental impacts, including a longer shipping season into the Port of Churchill, a significant stress on polar bear populations, the need for human adaptation to a changing climate, and noticeable impact on the meteorology of northeastern Manitoba.

In the community-based model (Dumas et al. 2006), ice thickness declined and the duration of the ice-free period increased across the Arctic. Changes in Labrador were less distinct and more variable, probably because of the more southerly climatology at the site and the greater importance of snow cover in controlling ice growth. Within the Canadian Archipelago, ice thickness declined between 25 and 40 cm and the ice-free period increased by 22 to 49 days during the 2041-2060 period. In the interval 2081-2100, ice thickness declined still further to between 44 and 65 cm and the ice-free period increased by 37 to 84 days. The delay in freeze-up was greater than the advancement of break-up, probably reflecting the normal asymmetrical nature of the two processes. One significant finding was the change from multi-year ice to seasonal ice at Alert and Mould Bay by 2041-60.

2.1.8 Acknowledgements

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2.2 Reducing Human Vulnerability to Environmental Changes in the Canadian Arctic (Project 4.2)

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2.2.1 Abstract

This project built on work in the climate hazards literature, which conceptualizes vulnerability as a function of the exposure of a community to risks and the adaptive capacity of the community to deal with the exposure. This approach began with an identification of the conditions the community considers as risks (exposures) and the community's ability to prepare for, avoid, moderate and recover from the effects of exposure to changing conditions (adaptive capacity). Both exposures and adaptive capacity were identified through systematic iterative participatory methods, involving community members, instrumental records and documents. Traditionally, indigenous peoples in the Arctic have been highly adaptive in the face of stresses, including environmental changes. However, there is evidence that the nature and speed of some changes, beyond the control of Arctic people, may already be approaching or exceeding adaptive capacity thresholds.

This project assessed the vulnerability of several coastal Inuit communities through empirical documentation and analysis of communities' experiences with environmental (including climatic) exposures and risks, and identified adaptive options and resource management strategies to deal with these risks under a changing climate and its effects. Inuit representatives were active partners in the community case studies, through facilitation, field research design, key informant selection, translation and interpretation. Traditional Ecological Knowledge/Inuit Qaujimajatuqangit was combined with other data sources from ethnographic methodologies and government and scientific records. Changes in environmental conditions (including climate) were estimated (future exposure) from climate scenarios as the basis for characterizing the nature of risks estimated to be faced by communities in the future. The research included explicit analysis of decision-making institutions and processes as a basis for identifying feasible policy interventions. Outcomes of the research were assessments of the degree to which the adaptive capacity of the communities can accommodate future exposures and what changes in policy or management might improve future adaptive capacity, and consequently decrease future vulnerability.

2.2.2 Key Messages

- Arctic communities are already experiencing effects of climatic change, and they are extremely vulnerable to further changes in environmental conditions.
- Vulnerability to climate change is not felt in isolation of other stresses on northern communities, and effective vulnerability assessment needs to consider climatic and other environmental stresses and risks, as well as socio-economic pressures, constraints and opportunities.
- Climate-related risks threaten the sustainability of Inuit livelihoods. These relate to decreased predictability of weather, wind, and ice, changes in the timing of freeze-up and break-up, thinner sea ice, permafrost degradation, and localized shoreline erosion. Associated impacts include decreased access to harvesting areas, risks to safety while traveling, and higher fuel costs to reach more distant hunting grounds.
- Effects are not uniform across or within Arctic communities. Inuit youth, for example, are particularly vulnerable to unreliable, changing conditions in the Canadian Arctic. Conditions that currently pose risks to youth knowledge transmission are expected to be amplified by future climate change.
- Common adaptation strategies at the local level include a combination of traditional and technological solutions. Traditional adaptation strategies involve a renewed emphasis on teaching younger generations traditional skills, sharing of country foods (particularly with elders) to ensure food security, taking along extra gear to wait out unsafe conditions, and making adjustments in hunting locations, species har-

Figure 1. *Case study locations for ArcticNet project 4.2: Ulukhaktok 70°44'11"N 117°46'05"W, Tuktoyaktuk 69°26'34"N 133°01'52"W, Arctic Bay 73°02'11"N 085°09'09"W, Igloolik 69°22'34"N 081°47'58"W, Kinngait (Cape Dorset) 64°13'54"N 076°32'25"W, Pangnirtung 66°08'52"N 065°41'58"W, Hopedale 55°29'2.54"N 60°12'11.48"W.*

vested and timing of activities. Technological solutions include the use of satellite imagery, weather forecasting, Global Positioning Systems, VHF radio communication and snowmobiles.

- Climate and environment-related risks are compounded by challenges associated with the encroachment of southern culture, the introduction of wage-earning economies, and erosion of traditional kinship systems.
- Vulnerability reduction is best achieved by actions which serve immediate needs and enhance the ability of communities to cope with current exposures. In many cases, adaptation to climate change is related to strengthening social and knowledge networks in northern communities. Adaptation planning has a higher likelihood of success if mainstreamed into other policy concerns, such as resource co-management agreements.

2.2.3 Objectives

The broad aim of this project was to improve the scientific understanding of the processes that determine the vulnerability of northern Canadian communities to changing environmental conditions, and to identify adaptation needs and opportunities to enhance community well-being. This aim was achieved in seven case study communities (Figure 1). Case studies were guided by the following research questions:

- To which biophysical and socio-economic conditions are communities sensitive, and how? How are these expected to change in the future?

- What is the ability of local communities to manage changing conditions, and what adaptive strategies have been employed in the past?
- How do social, cultural, economic, and political processes operating at multiple scales affect adaptive capacity to changing environmental conditions?
- What further adaptations are needed and what can be done to enhance the adaptive capacity and well-being of communities?

2.2.4 Introduction

The Canadian Arctic is experiencing rapid changes in environmental conditions and in many aspects of northern economies and societies (ACIA 2004, AHDR 2004, IPCC 2007). The Arctic Human Development Report (AHDR) and the Arctic Climate Impact Assessment (ACIA) emphasize that Arctic peoples are susceptible and responding to changing conditions. The ACIA predicts unprecedented climate change for the Arctic regions, and changes have already been documented by instrumental records (Johannessen et al. 2004, Overland et al. 2004, McBean et al. 2005) and local and indigenous observations (Krupnik and Jolly 2002, Helander and Mustonen 2004, Ford 2005, Huntington and Fox 2005, Nickels et al. 2005). These changes have serious implications for ecosystems and people's livelihoods and well-being, and they occur in the context of ongoing social, cultural, economic, and political transformations in northern communities (Fenge 2001, Duerden 2004, Ford and Smit 2004).

While there is general agreement that changes in climate and associated conditions are likely to pose significant challenges for communities, the nature of these risks and the most effective means of dealing with them are not always fully understood (Nuttall 2001, 2005; ACIA 2004; Duerden 2004; Ford and Smit 2004; Kofinas 2005; McCarthy et al. 2005). There is a need to document the particular environmental, socio-economic and political conditions to which local communities are sensitive (and in what way) and to assess the strategies employed to deal with changing conditions in communities across the Arctic. Similarly, conditions that facilitate or constrain adaptive capacity or resilience of Arctic communities need to be identified. Achieving these goals requires data inputs from both scientific sources and local and indigenous knowledge. These provide a comprehensive understanding of changing conditions in the natural environment and opportunities to better deal with changing conditions in Arctic communities (Hovelsrud and Winsnes 2006).

This project addressed research needs by developing and applying a theoretical framework for community vulnerability and adaptation assessment. This involved a systematic, stakeholder-based methodology that established procedures for case study selection and implementation in collaboration with Northerners. The research undertaken under this program built on and expanded the research team's existing expertise and understanding of the processes that shape vulnerability and adaptation to changing social and environmental conditions. It applied these concepts to a number of northern case studies thus building a solid baseline understanding of climate change vulnerability and its determinants in the North.

2.2.5 Activities

This project followed a rigorous methodological framework for assessing current and future vulnerabilities. This framework (outlined in Figure 2) is based on the principles outlined in Lim et al. (2004), Berkes and Jolly (2001), Turner et al. (2003), Keskitalo (2004), Ford and Smit (2004), and Smit and Wandel (2006). The methodology was based on the notion that a crucial aspect of vulnerability assessment is to gather and understand the stakeholders' own information on their exposure sensitivities and adaptive capacity. The open, unbiased and active engagement of community representatives and other stakeholders was a necessary element of this approach. Beyond this, researchers gathered data on exposures, adaptive strategies and capacities from all possible sources including instrumental records, published scientific research papers, models, collaborations with colleagues in the natural and social sciences, unpublished or "grey" literature including reports housed in the communities and northern research organizations, as well as key informant interviews and climatic records.

Stakeholders, community members, local leaders and decision-makers were an integral part of every stage of the methodological approach outlined in Figure 2. Communities themselves had input into the project design (Who should be consulted for the research? When is the most appropriate time for work to be undertaken?). Active engagement of indigenous people at this stage involved visiting all the communities before the licensing process began. During these visits, local research collaborators were identified, and these individuals played substantial roles in the phrasing of research questions, as well as the development of locally appropriate interviewing strategies.

The second stage of the methodology (Figure 2) involved assessing current vulnerability. This included the identification of relevant hazards (both climate related and other), or exposures. Exposure encompasses both physical hazards and occupants' characteristics that place people at risk. For example, permafrost degradation was relevant for a community if its use of the area is affected (either positively or negatively) by changes in the permafrost regime. Permafrost degradation was a key exposure for Tuktoyaktuk, which is located on ice-bonded sediments subject to shoreline erosion, and a lesser exposure in Arctic Bay, which is located on a protected inlet and has more stable geologic characteristics. The assessment of current exposures required collaboration of scientists in the natural sciences to identify physical hazards and scientists (working collaboratively with stakeholders) to identify which hazards are pertinent to the community; this was primarily achieved through collaboration with ArcticNet colleagues.

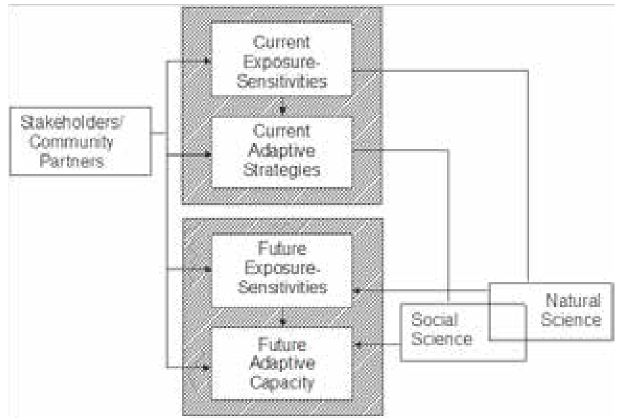

Figure 2. *Methodological framework for vulnerability assessment of northern communities.*

The gathering of information about future vulnerability (Figure 2) involved both scientific assessments and community insights. Where possible, estimates of future exposures were determined via the following two approaches. First, scientists analyzed conditions identified as current exposure sensitivities in order to estimate possible changes, trends or probabilities of change in those conditions, and to describe the ways in which existing hazards might change in the future. Second, possible changes in conditions from climate scenarios (including IPCC and ACIA) were specified even when not identified by community residents.

Future exposure sensitivities were evaluated in terms of the community's capacity to adapt, with information gathered from community members' responses to presented future hazards, from key informants involved in the institutions, risk management processes, resource management structures and policies related to adaptive capacity, and from social sciences that might bring insights from elsewhere on the nature of community resilience and adaptive capacity.

The research process went beyond the assessment of vulnerability outlined above. In all cases, researchers conducted follow-up visits in communities to bring the 'research back to the North' and verify the validity of the conclusions. Furthermore, this project (in collaboration with Inuit Circumpolar Council (ICC) and various contributors) facilitated the participation of Northerners in southern research meetings including the ArcticNet Annual Scientific meetings in 2005, 2006 and 2007, the ACUNS student conference in 2006, and the United Nations Conference of the Parties meetings in Montreal (2005) and Bali (2007). Beyond this, the researchers disseminated findings and recommendations as widely as possible, through scholarly articles, popular press, radio and television interviews, conference presentations, and contributions at planning workshops. In several cases, Northerners co-authored publications and presentations.

The process outlined here was followed for seven case studies (Table 1). In addition, individual case studies commonly had secondary foci based on community-identified needs and graduate student interests. The timing of all research activities, topics of particular emphasis, personnel involved and specific dissemination activities associated with each case study are outlined in Table 1.

2.2.6 Discussion and Conclusions

This research program represented one of the first comprehensive vulnerability assessments of communities in the Arctic. The researchers worked with Northerners to identify conditions that are currently problematic, or may become so in the future. Working with communities allowed the research team to first understand how northern livelihoods work with and in the natural environment, and how these livelihoods are affected by already existing climatic and non-climatic stresses. While climate change poses a very real risk to the sustainability of northern livelihoods, these are already challenged by existing environmental stresses and socio-economic pressures related to increasing integration into the southern wage-based economy. The research highlighted that climate does not act in isolation of other opportunities and constraints, and adaptation to changing environmental conditions has greater relevance if it addresses non-climatic conditions as well.

The research program provided detailed analyses of the overall vulnerability of seven case study communities, with particular emphasis on issues identified as relevant in regional contexts. Emphases included hunting behaviour (Arctic Bay, Igloolik), sea ice (Igloolik, Kinngait, Pangnirtung), food security (Arctic Bay), youth (Arctic Bay, Ulukhaktok), infrastructure (Ulukhaktok) and community planning/social learning (Tuktoyaktuk, Hopedale). All research was carried out with northern partners from within the communities who took active roles in research design and implementation. Whenever possible, Northerners participated in southern research conferences (ArcticNet ASM 2005, 2006, UNFCCC Conference of the Parties 2005, 2007, ACUNS Student Conference 2007).

The vulnerability research framework employed involved collaboration among Northerners, and natural and social scientists. This was achieved at the scale of the case studies, particularly through networking activities and a subsequent CCIAP-funded project that focused on a subset of the case study communities. However, further integration of the natural and social sciences (including wildlife biologists, sea ice experts, meteorologists, health and political scientists) was needed to achieve the policy-relevant, integrated science expected during the International Polar Year (2007-2008).

The research reported here is comprehensive and innovative, as reflected in the extensive dissemination record of the project team. The systematic data collection methods and analytic frameworks allowed for comparison of findings among the case studies (and in the circumpolar context through the International Polar Year). Furthermore, there is a need to "scale up" these case studies to link them to regional policy making institutions. Preliminary efforts have been made by the project team (including invited participation in regional/territorial planning exercises), but these results need to be further mainstreamed into policy. The team has established contacts with territorial governments and the Department of Indian Affairs and Northern Development, and continued

Table 1. *Key research and dissemination activities within ArcticNet project 4.2 (continued on next page).*

CASE STUDY: ARCTIC BAY	
Field researchers	James Ford, Johanna Wandel, Erin Pratley, Meghan McKenna
Secondary Emphasis	Hunting behavior (Ford, Wandel); food security (Pratley); youth (McKenna)
Pre-Research Visit	March 2004 (Ford); February 2007 (McKenna)
Field Season	June-July 2004 (Ford, Wandel); September-October 2004 (Pratley); May-July 2007 (McKenna)
Follow-Up Visit	April 2005 (Ford, Pratley); March 2008 (McKenna)
Dissemination	Publications: Ford et al. 2006a; Ford and Wandel 2006; Ford et al. 2007; Ford et al. 2008a Conferences: ACIA Release (Reykjavik, 2004); ArcticNet ASM (2004, 2005, 2007); ARCUS Arctic Forum (Washington, 2007); ESSP Open Meeting (Beijing, 2006); Aboriginal Policy Research Conference (Ottawa, 2006); American Association of Geographers (Denver, 2005; Chicago, 2006); AMAP meeting (Reykjavik, 2006); CAFF meeting (Helsinki, 2005); Northern Research Forum (Yellowknife, 2004) Media: CBC The National; Above and Beyond, 2006; Nunatsiaq News, 2007

CASE STUDY: KINNGAIT	
Field researchers	Gita Laidler
Secondary Emphasis	Sea ice
Pre-Research Visit	October 2003
Field Season	April 2004, December 2004-January 2005, May 2005
Follow-Up Visit	December 2006
Dissemination	Publication: Laidler 2006a,b Conferences: ArcticNet ASM (2005, 2006); American Association of Geographers (San Francisco, 2007)

CASE STUDY: PANGNIRTUNG	
Field researchers	Gita Laidler
Secondary Emphasis	Sea ice
Pre-Research Visit	October 2003
Field Season	May 2004, November 2004, February 2005, April-May 2005
Follow-Up Visit	December 2006
Dissemination	Publications: Laidler 2006a,b Conferences: ArcticNet ASM (2005, 2006); American Association of Geographers (San Francisco, 2007)

CASE STUDY: IGLOOLIK	
Field researchers	James Ford, Gita Laidler
Secondary Emphasis	Hunting behavior (Ford, Wandel); sea ice (Laidler)
Pre-Research Visit	February 2004 (Laidler); April 2004 (Ford)
Field Season	October-November 2004 (Ford, Laidler); June 2005 (Laidler)
Follow-Up Visit	April 2005 (Ford); Decembrer 2006 (Laidler)
Dissemination	Publications: Ford et al. 2006b; Ford and Wandel 2006; Ford 2007; Laidler 2006a,b; Ford et al. 2008b Conferences: ArcticNet ASM (2005, 2006); Aboriginal Policy Research Conference, 2006; American Association of Geographers (Chicago, 2006; San Francisco, 2007) Media: CBC The National

CASE STUDY: ULUKHAKTOK	
Field researchers	Tristan Pearce
Secondary Emphasis	Infrastructure (2005); youth (2006)
Pre-Research Visit	April 2005
Field Season	May-August 2005, August-September 2006, February-March 2007
Follow-Up Visit	August 2006 (infrastructure research); March 2007 (youth research)
Dissemination	Publication: Pearce et al. (submitted) Conferences: ArcticNet ASM (2006); Northern Research Forum (Oulu, 2006); Coastal Zone Canada (Tuktoyaktuk, 2006); Rapid Landscape Change (Whitehorse, 2005)

CASE STUDY: TUKTOYAKTUK	
Field researchers	Mark Andrachuk
Secondary Emphasis	Social learning
Pre-Research Visit	July-August 2006
Field Season	May-August 2007
Follow-Up Visit	March 2008
Dissemination	Conference: ArcticNet ASM 2007

CASE STUDY: HOPEDALE	
Field researchers	Ruth De Santis
Secondary Emphasis	Community planning
Pre-Research Visit	January 2007
Field Season	June-August 2007
Follow-Up Visit	March 2008
Dissemination	Conference: ArcticNet ASM 2007

work in this area beyond the 2004-2008 cycle of this particular project.

Finally, this ArcticNet project has laid the foundations for long-term longitudinal case studies of human community vulnerability including opportunities for monitoring the results of practical adaptation strategies over time (a key research area identified by Northerners in the research process). It is anticipated that members of the research team will secure further funds for Canadian Arctic research on northern communities that will allow them to move beyond a "snapshot" of one or two years to long-term research relationships.

2.2.7 Acknowledgements

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2.3 Vulnerabilities and Adaptation to Meteorological and Related Hazards (Project 4.3)

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2.3.1 Abstract

Severe weather and its potential impact on communities is a major concern for residents across the eastern Canadian Arctic. Strong and variable low-level winds, heavy snow, and freezing precipitation are among the most important weather hazards in the Arctic. A key objective of this project was thus to improve our understanding of the main critical weather-related hazards and the atmospheric conditions leading to their generation in the Canadian Arctic. The project also focused on better documenting weather variation and on using the meteorological data obtained to validate high-resolution numerical models. Extensive field projects were carried out between 2004 and 2008 at various locations on southern Baffin Island, often in collaboration with local communities and stakeholders. These studies indicate that, in the context of global warming, changes occur in the local prevailing weather conditions in many communities across the Canadian Arctic. Stronger and more variable surface winds, heavier precipitation in some regions and less precipitation in others are indeed observed, as well as a more frequent occurrence of freezing precipitation. For residents of Arctic regions, these changes lead to a reduced predictability of hazardous weather conditions. Finally, this project allowed for the determination of critical aspects of atmospheric hazards and for identification of vulnerabilities to changing weather conditions in several communities.

2.3.2 Key Messages

- Changes in atmospheric hazards are already occurring due to changing large-scale climatic conditions.
- Strong and variable surface winds are among the most important weather hazards in the Arctic.
- Freezing rain in the Arctic is associated with stronger surface winds and a longer period of below 0°C temperatures after the freezing rain event than in locations further south. Thus, freezing rain events in the Arctic may lead to greater likelihood of major transportation disruptions and infrastructure impacts.
- Climate change results in reduced predictability of hazardous weather conditions

2.3.3 Objectives

The main objectives of this project were:

- To determine and improve our understanding of the most critical weather-related hazards in the Canadian Arctic;
- To investigate large-scale and local atmospheric conditions conducive to the generation of hazardous weather conditions;
- To better document weather variations in the vicinity of Iqaluit and Pangnirtung through field studies;
- To use data collected during field projects to validate high-resolution numerical models;
- To communicate progress to researchers within ArcticNet, to the local populations, and to other stakeholders.

2.3.4 Introduction

Due to its impact on transportation and surface infrastructure, hazardous weather is a major concern for inhabitants of the Canadian Arctic. Residents of Nunavut and other Arctic regions have reported that they are most concerned with strong and variable surface winds, heavy snowfall, and freezing precipitation. Furthermore, Inuit have reported an increase in both sudden and unanticipated changes in the weather that limit their predictive and adaptive capabilities (Ford et al. 2006a,b). There are concerns over future changes in the frequency of storms (McCabe et al. 2001, Yin 2005).

Hazardous weather can have significant impacts on communities. Strong winds can cause dangerous flying conditions and, when coupled with heavy snowfall, are associated with significant low visibility conditions. Snowdrifts frequently block roads and bury entire buildings (Wallace 2006). Most communities are located near the coast where surface winds often have a significant impact on sea ice and sea state (*e.g.*, wave) conditions. In addition, freezing precipitation can impact roads and runways and, when coupled with strong surface winds, can damage power lines. Freezing precipitation may also have catastrophic effects on wildlife (Monro 2006). However, few studies on hazardous weather conditions and the detailed structure and evolution of storms occurring in the Arctic have been published.

To address the above concerns, researchers from this ArcticNet project, in collaboration with various partners, have conducted climatological case studies of hazardous weather, with special emphasis on the eastern Canadian Arctic. The meteorological extremes − and the key factors leading to such extremes − that occur in the present climate and that have significant impacts on humans were identified. This project also examined whether the contributing factors and their associated extremes are expected to occur in the future and, if so, whether their frequency, magnitude and location are likely to change. Studies conducted included the use of long-term weather data to investigate the occurrence and large-scale forcing of freezing precipitation, as well as the orographic modification of low-level winds. Short-term variability of surface characteristics, including atmospheric pressure and wind speed and direction, was also assessed.

Autumn is one of the two main storm seasons in the eastern Canadian Arctic. Such storms are characterized by heavy snowfall, strong winds, and resultant blizzard conditions. To better understand these storm systems, autumn field projects were conducted during three consecutive years (2005, 2006, 2007). This study was initially carried out at Iqaluit and efforts were later extended to include Pangnirtung.

2.3.5 Activities

A number of activities funded by ArcticNet were carried out between 2004 and 2008. Several field studies were conducted on southern Baffin Island, along with various activities with other research groups and local communities:

1) A small preliminary field project was conducted in Iqaluit in autumn 2004, during which meteorological surface data was collected using a portable weather station. Building on this initial study, a second and larger field project was conducted in Iqaluit in autumn 2005. Once again, meteorological surface data was collected using several portable weather stations. One portable weather station was used to collect meteorological measurements in view of the planning of a new housing subdivision in Iqaluit. The data has been made available to the community through the Nunavut Research Institute (NRI). Weather balloons, which provide detailed upper air measurements, were launched at 3 - 4 hour intervals and high-resolution photographs of precipitation particles were also taken during several storm events. A third project was conducted in autumn 2006 at Iqaluit and Pangnirtung. Surface measurements were completed at Iqaluit and weather balloons were launched simultaneously at Iqaluit and Pangnirtung.

2) Major research activity was carried out in autumn 2007. The STAR (Storm Studies in the Arctic) field experiment was conducted in October and November to examine storms over southern Baffin Island and surrounding areas. The goal of this effort was to provide unprecedented details on these storms, as they were monitored using a wide range of equipment, including aircraft, radar, sonar, weather balloons, and additional weather stations. Special on-the-ground enhancements were based in Iqaluit and Pangnirtung.

3) High precipitation events can pose a hazard to communities in the Arctic. A study was conducted to further the understanding of the synoptic and mesoscale mechanisms through which hazardous precipitation is produced in both the warm and cold seasons (Gascon 2008).

4) Strong and variable surface winds are considered to be among the most important weather hazards in the Arctic. Therefore, various aspects concerning the low-level wind field in the Canadian Arctic were analyzed. An extended study of extreme surface wind conditions in the Canadian as well as the European Arctic was also conducted.

5) Another study was carried out in the Clyde River (Nunavut) area to assess the degree to which weather station observations match trends in winds observed by residents of the local community (Gearheard et al. 2009).

6) Severe weather events affect the daily lives of people living in the North. People's perceptions of weather and changing weather patterns in Aklavik (NWT) and Old Crow (Yukon Territory) were investigated to understand how weather-related problems affect both communities' residents. The rich local knowledge contained in the Arctic Borderlands Ecological Knowledge Coop's community monitoring database was mined to study changing weather patterns, notably the increasing unpredictability of the weather, and how they impact people. Particular attention was given to changes in the timing of freeze-up and break-up of sea ice and ice characteristics over the past 10 years, how the latter affected severe weather events, snow conditions and overflow, and whether the associated problems are increasing or decreasing in frequency. Furthermore, the major weather-related stressors were identified for each

year and for each community, as perceived by the most active hunters and harvesters.

7) Indigenous residents of Arctic communities are experiencing increasing difficulties in predicting weather conditions using traditional knowledge. A study was undertaken to examine weather skill scores of forecasters in Edmonton and determine if they are experiencing the same difficulties as in the North. A skill score database was used to compare forecast assessments of Arctic centers to those of larger urban areas of the Canadian Prairies in order to detect seasonal and inter-annual variations in forecast skill scores.

8) In addition, numerous outreach activities were carried out while the researchers were in Nunavut. An advertised community lecture was organized and given at the Natural History Museum in Iqaluit each year. In autumn 2004, a field trip was organized with the Environmental Technology Program at the Nunavut Arctic College (NAC) for the installation of the weather station at the new subdivision site in Iqaluit. In autumn 2005 and 2006, field trips to the official weather station at the Iqaluit airport were organized with the Environmental Technology Program at NAC, during which the meteorological sensors were explained and a weather balloon was launched. During autumn 2006, a lecture was given to the French school in Iqaluit and an interview was given to the French radio station. A short documentary detailing the research was shown on CBC North Television. An article entitled “High Impact Weather at High Latitudes: A Nunavut Perspective” was published in the ArcticNet Fall 2006 newsletter (Roberts et al. 2006).

2.3.6 Results

Winds

The climatological features of strong surface winds at Iqaluit are discussed in Nawri and Stewart (2006), where the local and large-scale conditions associated with extreme surface winds in different seasons are documented. On southern Baffin Island, strong surface winds are generally associated with low-level jets, *i.e.*, wind speeds within the lowest few hundreds of meters, which are larger than those of the overlying flow. Because wind speed usually increases from the surface to the top of the troposphere, these strong surface winds represent extreme flow conditions, which are frequently forced by the relief and orography and other terrain features. The connection between the prevailing surface wind conditions at Cape Dorset and Iqaluit is discussed in Nawri and Stewart (2006). The investigation of dynamical influences of the large-scale atmospheric circulation on local surface wind conditions over complex terrain allows for the downscaling of large-scale weather and climate predictions, and the development of future scenarios for local prevailing wind conditions. Significant changes in local wind conditions may be the result of small changes in the large-scale circulation. Vulnerabilities to changes in the prevailing wind conditions have been identified for several Canadian Arctic communities, and this study allowed for estimation of the likelihood of such changes occurring for predicted changes in the large-scale circulation. The above study investigated the wind dynamics within orographic channels, such as valleys or fiords, or between two islands. A similar study addressing the low-level flow along the seaward side of mountain barriers was also conducted at Clyde River.

Surface weather variability and associated predictability are also considered to be among the most important aspects of high latitude weather. Throughout the Canadian Arctic, there are indications that short-term weather variability is changing. Therefore, a series of analyses were conducted, addressing the variability on different time-scales of various surface weather conditions at twelve locations in the Canadian Arctic. Pressure, wind speed and direction are discussed in Nawri and Stewart (2008). It has been observed that the local temporal variability of surface pressure is mainly determined by the large-scale atmospheric circulation, and therefore shows a

well-defined spatial pattern within the study domain. However, surface wind speed and direction are significantly affected by local terrain features, and their temporal variability therefore does not show any consistent spatial patterns. There were no significant long-term trends in the variability of surface pressure, and only a few local trends within the last 30 years in the amplitude and mean surface wind speeds. Decreasing trends in these latter two variables were found in the central part of the Canadian Arctic in Kugluktuk, Cambridge Bay, and Yellowknife, and increasing trends were observed in Iqaluit. Similar analyses addressing the variability of temperature, precipitation, blowing snow, and visibility were also conducted.

The study carried out in the Clyde River area assessed the degree to which weather station observations reflect trends in winds observed by residents of the local community. This study revealed that there is some agreement but also disagreement between these two types of information (Gearheard et al. 2009). Consequently, weather station information has to be interpreted carefully because it may not be representative of conditions in the surrounding areas where hunters travel.

Some of the greatest impacts from severe weather are linked to sustained periods of strong winds. The Baker Lake region is particularly prone to such conditions, which are enhanced in the Arctic due to meteorological conditions and topographic features (Nadeau 2007). Factors such as the slowing down of synoptic systems as they deepen over open water contribute to the duration of high wind events.

Freezing precipitation

The study of the surface, upper-air, and synoptic features associated with freezing rain in the eastern Canadian Arctic is discussed in Roberts and Stewart

(2008). Freezing rain in the North occurs in a variety of synoptic and vertical atmospheric conditions and is associated with stronger surface winds and a longer period of below 0°C temperatures after the freezing rain event than in locations further south. Thus, freezing rain events in the Arctic may lead to greater likelihood of major transportation disruptions and infrastructure impacts.

Storms

The meteorological studies of this project allowed for the acquisition of the first documentation and analysis of the structure and evolution of storms at a high temporal resolution as the storms passed over Iqaluit and Pangnirtung (Nunavut). The studies also produced the first documentation and analysis of the local vertical structure of storms within the fiords surrounding Pangnirtung. The additional surface and upper-air data measurements allowed for the first detailed validation of Environment Canada's high-resolution limited area model (GEM-LAM) at high latitudes.

Data collected during the field project conducted in autumn 2005 in Iqaluit was analyzed and the consequences/impacts of storms are discussed in Roberts et al. (2008). This analysis revealed that autumn storms vary in many aspects, including origin, circulation, frontal structure, and precipitation type, as well as intensity of wind and precipitation. All of these aspects contribute to the complexity/difficulty of prediction and adaptation in this region. In particular, the storms coincided with hazardous surface conditions including strong winds and precipitation and low visibility due to blowing snow and fog. These conditions limited surface visibility to less than 2 km at times.

2.3.7 Discussion and Conclusions

This ArcticNet project has made substantial progress in a variety of aspects addressing vulnerabilities and adaptation of northern communities to atmospheric and related hazards. Key issues have been identified, means through which hazardous conditions are formed have been examined, and trends of those conditions have been assessed. Furthermore, researchers have worked with many groups and individuals impacted by such hazardous conditions.

Contributions have been made at both the community and scientific level. Researchers have shared their work with Arctic communities. For example, lectures and field trips were given during the projects conducted in Iqaluit and contacts and collaborations were established with the Clyde River community. In addition, a major field experiment was carried out in collaboration with Nunavut partners in autumn 2007.

Critical aspects of atmospheric hazards have been determined. Hazardous conditions are forced by large-scale flow and/or orography and other terrain features. Generally, there were no consistent trends in the occurrence and variability of hazardous conditions. Substantial differences in the hazardous conditions between the Iqaluit airport and portable weather stations have further shown the variability in strength of such hazards, even at small spatial scales.

Very few studies specifically detailing weather hazards in the Canadian Arctic have previously been conducted despite the recognized importance of such hazards. In effect, this project accounts for nearly 50% of the journal articles in the Prairie Region and Northern Region components of the National Atmospheric Hazards Project of Environment Canada.

This work generated positive impacts on stakeholders, notably:

- City of Iqaluit: On the basis of needs from NRI and the City of Iqaluit, existing data has been analyzed and a special weather station was erected in the city in support of their plans for creating a new subdivision.

- *Environment Canada*: Environment Canada has identified a number of key forecast issues, and comprehensive evaluations of their model-based outputs over southern Baffin have been carried out. Results were conveyed to Environment Canada and will contribute to the better prediction of hazardous events.
- *INAC/Qulliq Energy Corporation*: Both groups are concerned with the effects of extreme weather conditions on operations, including the potential development of a new pier on an island in Frobisher Bay. The project team has been working with these groups, in part through STAR to address their concerns. This has included installing special observing sites and interpreting results for their benefit.
- *First Air*: Through preparations for STAR, First Air identified hazardous flying conditions as a key issue. Special measurements and validation of wind shear and flight-level icing were identified as particular issues to be examined.
- *Clyde River*: Through discussions with the Hunters and Trappers Association (HTA) and other community groups, wind was highlighted as a critical issue. Information gathered from the study of wind dynamics that includes both instrumental data and local knowledge contributed directly to the development of new adaptive strategies in hunting and fishing practices.

2.3.8 Acknowledgements

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2.4 Climate Change, Key Traditional Food Species and Community Health in the Arctic (Project 4.4)

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2.4.1 Abstract

Traditional/country food is well documented as a critical resource for the health and well-being of northern populations. Climate-related changes and variability in the North have been associated with changes in animal, fish and plant population health and availability. Changes in ice, snow, precipitation regimes, and other environmental factors have the potential to influence travel and transportation in the North and thus Inuit accessibility to these resources. Therefore, climate has the potential to influence nutrition and health status among Inuit via its impacts on aspects of traditional/country food security. Through both qualitative and quantitative approaches, this project investigated the relationship between observed climate changes in Canadian Arctic Inuit communities and traditional/country food consumption. Working in five Arctic communities, it was concluded that climate and environmental change and variability have both positive and negative impacts on northern diets, and that these impacts have direct implications for nutrient intake and contaminant exposure. Changes in environmental conditions appear to be impacting both traditional/country food availability and accessibility in all regions.

2.4.2 Key Messages

- Significant climate changes have been reported across northern Canada and are already being experienced by Inuit.
- Both positive and negative impacts of climate and environmental changes on the traditional/country food harvest of five communities are reported.
- Environmental changes are having impacts on both the availability of wildlife species and their accessibility by hunters.
- It is possible to relate wildlife harvest data to traditional/country food use at both community and regional levels.
- Environmental change can have a significant impact on the quality of the traditional diet.
- Preliminary results suggest that some harvesters are developing adaptation strategies, which are effective to date in coping with the adverse effects of environmental change.

2.4.3 Objectives

The overall objective of this project was to investigate the health impacts of climate change on Canadian Arctic communities in relation to traditional/country food consumption. Specifically, the project focused on:

- Nutrition and potential changes in intake of nutrients;
- Exposure to contaminants;
- Levels of food security (availability and access to traditional/country foods).

The research sought to investigate to what extent, and how climate change is affecting the traditional/country diet profile of Inuit residents presently and potentially in the future, and what implications this may have for individuals' health. In addition, an attempt was made to describe who is most at risk for these impacts within Arctic and Subarctic communities, and to identify the factors that influence vulnerability to the negative impacts of climate change on traditional/country food security.

2.4.4 Introduction

Traditional/country food is well documented as a critical resource for northern populations due to its nutritional, economic, social and cultural benefits (*e.g.*, AMAP 2003, VanOostdam et al. 2005). However, these important foods are also the main source of exposure for many environmental contaminants among northern Aboriginal people via their traditional/country diet based on land and sea species

(VanOostdam et al. 2005). Climate-related changes in the North have been associated with alterations in animal, fish and plant population distribution, abundance, morphology, behaviour and community structure (availability) (ACIA 2005, Nickels et al. 2005). Climate changes have also been associated with changes in ice, snow, precipitation regimes, and other environmental factors potentially influencing travel and transportation in the North. Recent studies (*e.g.*, Furgal et al. 2002, Guyot et al. 2006, Tremblay et al. 2006) have suggested that these climate-related changes are influencing components of Inuit traditional/country food security. In this way, climate has the potential to influence nutrition and health status in relation to such aspects as the incidence of disease, contaminant-affected health outcomes (*e.g.*, child development) and general individual and community health related to aspects of diet and lifestyle (Berner and Furgal 2005). A better understanding of the key environmental variables influencing availability, accessibility and quality of principal traditional/country food resources is required to protect and promote the role of these foods in the Inuit diet in the context of projected climate and environmental changes in the future.

2.4.5 Activities

A combination of approaches, including modelling and qualitative work, has been used in this study, integrating both scientific and local/traditional knowledge. Specific methods of choice for representative communities in each of the regions have varied depending on the level of information already available for each community. In cooperation with a co-funded study on this subject, work has been conducted in the Yukon, Northwest Territories (NWT), Nunavut and Nunavik since 2004. Focus groups and dietary interviews have been completed in four communi-

ties across the Canadian Arctic, and the correlation between self-reported food use data and harvest data was studied at both the community and regional levels. As well, scenarios of climate change and impacts on diet and nutritional intake have been modelled at both the community and regional scales.

Specifically, focus groups and dietary survey studies were conducted in Beaver Creek, Yukon, Fort Providence, NWT, and Kugaaruk and Pelly Bay, Nunavut. Access to harvesting data for the region has permitted the team to begin modelling the relationship between harvest data and traditional/country food use in the Nunavut communities. Additionally, a template for a food security questionnaire has been developed. This was used to measure the status of food security in Nunavut as part of the Nunavut Health Survey.

Focus group and individual semi-directed interviews were conducted in Kangiqsualujuaq, Nunavik in 2006. Additionally, questions related to hunting and fishing activity, challenges faced on the land and their potential link with climate variability and change were posed as part of the Qanuipitaa Health Survey in all Nunavik communities. Analysis of this data has identified key environmental factors influencing aspects of traditional/country food security at the individual level, as well as factors facilitating or hindering the harvesting of traditional/country foods from the land and for which there is a plausible causal link with climate change. Finally, work in Kangiqsualujuaq has included the production of a video documentary on the topic of traditional/country food security and climate change in Nunavik to communicate the results of this work and general information on the topic to community residents and others.

2.4.6 Results

In 2004, food frequency questionnaires and focus groups were used to collect data from Deh Gah Got'ie First Nation in Fort Providence, NWT and White River First Nation in Beaver Creek, Yukon to investigate the link between self-reported harvest data and estimated average daily intake of country/

Table 1. *Nutrients affected by changes in traditional/country food as a result of observed climate changes in ice, snow and water*

OBSERVATION	CONSEQUENCE	COUNTRY FOOD	NUTRIENTS AFFECTED
► thin ice	use boat earlier	↑ fish	vitamin D, protein, ω-3 fatty acids
		↑ caribou	iron, zinc, protein
		↑ seal	iron, protein, ω-3 fatty acids
► rotten ice	travel dangerous	↓ seal	vitamin D, protein, ω-3 fatty acids
► lower water table	local streams dried up	↓ fish	iron, protein, ω-3 fatty acids
	access to new islands	↑ caribou	iron, zinc, protein
► ↑ snow	↓ access to vegetation for animals	↓ caribou	iron, zinc, protein
► variable floe edge proximity	shift in proximity of animal populations	↑↓ seal	iron, protein, ω-3 fatty acids
		↑↓ walrus	vitamin A, ω-3 fatty acids
		↑↓ polar bear	vitamin A

traditional food (TF). Focus groups determined the self-reported community harvest numbers for key species of TF in the 12 months prior to the meeting. The average available food intake per person per day was calculated for each species using the edible weight of each species, self-reported harvest data, and number of known TF consumers in the community. Top TF species, in descending order of percent of the total harvest, include moose, barren-ground caribou, whitefish, snow goose, woodland caribou and sucker fish. Land animals made up 63% of the total harvest, followed by fish (23%) and birds (14%). Of all the TF surveyed, moose and whitefish had the best agreement between self-reported food use and semi-quantitative harvest data since both are key TF species and were easily counted due to size and preparation method, as recall accuracy was more likely. Results of this study showed that reasonable estimates of harvest data, but not nutritional assessment, can be obtained using semi-quantitative methods such as focus groups. The same approach was also used to compare self-reported food use data and harvest data collected in Nunavut. Generally good agreement was observed.

Members from both communities are witnessing variable changes in climate that are affecting their TF harvest (Guyot et al. 2006). New species and changes in migration of species being observed by community members have the potential to affect the consumption of TF. Similarly, changes in water levels in and around harvesting areas are affecting access to harvest areas, which in turn affects the TF harvest.

To study the impact of climate change on the Inuit TF systems, two two-day focus groups were conducted with knowledgeable community members in Repulse Bay and Kugaaruk, Nunavut, in 2005 (Nancarrow 2007). Participants from both communities found that climate change was affecting the TF harvest in both positive and negative ways. Key nutrients that could be affected are protein, iron, zinc, ω-3 fatty acids, selenium and vitamins D and A (Table 1).

Dietary data previously collected during 1997-1999 in five Inuit regions of northern Canada by the Centre for Indigenous Peoples' Nutrition and Environment (CINE; Kuhnlein et al. 2000) were used to calculate the relative importance of each TF to nutrient intake in the Inuit diet (Li 2006). Caribou and ringed seal accounted for 45% and 8% respectively of the average daily energy intake from TF among Inuit. Different scenarios for decreasing TF harvest were assumed. It was found that a decrease of 10% or 50% of caribou will result in a decrease of over 5% or 25% in protein, zinc, and iron for most region, sex, and age groups. Similarly, a decrease of 10% or 50% of ringed seal will result in a decrease of over 1% or 10% in protein, ω-3 fatty acids, and minerals for people in the Baffin region.

A workshop was held in Nunavik with elders in Kangiqsualujjuaq in the fall of 2006 to document changes in environmental conditions observed in the area and their implications for food-related activities (*i.e.*, hunting, fishing and berry collecting). This work identified a series of changes related to weather patterns, winds, ice and snow conditions that have made hunting and travel on the land more difficult and therefore have impacted access to key food species (Table 2). Changes in animal conditions and behaviour are also reported to have impacts on the quality of country foods available.

In-depth interviews with 21 hunters and local experts were held during the fall hunting season in 2006 to identify and document the perception of changes in key environmental variables that have an impact (positive or negative) on individuals' ability to locate, hunt and fish key food species in this community. These interviews were repeated in the community during the spring hunting season in 2007 to cover variability in seasonal knowledge.

Preliminary results from interviews with hunters, fishermen and other collectors in the community of Kangiqsualujjuaq identified a variety of environmental changes that impact the availability and quality of TF, as well as individuals' access to these resources. Key changes in environmental conditions mentioned that have an influence on the availability and accessibility of TF resources included the later freeze-up and the lack of snow, thereby restricting travel on the land to access hunting and fishing areas in the winter and spring. Thinner ice has also been reported to cause more risky traveling on the land. Indeed, the closer presence of polar bears around the shoreline appears to restrict camping for long-term hunting and fishing trips/excursions in this area.

Different periods for fishing and hunting were observed, including Arctic char migrating upstream in rivers earlier and snow geese tending to stay longer in the fall. Also, the availability of rock ptarmigan seemed to have decreased in the areas as well as the numbers of bird eggs to be collected. In addition, participants interviewed identified a number of changes in the quality of TF, including a different taste of the caribou meat, abnormalities in the Arctic char flesh and a thinner layer of fat on seals and the caribou. Some of these changes were attributed to warmer temperatures, the presence of contaminants in the environment and/or differing consumption behavior of these species. Although all participants reported impacts associated with the documented environmental changes, when asked about getting enough TF for their household needs, slightly more than half of the respondents reported being satisfied with the amount of food they could get. These preliminary results suggest that some harvesters are developing adaptation strategies which are effective to date in coping with the adverse effects of environmental change.

In association with the Qanuippitaa Health Survey in Nunavik, questions were also asked regarding individuals' challenges regarding the ability to find and hunt key TF species over the years 2003 to 2007 (Furgal and Rochette 2007). Half of the participants (51%) asked in the survey reported that some animals have become harder to find and hunt during the same season over this period. These reports were more common among men, hunters 50 years old and over, those with elementary school level education, those with an individual income under 20 000$ and among those that were more frequent hunters throughout the year. The majority of people who

Table 2. *Summary of most frequent observations of environmental change and their reported effect according to Kangiqsualujjuaq elders (those effects of relevance to traditional food security are presented in* ***bold italicized*** *font; elders of Kangiqsualujjuaq et al. 2008).*

ENVIRONMENTAL COMPONENT	CHANGE / OBSERVATION	OBSERVED / POTENTIAL EFFECT
Sky & Stars	Constellations of stars have changed location in the sky	Stars are no longer trusted for navigation purposes
Temperature	Rapid fluctuations in temperature; Warmer temperatures in winter and summer	Difficulty predicting temperature; Residents more susceptible to cold temperatures
Weather Patterns	Unpredictable weather changes; Shorter winters; Longer spring and summer; Significant weather pattern changes	***Travel has become more difficult due to inability to predict weather; Difficulty planning for spring travel because spring is longer now (thaws are unpredictable)***
Winds	Winds have become stronger and change direction more rapidly	***Stronger and gustier winds are making travel by land and sea more difficult***
Ice	Ice is thinner; Early melting of ice; Fewer ice floes; Freeze-up is later	***Thin ice makes travel more dangerous; Travel routes for hunting have been changed; Faster and unpredictable spring thaws make travel difficult***
Snow	Much less snow; Snow is softer; Early melting; Unpredictable snow arrival	***Hunting is limited and more challenging; Inability to store fresh meat in the snow; Seals must give birth directly on the ice***
Land	Melting permafrost; Ground is softer; The ground thaws faster	Some areas of land are avoided due to ground slumping; Ground sinking
Mammals	Changes in animal behaviour and movement patterns; More beavers and squirrels observed; Hooded seals are now common	***Change in quality and taste of meat; Changes in residents' diet; Fear of contamination***
Birds	Fewer eider ducks and other species; New species of birds; More robins and sparrows	Difficult to identify new birds; ***Uncertainty about hunting new species***
Fish	Fewer fish in rivers / landlocked lakes; Fish are thinner; Less fat in their flesh	Catch less healthy fish; Must help fish reproduce and migrate now

reported that some species were harder to find and catch specifically identified that caribou (60%) and beluga (53%) were more difficult to find and hunt today. Most (47%) attributed these difficulties with hunting caribou to changes in animal distributions, with animals currently being located further from the community than in past years. A smaller proportion (14%) attributed these difficulties to changes in the landscapes, sea or weather conditions. Key reasons mentioned for difficulties in locating beluga were related to a perceived reduction in numbers of animals today (22%) and change in their distributions (18%).

2.4.7 Discussion and Conclusions

It is a challenge to relate qualitative observations in climate and associated environmental changes as reported by the local communities to direct and indirect impacts on the health of these peoples. Use of different models to link the qualitative observations to quantitative harvest, food use and nutrient intake data was attempted. By comparing the nutrient intake levels to the benchmark levels for nutrient requirements, this work should allow us to set up goals for wildlife and country food harvest and develop plans for adaptation. The dietary studies conducted in the four communities in the Canadian North have allowed for the description of links between the quantity of each TF used and the relative importance of key nutrient intakes in both Dene and Inuit diets. Tools were also developed to link the harvest data to individual food use data. These tools allowed for relating changes in TF harvest due to environmental change in different regions or communities to food use and diet quality.

The qualitative research in all regions has allowed for detailed description of the relationship between key environmental factors (*i.e.*, warming temperatures and earlier ice break-up) and their influence on TF availability (*i.e.*, distribution and animal numbers), accessibility (*i.e.*, hunters' ability to reach the animals *via* travel over land or ice), and quality (*i.e.*, wildlife health, fat content, perception of food safety issues). Collectively, observations of change in environmental conditions and their influence on these three aspects of TF security, as well as the impact of these changes on nutrient intake were described.

This project has resulted in the development of maps that show the key nutrients of concern in different regions of the Canadian North and also which animal species are most important in determining intake. This tool aims to facilitate exchange of knowledge with the wildlife biologist to develop management plans with such organizations as the local Hunters and Trappers Organizations (HTOs) in northern communities, and to develop harvest plans for years to come.

2.4.8 Acknowledgements

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2.5 Surveillance and Management of Climate Change Impacts in the North: Implications for Northern Public Health Policy and Infrastructure (Project 4.5)

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2.5.1 Abstract

A strong and well-integrated public health system is critical to the health and well-being of a community. Challenges in maintaining these systems in remote areas are augmented not only by the difficult access to these locations, but also by limited resources and personnel. The potential impacts of climate change on the environment and on community health are only now being realised through recent impact studies, risk modeling and projections based on data that have been collected to develop these models. Clearly, these will only be as good as the quality of the data that they are based on.

This project has provided a review of existing public health monitoring and surveillance networks in four Inuit regions of Canada: Nunatsiavut, Nunavik, Nunavut and Inuvialuit, in order to determine their current state. The challenges and advantages identified in each of these regions will help public health officials to plan ahead and to build in adaptability in response to long- and short-term impacts of climate change on the health and well-being of residents. Via the conduct of this project, it was recognized that improvements in some aspects of community health surveillance are needed to ensure high quality data. This has already prompted a pilot study of a syndromic surveillance system, using Palm© handheld computers for patient visits and data collection by nurses in communities, nursing stations and health centers in Nunavik. The necessity for understanding the links between high impact weather events on community water sources and ultimately the potential risk to human health has resulted in a proposal to investigate these relationships in Nunatsiavut. Similarly, innovative actions and research will also be developed, based on the review of the surveillance systems in Nunavut and the Inuvialuit Settlement Region. Inherent in all of these studies is the interaction and collaboration with community members and health officials. With the goal of improved community health, this project focused on capacity building through exchange of knowledge, training and education related to the importance of understanding the links between climate, environment and health.

2.5.2 Key Messages

- Accurate, consistent and standardized data collection for the surveillance of infectious disease is a necessity for an excellent public health system.
- Challenges in the provision of an excellent public health surveillance system include the limited availability and high turnover of health practitioners and officials in the North, and the need for tools that will facilitate excellent data collection and analysis.
- Reliable baseline data on infectious illnesses is critical for determining any changes in the rates or types of illnesses reflected in patient visits over time. This type of baseline data is necessary for determining any changes in disease patterns that may be due to changes in climate over time.
- Innovations in surveillance, such as an electronic system of data capture and storage would enhance the quality of patient visit data and thus provide reliable data for better understanding the health concerns in northern communities.
- There is a need to test the enhancement of monitoring and surveillance by piloting a syndromic surveillance system that uses an automated system of data collection to replace the current paper-based system. This innovation could provide local health practitioners with a useful tool that would enhance the quality of patient visit data collection and reduce time needed for administration.
- The impacts of climate change on the environment will likely cause further stresses on an already over-taxed public health system. Information on the current state of public health surveillance in the four Inuit regions is required to identify both key gaps and challenges that might be addressed, as well as to highlight positive aspects of these systems that will allow for necessary flexibility and adaptability in the future.
- Exploring possible relationships between local water turbidity, weather measurements and patient visits for gastroenteritis may provide a way to enhance knowledge exchange with the community about climate change impacts, and also to enhance public health surveillance, particularly in light of increasing extreme weather events.

2.5.3 Objectives

- To enable the prospective evaluation and management of health impacts associated with major ecological shifts, including the eventual opening of the Northwest Passage and other waterways;
- To work collaboratively with northern managers, organizations and individuals to build capacity to support surveillance and management of climate change health impacts in the North;
- To build capacity, and inform and mobilize the necessary human and other resources to move towards the development of surveillance systems and programs, through education and training, partnerships and information sharing, pilot projects, fund mobilization, and other mechanisms;
- To develop case studies describing the current state of health and environment surveillance with respect to climate impacts and their links to public health action for each of the Inuit regions: Nunatsiavut, Nunavik, Nunavut, and Inuvialuit;
- To design and implement a syndromic surveillance-based pilot project that will result in improved Community Health and Environmental Surveillance (CHES) programs for each northern region – and eventually across all regions;
- To relate findings from ArcticNet Phase 1 and from a drinking water surveillance study in Nunatsiavut (see Theme 2 Projects in the ArcticNet Compendium Vol. 1) to the development

of a pilot study for examining the relationship between water turbidity, weather (precipitation, weather, and wind) and community cases of gastroenteritis, as a way to obtain baseline information and enhance knowledge exchange with communities about environmental impacts of climate change.

2.5.4 Introduction

A potential impact of the global warming of the Earth is the intensification of the hydrological cycle (Miller and Russell 1992, Knox 1993, Tsonis 1996). As a result, extreme weather events will increase due to high levels of precipitation, evapotranspiration and runoff, with the subsequent stresses and changes imposed on our physical environment (Houghton et al. 1996). It has been suggested that these changes may increase the risk and incidence of infectious disease (Shope 1991, McMichael et al. 1996, Colwell et al. 1998). New pathogens may also emerge. In Canada, waterborne illness is thought to account for a large proportion of enteric illness (reviewed by Charron et al. 2004). In 2001, there were 4200 reported Canadian cases of giardiasis and 1600 cases of cryptosporidiosis (Health Canada 2002 as cited by Charron et al. 2004). However, the actual incidence is likely much higher due to under-reporting (Frost et al. 1996, Majowicz et al. 2001, 2005). Given predictions of severe climate change in the Canadian North, the value and sensitivity of improved disease surveillance in Inuit communities is increasingly apparent. With emerging observations of climate changes in the North, health indicators and infectious disease occurrence in Arctic communities may experience alterations in incidence and distribution over time and space.

The role of changes in climate over time is of particular concern in the North due to the close relationship (social, cultural and physical) between Inuit and their environment, such as their dependence on traditional foods from hunting and fishing. How extreme weather events and changes in the duration of seasons might impact water quality is also of major concern in these areas, where historically safe sources of potable water are potentially at risk. For instance, the link between human health and water quality indices, such as turbidity and total coliforms, has been shown to be of concern (Atherholt et al. 1998, Willocks et al. 1998, Aramini 2000, Curriero et al. 2001, Miettinen et al. 2001, Patz et al. 2001, Rose et al. 2001, Auld et al. 2004, Schuster et al. 2005, Thomas et al. 2006) and was explored here using a number of different approaches.

This project area also focused on preparedness for potential impacts of climate change by recognizing the necessity of obtaining a clear understanding of current community health status (baselines), projecting forward to potential impacts on this status due to environmental changes brought about by warming trends, and by investigating novel methods that might enhance capacity and adaptability to these challenges.

Case studies assessing the capacity of public health surveillance and environmental monitoring among the Canadian Inuit regions of Nunatsiavut, Nunavik, Nunavut and Inuvialuit have been completed. The motivation behind these case studies and associated public health research stems from the recognized limited capacity for disease and other forms of surveillance in Inuit health systems, which are likely to be impacted by changes in environmental conditions. The Nunavik Public Health authority (Santé Publique Nunavik) has identified surveillance of gastrointestinal illness as a priority research theme for the region. Inuit communities in Nunavik currently experience poorer levels of health than other regions of Quebec and Canada, with a significantly younger population profile, lower average income, lower life expectancy, and higher poverty rates (Owens et al. 2006). Nunavik health officials, usually nurse practitioners in communities, currently collect patient visit data, including basic diagnosis and treatment. Only one community enters patient data information directly into an electronic format. All the other communities use paper forms initially, followed by a transfer of these data into an information management system. The system is called Intégration-CLSC1 and has been in use all over the province for several years while Nunavik just started using it in 2007. The time between the patient visit and the transfer of these data to the computer varies. Resource limitations, however, have constrained both detailed analysis of these data and reiterative communication of data trends to health practitioners in Nunavik. Diagnostic details of currently collected data, although unclear, are expected to be limited. These data, however, represent a potential source of useful public health information for Nunavik communities, as well as an opportunity to expand surveillance activities by building on the existing data collection system. The Nunavik Public Health department has indicated that more detailed collection of infectious gastroenteritis surveillance data by health practitioners in Inuit communities would be a sensible and priority research focus for the region.

The integration of these various aspects of public health-related concerns, with a focus on infectious gastroenteritis in Inuit communities, was ultimately intended to improve both community health and understanding of environmental risks associated with maintaining a safe water supply, and also to potentially impact policies for public health and adaptation to a changing climate.

2.5.5 Activities

Case Studies in Four Inuit Regions

Meetings and workshops were held in 2006-2007 with Nunavik, Nunavut, Inuvialuit and Nunatsiavut representatives on several occasions (in Québec City, Montréal, Ottawa, Goose Bay, Kuujjuaq, by conference call). These discussions were held to review and finalize the case studies of surveillance and monitoring capacity conducted in each region and to implement the pilot projects for syndromic surveillance of infectious gastroenteritis (Nunavik) and drinking water surveillance (Nunatsiavut), which were developed from these initial reviews.

Following these discussions, and based on the results of the regional assessments, regional authorities and research team members in Nunavik and Nunatsiavut identified activities through which to enhance regional health surveillance and monitoring associated primarily with potential health endpoints that are expected to be impacted by regional climate change and variability. Additionally, in these discussions, the teams and regional authorities could identify further issue-specific investigations required to support directed surveillance and monitoring activities around key issues, as was the case in Nunatsiavut with their concerns related to climate change and waterborne diseases. The two specific follow-up activities to regional report reviews already underway in Nunavik and Nunatsiavut are described below.

Enhancing Public Health Surveillance with Palm Handheld Technology in Nunavik

In Nunavik, a syndromic surveillance project is currently in its test period. Nurses in Ungava Bay health stations (CLSC and Health Board) have been provided with Palm© handheld (“Palm”) computers programmed with the Quebec Health I-CLSC patient visit forms and codes. The project will evaluate the use of Palms as compared to the current paper-based system for visit records by assessing the impact on time spent on paperwork and manual data entry, data quality and access to medical information provided in the Palms. Gastrointestinal illnesses were chosen as the priority area for focused reviews of the patient visit data. Retrospective and prospective data analysis of the trends in patient visit codes for gastroenteritis will be considered with regards to age groupings, gender, community and season. A comparison of the data quantity and quality pre- and post-implementation of the Palm technology will be made. At the end of the test period of one year, an evaluation of the usefulness of the Palm system compared to the current paper-based surveillance system will be made. This will be done using a qualitative analysis based on interviews with health officials, computing support, and other health community stakeholders.

Water Quality, Weather and Infectious Gastroenteritis

A pilot project in Nunatsiavut communities has been proposed to investigate the relationship between source water turbidity (prior to treatment), weather measurements (precipitation, temperature and wind) and local cases of infectious gastroenteritis. This project will potentially provide a simple way to increase awareness of how extreme weather events might impact the risk of contamination of the raw water supply. Engaging the community with this type of research will provide a means of enhancing capacity through education on the topic of weather and its relationship with water quality, and the importance of water treatment to ensure a safe drinking supply.

2.5.6 Results

Case Studies in Four Inuit Regions

The final report for the Nunavik case study was presented to stakeholders and published for dissemination in 2006. Descriptions of core activities undertaken in Nunavik for each possible type of health impact associated with climate change were tabulated (Table 1; Owens et al. 2006). For each health impact, information on methods of detection, how the information was registered, how it was confirmed, where it was reported, how it was analysed and any feedback mechanisms were recorded. Observations and recommendations for Nunavik covered a number of topics related to environmental phenomena, classic categories of health outcomes and determinants of health (Owens et al. 2006).

Enhancing Public Health Surveillance with Palm Handheld Technology in Nunavik

In response to Phase I findings that recommended an enhanced method of surveillance of community disease trends that is not heavily reliant on paper-based methodology, an electronic and partially automated method of patient visit surveillance was created. The introduction of Palm technology to enhance health monitoring involved collaborating with a team from the Geomatics Department at Université Laval to program Palm handheld computers with the patient visit forms for use by nurses in the health centres of Nunavik's Ungava Bay area. Interaction and feedback from nurses and other health officials was requested for creating the current prototype. After some iteration between the Geomatics team and the users (nurses and CLSC staff) to enhance the technology, a training session for all users in the Ungava Bay communities took place and the test period of one year started (November 2007 to November 2008). Training on these programmed Palm handhelds has been initiated and met with positive interest by the current pre-test group of nurses.

Table 1. *Classic categories of health outcomes and determinants of health (Owens et al. 2006) for a number of topics related to environmental phenomena in Nunavik.*

CATEGORIES
General
Extreme Weather Events
Property Loss Influencing Income and Social Status
Food Security
Infectious Disease and Drinking Water
Infectious Disease, (Other) including seroprevalence monitoring
Stress-Related Health Impacts (including mental health disorders, suicide, etc.)
Travel Related Accidents
Animal Health
Biomonitoring of Chemical Contamination
Permafrost Melting
Indoor/outdoor Air Quality
Chronic Diseases and Cancer
Allergies
Eye Damage

2.5.7 Discussion and Conclusions

Results of the Nunavik case study identified a number of strengths and unique characteristics of current public health surveillance and environmental monitoring activities and the context within which these operate in Nunavik (Owens et al. 2006). Integration of the health impacts and risks due to changes in the environment is still an area that requires further attention. Resources, such as the Nunavik Research Centre, were highlighted as valuable in providing and supporting the implementation of health and environment monitoring and surveillance programs.

The public health system of Nunavik operates as part of the government of Québec, thus it benefits from the clarity of roles, responsibilities and programs that are determined by that province. This contrasts with the more complex situation found in the three other Inuit regions where different levels of government are involved in the public health system and thus the networks for environmental health monitoring and surveillance. The Nunavik system also has a more extensive and organized network of researchers in Québec working on these topics than in the other regions. However, Nunavik was found to have less access to Federal programs focused on environmental monitoring initiatives, such as those for sea-level and permafrost melting. Based on the information that was available at the time of data collection, a comparison of the four regions using basic health status indicators revealed that Nunavik's population might in fact be more disadvantaged than any other Inuit population in Canada.

When the final case study findings for Nunatsiavut, Nunavut and Inuvialuit are available, more detailed and comprehensive comparisons of challenges and advantages in these different public health systems will be possible. It is well recognized that a surveillance system can only be as good as the data that it relies upon. The evaluation of the innovative syndromic Palm-based surveillance system established in Nunavik will be of great interest, particularly to health officials dealing with the challenges of providing an excellent service to remote communities.

The findings presented here support the continued research within Project 4.5, by focusing on strengthening the current surveillance systems, helping to establish solid baseline information (health and environment), historic demographic health information, enhancing monitoring and surveillance capacity through training and education within the organizations and communities, and furthering an understanding of risk management and environmental monitoring related to potential climate and environmental variability impacts on water quality and human health. Given the close relationship between Inuit and their environment, it will be important for researchers to continue to work collaboratively with community members to develop proactive adaptive capacity in order to address the changes that will likely occur in the North as a result of increased climate variability and warming. Results from various facets of current research on how quickly or how pervasively the warming of the climate will affect the environment are still emerging. This most recent and high quality data will feed into the predictive models that will allow for the development and understanding of different regional scenarios and risk aspects, which ultimately will help communities to be more flexible and resilient in response to challenges impacting their health and their environment.

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2.6 Science-Policy Interactions (Project 4.7)

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2.6.1 Abstract

An overarching scientific objective of ArcticNet is to translate the growing understanding of a changing Arctic into impact assessments that will help Northerners and politicians to develop adaptation strategies and national policies. Theme 4 of ArcticNet was specifically aimed at "Adapting to Change in the Canadian Arctic: Knowledge Transfer, Policies and Strategies". An open dialogue must thus exist whereby: (1) relevant knowledge is brought to the attention of policy- and decision-makers; and (2) concerns and priorities of governments and organizations are brought to the awareness of ArcticNet researchers. An understanding of the institutions and processes of science-policy interaction at the federal and provincial-territorial level is integral to establishing a two-way transfer of information between scientists and decision-makers, based on the needs of those living in Canada's northern communities.

2.6.2 Key Messages

- There must be a process by which relevant information is brought to the attention of policy- and decision-makers;
- Mechanisms for governments and organizations must be put in place to communicate concerns, priorities and information needs to ArcticNet researchers.
- An open dialogue and two-way transfer of information, beyond providing accessible research results to stakeholders, is integral to the process of knowledge transfer and its use by policy- and decision-makers.
- Effective adaptation strategies in Canada's northern communities are developed through partnerships with Inuit, scientists and decision-makers. Integrated Regional Impact Studies (IRIS) provide one mechanism by which the link between communities, scientists and government representatives may be established, to ensure effective transfer of traditional and scientific knowledge to policy that will benefit those living in northern communities.

2.6.3 Objectives

The main objectives pursued by this project were:

- To critically assess the processes and engage institutions in the interactions between the scientific community and the policy- and decision-making communities in Canada, with focus on those relevant to the North;
- To identify the priorities of government and Inuit organizations and the information needed to assist in the development of policies, strategies and approaches;
- To develop strong working partnerships with ArcticNet researchers, partners and key decision-makers representing Nunavut Tunngavik Inc (NTI), Inuit Tapiriit Kanatami (ITK), Inuit Circumpolar Council – Canada (ICC), Government of Nunavut and the federal government to create an open dialogue that allows for and encourages two-way knowledge transfer;
- To facilitate collaboration between researchers, community members and decision-makers through workshops that include participants from national and international organizations, conferences and consultations with northern community members and representatives in appropriate provincial and territorial capitals and the national capital, with the aim of improving the communication of research results and developing a co-operative, inclusive problem-solving process;
- Continue to take a leadership role in defining policy needs of governmental and non-governmental organizations that may inform IRIS methodology and ArcticNet integrative assessment.

2.6.4 Introduction

As a research network of partnerships, ArcticNet is dedicated to the integration of the natural, social and health sciences, in consultation with those living in northern coastal communities, for the purpose of identifying northern adaptation strategies in response to climate change. The integration of science and policy is essential to the effective development and implementation of a climate change adaptation strategy for Canada's northern communities. Understanding the process of knowledge transfer and its use by policy- and decision-makers will facilitate collaboration with ArcticNet scientists and partners, governments and organizations and will assist with implementing means to improve the knowledge transfer process in ways that result in positive actions being taken.

The impact of climate change on coastal communities is nowhere more apparent than in the Arctic. A rapid decline in sea ice extent and thickness, changes in precipitation patterns and extreme weather events attest to increasing vulnerability in one of the most threatened regions of our planet. Effective adaptation strategies that meet the challenges of climate change and the needs of northern communities are essential to the protection and preservation of Canada's North and its people. One goal of Project 4.7 was to identify and define a knowledge transfer process that includes a two-way exchange of concerns, priorities and information between scientists and policy-makers, in order to facilitate the development of such strategies.

One instrument that may be used to improve the knowledge transfer process is the IRIS. ArcticNet IRISes are defined according to the political organization of the Arctic, as well as geography, physiography and the oceanography of these regions, and include the western High Arctic (Inuvialuit government), the eastern High Arctic (Nunavut government), the Hudson Bay and eastern Subarctic (Nunavik and Nunatsiavut). A regional counterpart to the Arctic Climate Impact Assessment (ACIA), known as the regional impact assessment (RIA), is one outcome that outlines assessments and policy objectives based on the two-way exchange between researchers and decision-makers. IRISes also have the potential to act as a formal process for stakeholder input through working and/or focus groups.

Central also to Project 4.7 were efforts to identify best practices in the communication of scientific information to communities and decision-makers. Recent consultations regarding existing models for adaptive management strategies highlighted the benefits of what is referred to as a participatory integrated assessment (PIA) model. Within the PIA model, communication is facilitated by a combination of scientific studies and dialogue. Essential also in effective communication strategies are "extension agents" or liaison officers who work with community members to set up training and infrastructure. In formalizing the knowledge transfer process, Project 4.7 aimed to ensure the establishment of effective adaptation strategies and regional action plans in Canada's Arctic coastal communities that meet the challenges incurred by climate change.

2.6.5 Activities

A number of ArcticNet activities were carried out between 2004 and 2008. The project team has engaged in several field trips to Iqaluit, held workshops and focus groups in Ottawa, in addition to informal interviews and consultations with individuals, groups and associations. Papers have been presented at conferences and several journal articles published or submitted.

An assessment of the priorities and concerns of government agencies and Inuit organizations was initiated in 2004, through a review of available literature and informal meetings with representatives of these groups. A significant portion of time and research has since focused on the planning and execution of field research, and in promoting communication between communities and ArcticNet researchers through interviews, organized focus groups, workshops and conferences. Activities have been conducted largely in Ottawa and Iqaluit. However, participation in national and international forums has provided consultation and partnering opportunities that have encouraged the collaboration and exchange essential to ensuring effective science-policy interactions within an international framework dedicated to adaptation strategies in the Arctic.

The initial project team was expanded in 2005 to include representatives from the health and natural sciences in ArcticNet, as well as the expertise of policy- and decision-makers from government, non-government and Inuit organizations. The expansion further broadened the capacity, scope and potential impact of the research undertaken, while ensuring the direct communication of relevant information between researchers and decision-makers.

In September 2005, a workshop held in Ottawa brought together climate scientists, political scientists and users of scientific information, to examine the information transfer process and facilitate dialogue between scientists, and decision- and policy-makers.

In November of 2005, this project was co-host to the science-policy symposium “From Research to Action” which examined the climate change science-public policy interface. The symposium brought 70 participants together to discuss the institutions and processes involved in science-policy interaction, with an emphasis on Arctic issues. Interest in the project was demonstrated by the five partners that joined and provided financial support, including Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), Department of Fisheries and Oceans (DFO), Natural Resources Canada (NRCan), Institute for Catastrophic Loss Reduction (ICLR) and Natural Sciences and Engineering Research Council (NSERC). Many of those participating noted such a meeting was the first of its kind, and found it beneficial. A report was prepared and made available in the spring of 2007 (CFCAS 2007).

The symposium was followed by a significant focus group meeting in Ottawa in early 2006, with participation from 25 leaders in science-policy interactions from the Government of Canada and Government of Nunavut, academic institutions and Inuit agencies, including ICC and ITK. Participation by seven Assistant Deputy Ministers (ADMs) from federal government departments demonstrated the level of interest and support from senior representatives in the innovative research approach. The discussion centered on institutions important to science-policy interactions, means by which policy-makers and scientists can work to improve the two-way flow of information, and criteria that constitute good science-policy interactions.

A series of focused interviews followed in March 2006, when team members traveled to Iqaluit to meet with northern policy- and decision-makers from government and non-governmental organizations and agencies. Interview selection was based on prior consultations and recommendations from senior representatives of the federal and Nunavut governments, and representatives of agencies such as ITK and ICC. Interviews focused on the science-policy information flow in institutions, and served to strengthen existing relationships, build new partnerships and provide follow-up contacts for further research and discussion. The consultation process enabled the project to identify and document science and policy needs and expectations.

Consultations were followed by questionnaires on information transfer in the context of climate change in April 2006. Both the initial science-policy interview questions and follow-up questionnaire were forwarded to the project team, to provide a common format for further interviews by team members. The interviews resulted in and informed further research initiatives, as well as provided data/material for publication.

In June of 2006, a project collaborator facilitated the "Nunavut Federal Council Learning Event" workshop in Iqaluit. Several team members, including the project leader, participated in the workshop, which provided an opportunity for forging contacts and informal discussion of science-policy issues with inter-governmental representatives from the GN and federal government. Additional connections were made with policy specialists in academic institutions. The work of ArcticNet and this project in particular was highlighted in the presentation of 'The Research-Policy Interface' at this workshop.

A further objective of the June 2006 Iqaluit field trip was to undertake a second round (following the April 2006 consultations) of interviews with policy- and decision-makers representing government and non-governmental organizations in focusing on northern policy and science information flows. The follow-up meetings engaged policy specialists from GN, ITK, NTI and science advisors from Nunavut Research Institute (NRI). The interview process served to strengthen existing partnerships while forging new networks within the government of Nunavut and across agencies and organizations.

In March of 2007, this project took a leadership role in defining policy needs of government and non-governmental organizations in order to ensure that ArcticNet outputs and outcomes address the main science-policy questions of the day. An Integrated Arctic Science workshop was held in Ottawa to help define methodology, outputs and outcomes for an ArcticNet integrated assessment. As the research approach was innovative, interest was generated from an array of government departments because of its perceived importance. A number of ADMs from federal departments were present and contributed to the policy discussion of institutional policy needs within the context of ArcticNet research. The Integrative Arctic Science workshop sought to determine a process for identifying policy needs of stakeholders, including representatives from Inuit organizations and agencies, the Governments of Canada, Nunavut, Yukon and Northwest Territories and ArcticNet scientists within the ArcticNet research framework, in the context of IRIS. PIA were identified as a useful tool in ensuring a process whereby community needs, combined with scientific monitoring and prediction, identify priorities essential to the development of an action plan and effective adaptation strategy for Canada's northern communities. This project has an integral role to play in the implementation of such a program. Stakeholder input reinforced the need for ongoing and sustained communication among community representatives, scientists, policy-makers and industry to develop an assessment responsive to the needs of northern communities in addressing the impacts of climate change and modernization on northern coastal communities.

Formal and informal presentations throughout the four year term have provided avenues to underscore the importance of science-policy integration for ArcticNet and encourage forward momentum on this central objective. In particular, the project leader has been an invited speaker at sessions to discuss science-policy issues with the former Prime Minister, Premier of Manitoba, federal Deputy and ADM of Environment, DFO, NRCan, INAC, and Health Canada and the Director of the Nunavut Federal Council and officials from the Government of Nunavut.

Participation by the project leader and network investigators in national and international committees included the ACIA, the Canadian Northern Science and Technology Advisory Committee, Canadian Committee and Science Review Subcommittee for the International Polar Year (IPY), International Development Research Centre of Canada (IDRC), Intergovernmental Panel on Climate Change (IPCC) Plenary Meetings, the International Institute for Sustainable Development (IISD), National Roundtable on the Environment and the Economy (NRTEE) and the Scientific Advisory Committee for the International Arctic Research Committee (IARC).

2.6.6 Results

This project has been a conduit for ArcticNet in providing a network to policy- and decision-makers for the exchange of science-policy information. As much of the information is informally held, work has focused on building research approaches through literature reviews, methodology, background documents, interview questions and questionnaires. The project continued to explore the information transfer and policy development process, and identified the priorities and information needs of these groups as relevant to northern climate change issues.

A study of the northern governance structure, the process of information transfer between governments and Inuit organizations, and strategies and policies for addressing climate change in the Canadian Arctic, was initially undertaken in 2004. The role of government departments and Inuit organizations involved in developing policies and strategies for adapting to climate and other changes in Nunavut is discussed in Budreau (2005) and McBean (2004). The governance structure in Nunavut was mapped, as well as collaborative agreements and policy links among the various governments (local and regional northern bodies, and national bodies) that inform climate change strategies were noted in Budreau and McBean (2006). This knowledge provides the much needed basis for understanding and potentially improving the information transfer process.

Investigations have been undertaken of the legislative and policy responses to environmental change on the part of certain national and international climate change bodies in an effort to determine avenues available for Inuit organizations and governments dealing with rapid environmental change in the Canadian Arctic. The Government of Canada, the Arctic Council, and the Canadian Polar Commission have been examined to determine information priorities and processes of these groups (Budreau 2005; Schmidt 2007; Stone and Kushwaha, unpublished).

The Arctic Council, created to subsume the duties of the Arctic Environmental Protection Strategy (AEPS), which focused on the elimination of specific pollutants, was conceptualized to take on the broader mandate of promoting co-operation and sustainable development. Schmidt (2007) examined the Arctic Council's achievements against its mandate and the role scientific knowledge has played in the formulation of international policies designed to protect the Arctic environment.

The role and relevance of the Canadian Polar Commission (CPC), established in 1991, to promote Canadian research in the Arctic and Antarctic, has been evaluated against its expectations with the hope that the focus of attention might lead to the CPC securing sufficient resources to allow it to exercise its full potential. More work is necessary to complete the objective of the project.

As a result of this study, it became clear that the way research is being conducted in the Arctic today is changing. There is a greater awareness of the value of involving Northerners and incorporating traditional knowledge: the days when southern researchers ventured North with their graduate students, collected data and returned to publish their results in a learned paper are coming to an end. This more participatory approach is particularly useful in research on adaptation to climate change, and highlights the importance of the aforementioned participatory integrated assessment in the knowledge transfer process. A series of interviews were completed to examine these changes.

A critical look at the role of Traditional Ecological Knowledge (TEK) in the structures and policies of the Government of Nunavut and Government of Canada and its relative influence on perceptions of climate change in both the scientific community and for policy-makers has been undertaken (Cromar 2006). Further dissemination of information and collaboration ensued on this topic in the articulation by Cromar (2006) of the relationship between science and TK in the Canadian policy cycle.

This project and the project "Vulnerabilities and Adaptation to Meteorological and Related Hazards" (Project 4.3) shared information on the collaboration of scientific and Inuit traditional knowledge for the purpose of understanding weather and hazardous events and anticipating adaptation strategies. The project also examined how such partnerships can lead to better and more representative policy decisions by various levels of governance. This research was looking at a real and immediate response to both Inuit and western scientific understanding of changes.

Examination of the national science strategy (Brock 2005) continued through research as related to the National Science and Technology Strategy and its implications for northern sovereignty. In particular, the implications of Canada's Science and Technology Strategy for Aboriginal Canadians living in the Arctic were investigated (Lukovich and McBean 2009). This study explored the role of science and technology in establishing an Arctic strategy that recognizes and respects the needs of those living in Canada's northern communities.

The fourth International Polar Year began in 2007. This project played an integral role within this international framework to ensure that science-policy interactions establish effective and innovative adaptation strategies that will include and meet the needs of those living in the Arctic. This project also assumed a leadership role in establishing a framework and identifying a knowledge transfer process that translates into action for the benefit of those living in the North. IPY legacy issues were examined within this context.

As science-policy interactions occur at all levels of organizations, the networking and learning opportunities at meetings provide a new and deeper awareness for participants in understanding the processes and important institutional actors (or those that are ineffectual) in this field. As much of the team was affiliated with a broad array of committees and international conferences, links to ArcticNet in oral presentations and informal meetings have conferred higher recognition and knowledge about ArcticNet research. Team members assumed an advocacy role in science-policy initiatives, focusing on Arctic Science. Participation in discussion forums has spawned collaborative research between organizations. For example, this project and the National Round Table on Environment and Economy (NRTEE) spearheaded an investigation of policy implications of Arctic climate science.

The various science-policy workshops held by this project over the four-year term have provided a forum for stakeholders to meet and to state their policy and science needs. There is now significant participation by federal and territorial governments and Inuit organizations. Increased levels of participation and response provided a strong indication of the interest and value that the agencies and organizations placed on this project. As a consequence, opportunities have developed to strengthen dialogue with ArcticNet communities and established iterative consultation processes between scientists and policy-makers, beyond formal ArcticNet management structures, in order to identify needs and issues of importance to the implementation of an integrative assessment. These opportunities are outlined in the Integrative Arctic Science report (2007). Key issues, knowledge gaps and priorities related to adapting to climate and other changes identified by policy- and decision-makers, were articulated to ArcticNet scientists and written up in recommendations distributed to the ArcticNet Research Management Committee (RMC), to assist with implementing means to improve the knowledge transfer process in ways that result in positive actions being taken and integrated into the project. Recurring themes, such as the importance of community engagement in scientific endeavors, the need for measurable targets (both scientific indicators and policy targets) and data management, as well as the importance of monitoring and the establishment of an ArcticNet legacy through IRISes, in addition to the importance of international models and partnerships, were highlighted.

Additional recommendations outlined in this report point out priorities noted but not addressed in previous ArcticNet project workshops.

In examining the relationship between science and policy in developing integrative assessments, it was determined that integration should be driven by overarching policy questions that address issues related to land use, sustainability and economic development. Scientific indicators and policy targets assist in defining action plans for adaptation and modernization based on scientific evidence of changing parameters that directly affect the livelihoods of those in northern communities. Also emphasized was the understanding that, in order to link science and policy, climate change and modernization must be linked to development.

Determinants of best practices are based largely upon whether policy targets drive the science, and stakeholders are invited to participate, through a co-design and shared learning approach, in the assessment process. The development of formalized processes and systems for information exchange among stakeholders is seen as essential to securing a comprehensive and sustained action plan for Canada's Arctic, with scientific evidence and traditional knowledge as motivators for change.

The various workshops and focus groups sponsored by this project sought to determine science-policy objectives, such as a process for identifying policy needs of stakeholders, including representatives from Inuit organizations and agencies, the Governments of Canada, Nunavut, Yukon, Northwest Territories and ArcticNet scientists. Particular to ArcticNet, stakeholder input has reinforced the need for sustained communication among community representatives, scientists, policy-makers and industry to develop an assessment responsive to the needs of northern coastal communities in addressing the impacts of climate change and modernization.

2.6.7 Discussion and Conclusions

This ArcticNet project has made major contributions to the establishment of partnerships essential to science-policy interactions and effective decision-making. This is reflected in numerous workshops that explored existing mechanisms to enable a two-way exchange between scientists and decision-makers, and models to formalize the knowledge transfer process between ArcticNet researchers and policy-makers. Recurring themes from all workshops, including the importance of community consultations in scientific endeavors, measurable targets, monitoring programs and participation in international partnerships, are outlined in the 2007 IAS report, with priorities and recommendations for future action to ensure the development of adaptation strategies that meet the needs of those living in Arctic coastal communities. PIAs were also presented as a tool to formalize the knowledge transfer process.

Manuscripts on science-policy interactions by the project team members have also underscored the importance of such issues as intergovernmental relations, sovereignty, international models and Canada's science and technology strategy in the context of climate change for those living in Canada's northern communities, through an emphasis on the importance of the communication and partnerships between scientific researchers and decision-makers. This information improves our understanding of science-policy issues at various levels of government and non-governmental agencies, and illuminates the needs and concerns between the sectors.

This project helped ArcticNet to implement a framework for science-policy interactions using such concepts as extension agents, and instruments such as participatory integrated assessments and by developing a program that can be used in each of the four IRISes. In formalizing the knowledge transfer process, ArcticNet has the potential to develop an action plan that meets the challenges incurred by climate change and the needs of those living in Canada's northern coastal communities.

2.6.8 Acknowledgements

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2.7 Strengthening Climate Cooperation, Compliance and Coherence (Project 4.8)

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2.7.1 Abstract

An overall ArcticNet objective is to consolidate international collaborations in the study of the Canadian Arctic, and provide relevant information to decision-makers for the integration of the ever-increasing understanding of the Arctic into national policies and adaptation strategies. In order to meet this objective, this project focused on legal and policy analysis of the impacts of climate change in the Canadian Arctic. Furthermore, the project sought to focus on producing documents on the research of adaptation strategies. Through collaborations that span the globe, the implications of a changing climate on governance and interactions with Inuit land-claim organizations, environmental protection and human rights, and international sovereignty and diplomacy were studied. The project aimed to develop and disseminate legal and policy knowledge to multiple stakeholders. It has also worked steadily to forge new partnerships and build capacity between national and international legal researchers, northern researchers, organizations and communities, especially indigenous peoples and scientific communities, working on law and policy issues related to climate change and the Arctic.

2.7.2 Key Messages

- There are important intersections between global and domestic climate regimes, and other international regimes (such as environmental protection, human rights and international economic investment law), as these relate to indigenous peoples' concerns in the Arctic.
- Adaptation strategies, policies and solutions as an approach to dealing with climate change in the Arctic are perhaps a more realistic avenue to explore than mitigation of climate change. Adaptation policies that are put in place may also pose serious legal questions that can only be addressed with international, national and local governments and organizations working at the same table.
- The justice claim that Arctic climate change is a human rights violation for the Inuit is novel. The rights-based approach to climate change might serve to redefine the climate change debate in human terms – as a moral, social and cultural issue.
- National inter-governmental discussions and debates on the changing climate of the Arctic take place under the auspices of land claim or other legal agreements. These agreements have simultaneously placed restrictions and offered opportunities for cooperation between the federal government and Inuit groups and governments on the issue of climate change.
- The Inuit and the federal government perceive land claims and Inuit rights issues very differently. This could have legal implications in making climate change adaptation policies.
- The legal implications of northern climate change go beyond environmental changes. Economic considerations also exist, and because climate change is affecting the security of northern communities, changes might be needed in laws relating to accident and property insurance, to ensure that increased risks and burdens do not fall disproportionately upon the most vulnerable.

2.7.3 Objectives

The main objectives of this project were:

- To apply a perspective of legal pluralism, keeping a broad social and cultural lens in examining how communities and institutions govern their adaptation to climate change impacts in Canada's North;
- To interrogate the overall contribution of law and policy to this process of cultural change and, specifically, to the process of adaptation to climate change in the North;
- To study the adaptation strategies; for example, to examine how the laws and policies are gov-

erning northern efforts in response to events related to climate change (*e.g.*, floods, sea ice change, changes in wildlife, etc.);

- To investigate what northern communities might stand to gain from the adjudication of a human rights claim made on their behalf in a global or national legal arena, as well as how local adaptation strategies might be shaped, or fuelled, by international developments with respect to climate change treaties;
- To define governance and investigate the role of law in climate change adaptation in the North using a pluralist and sociological approach.

2.7.4 Introduction

Global climate change is already bringing about dramatic and far-reaching changes in the Canadian Arctic. Beyond the direct physical impacts, there are also various indirect, secondary impacts, such as cultural, social and economic reverberations from climate change affecting Aboriginal ways of life. Climate change ("hilaupuunnakpallianinga") has triggered a period of great instability and uncertainty in the North. Several ArcticNet projects have set out to document the physical changes brought on by climate change, whereas other projects tackle the social, cultural and economic consequences. This project, comprised primarily of jurists/lawyers, sought to identify and explore the governance challenges arising from climate change impacts in the Canadian Arctic.

One of the aims of this project was to produce research papers focusing on adaptation strategies. As such, rather than focusing on efforts to reduce GHG emissions, researchers examined, for example, the laws and policies governing northern efforts to relocate homes on sliding permafrost or threatened by flooding caused by rising sea levels, the rules governing modifications made to hunting practices and routes to respond to sea ice changes, or changes in land claim agreements that adjust to shifting wildlife ranges and migration patterns. It is however recognized that the mitigation of climate change is also a key priority for northern peoples and cultures. In particular, consultations have indicated that lack of progress on global emission reductions raises concerns over the long-term cultural survival (even taking into account fluid, rather than static, conceptions of culture). The goal of this project was also to undertake research in a way that is sensitive to specific contexts and places, recognizing that in the North there are diverse and distinct cultures, and that this leads to diverse and different impacts from climate change, especially where geographic distances between communities are great.

The research in this project adopted a pluralist and sociological approach to its definition of governance and to the investigation of the role of law in climate change adaptation in the North. "Governance" is intended to encompass forms of rule and authority that emanate from sources other than formal state law. It comprises the traditions, institutions and processes that determine how power is exercised and how decisions are made. Sources of authority are multiple and overlapping: they may be informal and formal, unofficial and official, and they coexist in complex social systems. Behaviour is shaped and influenced, and power is exercised through fluid and changing relationships among multiple interacting authorities operating at all scales and in all domains of human affairs. Throughout this project, an interdisciplinary research approach was pursued and drew upon geography, political science, anthropology, sociology, and ecology, though the focus was on the analysis of laws and governance structures.

"Law", for the purpose of this project, emanates from the international legal order, the national legal regime and a constellation of local laws and customs. In order to uncover the contribution of "law" or legal norms to the process of adaptation to climate change in the North, the projects were grouped into themes that fall into one or the other ends of this spectrum. That is, projects had as their primary reference point either international legal norms or local adaptation strategies. Within these categories, five themes were identified as topics of study: 1) Human Rights Approaches to Climate Change in the North; 2) International Climate Change Instruments and the North; 3) Economic Issues and Approaches to Climate Change; 4) Inuit Governance Structures and Climate Change Adaptation; and 5) Adapting Land Claim Agreements to Climate Change in the North.

2.7.5 Activities

This project was integrated into the ArcticNet network in 2005. Since the project was established, team members have engaged in field trips to the Northwest Territories, Nunavut, and Nunavik; they have attended and held workshops around the globe, and carried out formal and informal interviews and consultations with individuals, groups and associations on northern climate change issues. Meetings attended are summarized in box 1, and key presentations and meetings are further discussed below.

This project was conceived over a year after the start of Phase I of ArcticNet with the International Law Symposium on Sustainable Developments in Law and Policy on Climate Change held in Montreal during the COP 11/MOP 1 Meeting (2-4 December 2005). The symposium included a special workshop on Law and Policy Implications of a Changing Climate for Northern Communities chaired and paneled by ArcticNet project "Science-Policy Interactions"(see section 2.6). The event as a whole featured prominent collaborators from various ArcticNet projects. This current project also organized activities around 'Arctic Day' (6 Dec 2005) in Montreal at the COP 11 /MOP 1 and parallel events. This successful symposium was followed by in-depth discussions with policy-makers, academic and non-governmental organizations that took the form of interviews and meetings in Europe and North America. Interview selection was based on prior consultations and recommendations from other ArcticNet project leaders, government representatives, and non-governmental stakeholders, mainly from Inuit Tapiriit Kanatami (ITK) and the Inuit Circumpolar Council (ICC). The interviews were conducted under various themes of this project, and thus differed considerably in terms of content. Overall, the interviews did not only serve as a tool for primary sources, but also served to strengthen and build relationships and partnerships and allowed for two-way information exchange for further research and discussion. This project's research strategy also resulted from the symposium in Montreal (Scott et al. 2006). This strategy document articulates the research priorities identified in discussions that took place in the context of the December 2005 Climate Law symposium, in consultations with several northern residents, leaders and Inuit organizations in the North over the summer of 2006, and in various meetings between network investigators and researchers. Through the creation of the strategy, those serving as network investigators, collaborators and project staff were identified.

Throughout 2006, several meetings were held between researchers and network investigators involved in this project and researchers from other ArcticNet projects. Project team members were provided with background information on the need for adaptation in the North, and the scientific hurdles associated with mitigation and adaptation. These meetings provided a framework on which to study the legal implications of adaptation policy-making.

In November 2006, team members attended the International United Nations Framework Convention on Climate Change Conference of the Parties 12 (MOP 2) in Nairobi and served as primary instructors for the "Sustainable Development Law on Climate Change" Law Training Course (parallel event) and the Centre for International Sustainable Development Law side event, "Sustainable Development Law on Climate Change: Emerging Legal Regimes & Mechanisms". The learning course featured draft materials prepared for a legal capacity building manual on Sustainable Development Law on Climate Change, and the challenges faced by northern Canadians, the Inuit in particular. The event featured the international release of the Quebec Climate Change

Action Plan 2006-2012 and the report and outcomes from the successful international symposium "Strengthening Climate Cooperation, Compliance and Coherence", and featured the ArcticNet project. Team members also took the opportunity to network and seek out new international input on their work, and maintain existing linkages. One linkage they maintained was with the Government of Nunavut and ITK, as they took a particular interest in a talk entitled "Climate change effects on Nunavut" at the Climate Talk Series side event.

This project was represented at the fourth session of the Global Roundtable on Climate Change hosted by Dr. Jeffrey Sachs and The Earth Institute at Columbia University, New York (December 2006). This meeting brought together more than 150 critical stakeholders from all regions of the world, including senior executives from the private sector and leaders of international governmental and non-governmental organizations, to discuss and explore areas of potential consensus regarding core scientific, technological, and economic issues critical to shaping sound public policies on climate change. A critical contribution was made to the direction of the consensus statement entitled "The Path to Climate Sustainability: A Joint Statement by the Global Roundtable on Climate Change" which brought key northern perspectives to the roundtable.

From June to July 2007, field research was conducted in Arviat, Nunavut to pursue the pan-Arctic research strategy put in place through earlier field research in Nunavik in 2006, during which interviews with Inuit elders and community members were conducted. In Arviat, interviews were informal and held primarily with local youth, but also elders. In August, researchers traveled to Inuvialuit communities to conduct further interviews. The research finalized the regionally varied study set in place in 2005. The combination of the two field research trips, along with the earlier trip to Nunavik, provided a diverse range of perspectives.

2.7.6 Results

The project has provided ArcticNet with a new dimension – a truly social science and governance perspective on the issues of northern climate change. This has allowed the project to focus on five specific juridical and social science areas (see introduction) that are often left unaddressed in a formal way by researchers, policy-makers and scientists. The project explored new options and ways to fit within the IRIS framework. It presented policy solutions and explored the uncharted waters of the legal responsibilities and challenges associated with land claim rights, human rights and climate change. Another outcome was the identification of priorities and information needs of Inuit and northern groups as relevant to northern climate change issues.

Worldwide efforts to address climate change have culminated in multilateral treaties, such as the 1992 United Nations Framework Convention on Climate Change (UNFCCC) and the 1997 Kyoto Protocol (KP). Terry Fenge of the Inuit Circumpolar Conference, who served on the Arctic Climate Impact Assessment Steering Committee, argues that Inuit people have only just begun to play a central role in shaping such agreements, and that more involve-

ment is essential. McBean and collaborators (see section 2.6) have noted the serious dangers posed by rising emission levels for Arctic ecosystems, and the pressing need to better address the needs of northern communities, as this region is already facing significant impacts. Active international investigations of this topic and how international climate change instruments are applicable to the North have been completed. Exploration mechanisms addressing the specific needs of northern indigenous peoples, within the context of climate change and how northern communities could access cooperation and funding, (in spite of their location) were of particular interest.

Particular attention was given to the dynamics between the international legal order, the national legal regime and local adaptation strategies. The research took note of "encounters" or "interfaces" between global and national regimes designed to tackle the problem of climate change and the locally generated strategies for coping with changing climates. The studies considered the extent to which emerging and evolving governance structures draw on local, national and global sources of inspiration in the context of particular communities at particular junctions in time. The research documented the extent to which local governance mechanisms, national law and policy, and global legal norms inform and reinforce each other. It addressed both the "uptake" of traditional ecological knowledge (TEK) in international environmental treaty negotiation processes, and the degree to which traditional practices give shape to claims made under international human rights mechanisms. It was recognized that the global source can also "provide means for local entities to gain access to, engage with, and draw benefits from global forums and discourses". In this way, this research project advanced a nuanced analysis of both the localizing and the globalizing forces that are influencing the development of adaptation strategies in the context of a changing climate.

The right to maintain cultural traditions through the right to housing, as expressed in the International Covenant on Economic, Social and Cultural Rights, contains seven criteria, all of which must be met. Among the seven elements are: 1) housing must be culturally adequate; 2) its location must allow access to employment, services and social facilities; and 3) certain services, materials, facilities and infrastructure must be available to the dwellers. These elements are of special significance to the Inuit because of the unique nature of their homes and building materials, as well as the location and climate-specific nature of their ways of life.

Three topics are of particular interest with regard to the right to housing, and can be expanded to broader human rights implications related to environmental law. Project members have put special emphasis on investigating these three areas. The first area is how international human rights laws support and influence adaptation efforts, and how a claim can be advanced that climate change violates the Inuit right to housing, on the grounds of cultural adequacy. Secondly, the Inuit can mobilize human rights laws 'on their own terms'. Nunavut Tunngavik Incorporated (NTI) explains that Inuit peoples can and should present the impacts of climate change as a human rights issue in order to educate the rest of the world on what is occurring in the North. Therefore, the question of how international human rights claims can best be mobilized and harnessed as part of political and awareness-raising strategies was explored. Specifically, will advocacy of the human rights impacts from climate change be sufficient to help the local Inuit people adapt to climate change? And if not, how can such claims form part of a broader local, national and international strategy? Investigations into this topic have included a review of perspectives that are critical to a rights-based approach. The third area of examination concerned the remedies that might be sought in such claims, and how emerging concepts of compensation and collective responsibility, developed in other areas of law, can inform the arguments of indigenous peoples and northern communities in these cases. The main question posed was: 'Can mitigation by other nations provide funds for adaptation, and if so, how could a legal claim be made for such a support?

For the first time, this project investigated the availability of property and other forms of insurance in Arctic communities in light of climate change, and whether insurance is available to persons in Arctic communities as an economic instrument to address risks relating to climate change. For example, the "Inuit Perspectives on Climate Change Adaptation Challenges in Nunavut – Summary Workshop Report 2005" (Nunavut Tunngavik 2005), published by NTI identifies the need for harvester's insurance and/or emergency compensation funds. What mechanisms exist to deal with the drastic disruption of household and livelihood when harvesting equipment is lost because of variability in sea ice conditions? Also of interest is how the problem of a changing Arctic is being approached by the insurance industry. If it can be stated that climate change is affecting the security of northern communities, the question of what changes might be needed in laws relating to accident and property insurance must be addressed to ensure that increased risks and burdens do not fall disproportionately on the most vulnerable.

Attention to the dynamics between the international legal order examined by other project members and the local adaptation strategies adopted by particular communities may offer insights that can be useful in other contexts, and are of broad relevance. For example, it was examined how vulnerable communities with little political voice engage with and resist a truly global phenomenon, and how they interact with powerful global interests and institutions and ways of knowing. Tensions include the need to demonstrate support for mitigation strategies popular in the South, the desire to exploit the very limited options for northern economic development, raising awareness regarding the impact of climate change on the northern way of life and cultural survival and the need to exploit natural resources, such as hydro-electricity and natural gas, to survive. As it becomes increasingly difficult to survive on the traditional economy, for reasons related to climate change, there is an attendant shift towards a wage-based economy and gradual loss of traditional and land-related skills.

The research into local laws and customs pertinent to the question of climate change adaptation in the North focused on the proliferation of multiple and interacting institutions of governance; the centrality of land claims agreements to local adaptive capacity, and the implications of contested Arctic sovereignty, not in a strictly international law or international relations sense, but within a study of local social dynamics and political economy.

Doctoral research focused on working closely with the Inuvialuit of the Canadian western Arctic to involve community members, particularly elders, into the process of telling stories about their history and contemporary circumstances. This often had relevance and connections to the changing climate and the Land Claims Agreements. The documentation collected was reworked to write a high school textbook for the Northwest Territories based on Inuvialuit oral and written history. Another research project in which ArcticNet findings are involved is the production of a document for the Nunavut Department of Culture, Language, Elders and Youth that will help develop a locally appropriate curriculum for local students.

Linkages have also been established with traditionally unstudied aspects of northern climate change, such as the encroachment of forests on Arctic territory (Streck et al. 2008, Streck and Scholz 2006). This resulted in new formal and informal organizational linkages and collaborations. This ArcticNet project has also been active in outreach activities, such as the Arviat Summer Science Camp where the focus was on regional, national and global climate change science and issues.

2.7.7 Discussion and Conclusions

This project has been an international force for ArcticNet. Through attending international seminars, meetings and UNFCCC sessions, members have promoted and received feedback from renowned members of the international political community. The team has also been able to communicate and exchange ideas with national policy-makers and key decision-makers, often informally, about adaptation strategies in the North. At the same time, the project has excelled in local Arctic fieldwork that spans the IRIS regions. This diversity in both geography and demographics makes this a well-rounded project with much to offer to other ArcticNet projects.

By focusing on the specific practical implications of climate change for northern communities, this project nuanced a general set of assertions about how disproportionate impacts of climate change on northern communities ought to gain legal recognition. One working hypothesis has been that, like small island states, Inuit communities should have particular legal recognition for their claims within the Kyoto and post-Kyoto frameworks, and ultimately within domestic Canadian law as well. Although project members remain committed to that hypothesis, it appears that the vulnerabilities of Inuit communities to climate change are in fact added to an existing and complex set of social pressures. It may seem that paying special attention to impacts on Arctic communities is a disproportionate response to direct climate change impacts on those communities. Yet, patterns of economic and social behaviour that have had adverse effects on Inuit and other indigenous communities for decades are perhaps some of the most overwhelming symptoms of climate change. There is therefore legitimacy to giving particular weight to the claims and concerns of indigenous communities, and Canada's absence of recognition for the Declaration of the Rights of Indigenous Peoples only serves to highlight the current legal vacuum.

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