ArcticNet ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ

Impacts of Environmental Change in the Canadian Coastal Arctic

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

VOLUME 1

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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 ᓛᕝ, ᑯᐸᐃᒃ ᓯᑎ, ᑲᓇᑕ

ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐱᑕᖃᕈᓐᓇᖅᑎᑕᐅᔪᖅ ᑖᒃᑯᓇᙵᑦ ᑮᓇᐅᔭᒃᓴᖃᖅᑎᑕᐅᓪᓗᓂ ᑐᑭᓯᒐᓯᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᑐᑭᓯᓐᓂᐊᖃ-ᑎᒌᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ, ᑲᑐᑎᔭᐅᓪᓗᓂ ᐱᓕᕆᐊᕆᔭᐅᔪᖅ ᑖᒃᑯᓇᙵᑦ ᓄᓇᒥᐅᑕᕐᓂᒃ ᖃᐅᔨᓴᐃᔨᒪᕆᑦ ᐊᒻᒪᓗ ᐃᑯᒪᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑎᑦ ᑲᑎᒪᔨᖏᑦ, ᑲᓇᑕᒥ ᐃᓕᓐᓂᐊᕐᕕᒃ ᐃᓅᓯᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᐃᓂᖅ, ᐃᓄᓯᕐᒥ ᖃᐅᔨᓴᐃᓂᒻᒪᕆᒃ ᐊᒻᒪᓗ ᐃᓄᒃᓱᑎᑦᓱᓐᓇᖅᑕᑦᑎᒍᑦ ᖃᐅᔨ-ᓴᐃᓂᖅ ᑲᑎᒪᔨᖏᑦ, ᐊᒻᒪᓗ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ.

ᐅᑯᐊ ᐱᑐᒃᓯᒪᕕᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ ᐊᔾᔨᐅᖕᖏᑑᔪᒥᒃ ᐱᓇᓱᐊᖃᑎᒋᔭᖏᑦ ᐊᕙᑖᓂᑦ ᐃᓕᓐᓂᐊᕐᕕᒃᔪᐊᓂ, ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ, ᒐᕙᒪᒃᑯᑦ ᐊᒻᒪᓗ ᑮᓇᐅᔭᓕᐅᕐᓯᐊᕋᑎᒃ ᐊᐅᓚᑦᓯᐊᔪᑦ ᑐᕌᖅᑐᑦ ᑐᓄᑎᒍᓐᓇᖅᓗᒍ ᑲᓇᑕᒥᐅᑦ ᖃᐅᔨᓴᖅᓂᖏᑦ ᐊᒻᒪ ᓈᒻᒥᓂᖅᑐᓕᕆᓂᖅ ᐱᓕᕆ-ᓐᓂᐊᕐᓯᐊᖅᑐᑦ ᑕᒪᑐᒧᖓ ᒪᑭᑕᓇᓯᐊᕐᓂᕐᒧᑦ ᐊᒻᒪᓗ ᐃᓅᓯᕐᒥ ᐃᑲᔪᑎᓂᐊᖅᑐᓄᑦ ᑕᒪᐃᓐᓄᑦ ᑲᓇᑕᒥᐅᓄᑦ. ᑕᐃᒪᓗ ᐃᓗᓪᓕᓇᓗᐋᖅᑕᖕᒐ ᐃᓚᖕᒐ ᒐᕙᒪᑐᖃᒃᑯᑦ ᓄᑖᓂᒃ ᐱᕆᐊᓪᓚᒍᑎᓕᕆᓂᖅ ᐋᕿᒃᓯᒪᐅᑎᖏᑦ, ᐅᑯᐊ ᑲᓇᑕᓕᒫᒧᑦ, ᐊᒥᓱᑦ ᐃᓂᖅᑎᕆᔪᓐᓇᖅᑐᑦ ᐊᒻᒪᓗ ᐊᒥᓱᑦ ᖃᓄᐃᓐᓇᖅ ᐱᓕᕆᔪᓐᓇᖅᑕᓕᑦ ᑲᑎᖕᒐᔪᑦ ᐱᐅᓂᕐᐸᖑᔪᒥᒃ ᖃᐅᔨᓴᐃᓂᕐᒥᒃ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑕᐅᓕᖓᓐᓇᖅᑐᓂᒃ ᐊᒻᒪᓗ ᐋᕿᒃᓯᒪᐅᑎᖏᑦ ᖃᑭᒐᓯᐊᕈᑎᕆᔭᐅᓐᓇᖅᑐᓂᒃ.

ᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᖃᑎᒋᔭᖏᑦ ᑖᒃᑯᓇᙵᑦ ᑐᑭᓯᒐᓯᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ ᑎᒥᖑᖅᑎᑕᐅᓯᒪᔪᑦ ᑮᓇᐅᔭᓕᐅᖅᑎᐅᓯᒪᐊᖁᑎᒃ ᑯᐊᐳᕆᓴᙵ ᐊᑖᒍᑦ ᐊᑎᖃᖅᓗᑎᒃ "ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᑎᒥᖓ" ᑕᐃᑲᓂ ᑎᓯᐱᕆ 2003.

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

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

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

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

Canada

Coming together in the study of a changing Canadian Arctic.

ᐊᐅᓪᓚᖃᑎᒌᒃᓯᒪᔪᑦ ᐃᓕᑦᑎᓇᓱᖃᑎᒌᒃᑐᒡᓗᑎᒃ ᐊᓯᑦᔫᕐᐸᓪᓚᐊᓂᖓᓂᒃ 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 that will be impacted first and most severely by the present warming of Earth's lower atmosphere. Many of the symptoms of a warming Arctic anticipated by climate models are already 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 will interact to bring about an irreversible transformation of the North. ArcticNet is a Canadian 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 the adaptation strategies and policies that will help northern societies and industries prepare for the full impacts of the environmental 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 first steps 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 achieve such early success, and the ArcticNet compendium editorial team for bringing this volume through to completion.

Louis Fortier, Scientific Director of ArcticNet

Martin Fortier, Executive Director of ArcticNet

ᐱᒋᐊᕐᓂᖓ

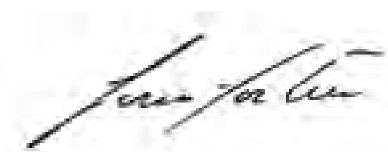
ᐅᓇ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓄᓇᖓ ᓄᓇᕐᔪᐊᒥ ᐊᒃᑐᖅᑕᐅᖃᕐᓂᐊᖅᑐᖅ ᐊᒻᒪᓗ ᐊᖏᙵᓚᖑᔪᐊᒥᒃ ᓱᑯᑕᐅᓗᓂ ᑕᒪᑐᒪᖓᑦ ᓂᒋᐊᓂᒐᖅᑐᓂᑦ ᐅᖅᑰᓯᕙᓪᓕᐊᓂᖓᓄᑦ ᓄᓇᕐᔪᐊᑦ. ᐅᓄᖅᑐᑦ ᑕᒻᔅᔭᐅᓕᖅᑐᑦ ᖃᐅᔨᑎᑦᑎᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ ᐅᕐᑰᓯᓂᖓᓄᑦ ᖃᐅᔨᔅᔪᑎᖄᖅᕈᑎᒃ ᓯᓚᐅᑉ ᖃᓄᐃᓐ-ᓂᖓᓂᒃ ᓴᓇᕿᑕᐅᔪᓂᒃ ᓇᓗᓇᐃᖅᑐᖅ ᑕᑯᔭᐅᔪᖅ ᓄᓇᑐᐃᓐᓇᒥ, ᑕᓇᐅᕐᒥ ᐊᒻᒪᓗ ᓄᓇᕐᔪᐊ ᓯᓚᑖᓂ. ᓇᐃᙶᖅᑐᒍ ᐅᖃᕈᓐᓇᖅᑐᒍᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓯᓚᒐᑕ ᐊᕙᑎᖓᒐᑕ ᐊᓯᑦᔨᕐᓂᖓ ᐊᒃᑐᖅᑕᐅᓂᖓᓂᒃ ᓱᕐᑯᐃᖅᑕᐅᓇᓱᒃᓯᒪᔪᓂᑦ 2004, ᐊᒥᓱᑦ ᐊᔾᔨᒌᙱᑐᑦ ᓯᓚᓐᓂᐊᖅᑐᑦ, ᐃᓅᓯᓕᕆᓂᕐᒥᒃ ᕿᓇᐅᔭᑎᒍᑦ ᐱᕙᓪᓕᐊᓂᖅ ᐊᒻᒪᓗ ᓄᓇᖏᓐᓄᑦ ᒪᕙᒪᓕᕆᓂᖅ ᑕᒪᔅᔭ ᐱᓕᕆᔭᐅᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓗ ᐊᓯᑦᔫᓂᐊᖅᑐᖅ ᑭᓯᖑᕐᑐᓂ ᐅᑎᕈᓐᓇᕐᓂᐊᙱᖅᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓐᓇᐅᖏᓐᓇᐅᔭᓕᕐᓂᐊᖅᑐᑦ. ᐅᑭᐅᖅᑕᖅᑐᒥ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᑦ ᓄᐊᑎᓇᔪᑦ ᖃᐅᔨᒪᔭᐅᔪᓂᒃ ᐊᒻᒪᓗ ᓱᕐᑯᐃᖅᑕᐅᓯᒪᔪᓂᒃ ᑭᙳᒨᒪᒋᔭᐅᓯᒪᔪᓂᒃ ᐋᖅᑭᒃᓯᓂᐊᕐᓗᑎᒃ ᓱᖏᐅᑎᑦᑎᔾᔪᑎᒃᓴᐃᑦ ᐊᒻᒪᓗ ᐊᑐᐊᒐᐃᑦ ᐅᑯᐊ ᐃᑲᔪᕐᓂᐊᖅᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥ-ᐅᓂᒃ ᐊᒻᒪᓗ ᑲᒻᐸᓂᐅᔪᓂᒃ ᐱᓂᒃᓴᕚᖅᓯᒪᓗᑎᒃ ᐊᒃᑐᖅᑕᐅᓂᖓᕐᓂᖓᓄᑦ ᐊᕙᑎᖓᑦ ᐊᒻᒪᓗ ᐃᓅᓯᖏᑦ ᐊᓯᑦᔨᕐᓗᑎᒃ ᓯᒃᔭᖏᑦ ᑲᓇᑕᐅᑉ ᐅᑭᐅᖅᑕᖅᑐᐊᓂ. ᐅᓇ ᑕᐅᕗᓇᔭᕆᑦ ᓴᓇᓗᒍ ᓯᕗᓂᒃᓴᕆᑦ, ᖁᔭᓐᓇᒦᒃ ᑕᒪᔅᔭᐅᖕᒪᑦ ᑐᓴᐅᒪᖃᑎᒌᖕᓂᖅ ᖃᐅᔨᒪᖃᑎᒌᖕᓂᖅ, ᒥᐊᓂᕆᓂᖅ, ᐋᖅᑭᒃᓯᐃᓂᖅ ᐊᒻᒪᓗ ᐃᓗᓪᓕᖅᓯᐃᓂᖅ, ᖃᐅᔨᓴᖅᑎᓪᒪᙳᑦ ᐊᒻᒪᓗ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᑦ ᑲᑎᓯᒪᔭᖏᓐᓂᑦ ᐱᓕᕆᑦᑎᐊᖅᐳᒋᑦ ᐱᐅᓐᖏᓪᓗᑎᒃ ᐊᒃᑐᐃᓇᔭᓚᐅᖅᑐᓄᑦ ᐊᒻᒪᓗ ᐊᖏᒃᓕᑎᓯᒪᓪᓗᒋᑦ ᐱᐅᔪᓂᒃ ᐊᑑᑎᖃᑦᑎᐊᖅᑐᓂᒃ ᐱᓪᓗᒍ ᑕᒪᓐᓇ ᐊᓯᑦᔨᕐᓂᖅ. ᑭᓲᓂᖏᑦ ᐱᑕᖃᖅᑐᑦ ᐅᑯᐊ ᓯᕗᓪᓕᕐᐹᑦ ᐱᓕᕆᔭᐅᔪᑦ ᑕᒪᑐᒧᖓ ᑕᕐᑯᔭᐅᓯᒪᔪᓂᑦ ᑲᔪᓯᑎᐊᖅᓯᒪᔪᑦ ᓯᕗᓪᓕᕐᓂ ᐊᕐᕌᒍᓂ ᑎᓴᒪᓂ (ᓴᕐᕿᓂᖓ 1) ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᑦ. ᖁᔭᓐᓇᒦᒃ ᑕᒪᑦᓯ ᑐᑭᓯᓇᓱᐊᖅᑲᑎᒌᑦ ᖃᐅᔨᓴᖅᑎᑦ, ᐃᓕᓐᓂᐊᖅᑐᑦ, ᐊᓯᖏᓪᓗ ᖃᐅᔨᓴᖅᑎᑦ, ᓴᓇᖅᑲᑎᒋᔭᕗᑦ ᐊᒻᒪᓗ ᐱᓇᓱᐊᖅᑲᑎᒋᔭᕗᑦ ᐃᑲᔪᖅᑐᑦ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᒃᑯᓄᑦ ᑲᔪᓯᑦᑎᐊᖅᑎᓪᓗᒋᑦ, ᐊᒻᒪᓗ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᑦ ᑭᓲᓂᖏᓐᓂᒃ ᑎᑎᕋᖅᑎᖏᑦ ᐱᓇᓱᐊᖅᑲᑎᒌᓚᐅᖅᑐᑦ ᐅᓇ ᑎᑎᕋᖅᓯᒪᔪᖅ ᐱᔭᙵᓇᑦᑎᐊᕋᓯᒃᕗᒍ.

ᓗᒃᑖᖅ ᓗᐃ ᕗᑎᐋ, ᖃᐅᔨᓴᖅᑐᓕᕆᓂᕐᒥ
ᑐᑭᒧᐊᒃᑎ, ᐊᖓᔪᖅᑳᖅ ᐊᒻᒪᓗ ᑐᑭᒧᐊᒃᑎ

ᓘᒃᑖᖅ ᒫᑎᓐ ᕗᑎᐋ, ᖃᐅᔨᓴᖅᑐᓕᕆᓂᕐᒥ
ᑐᑭᒧᐊᒃᑎ, ᐊᖓᔪᖅᑳᖅ ᑐᖏᓕᐊ ᐊᒻᒪᓗ ᑐᑭᒧᐊᒃᑎᑦ ᓴᓇᔨᖓ

Avant-propos

De toutes les régions du globe, c'est l'Arctique qui subira le plus tôt et 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. Tel que résumé 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 l'industrie à se préparer aux pleins impacts de la transformation environnementale 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, et le suivi et la modélisation de l'environnement ont permis 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 vers cette vision 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,
président et directeur général d'ArcticNet

Martin Fortier, directeur exécutif, vice-président
et directeur des opérations d'ArcticNet

Introduction

ArcticNet Compendium Editorial Team

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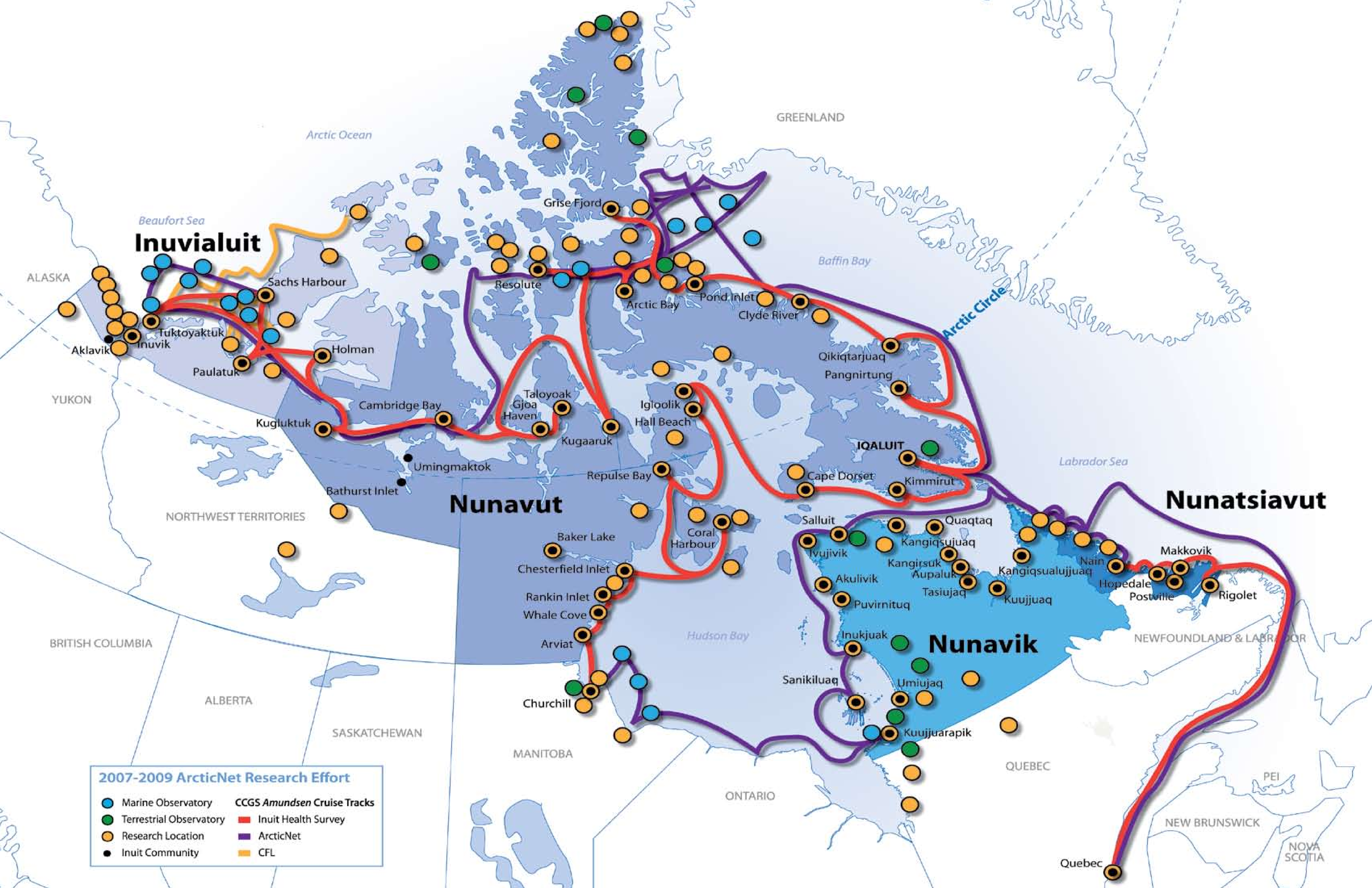
This compendium presents an overview of Phase I of the Canadian Networks of Centres of Excellence (NCE) program ArcticNet, which ran from 1 April 2004 to 31 March 2008. During this initial 4-year period, the basic structure of the ArcticNet research program was developed and put into place, and to achieve its objectives many new partnerships were established with Inuit organizations and communities, along with federal departments, industry, territorial agencies, municipalities and more than 20 research centres of excellence within Canada and abroad. New outreach and communication tools were developed to ensure the long-term value and application of ArcticNet research, with continuous feedback and information exchange among researchers and stakeholders by way of workshops, consultations and conferences. The latter included the ArcticNet Annual Science Meetings, held in Québec City (2004), Banff (2005), Victoria (2006) and Collingwood (2007). Part I of this Compendium describes the objectives and multiple approaches of ArcticNet, while Part II summarizes the four research themes and Part III presents an illustrative subset of ArcticNet projects and results. The final section of the Compendium (Part IV) provides a compilation of refereed articles, book chapters, books and monographs that were published for all four themes over the period 2004 to 2008. This publication list is further updated on the ArcticNet website (www.arcticnet.ulaval.ca).

The ArcticNet mission is defined as: "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". Chapter 1 of this compendium describes the rational for focusing on the coastal Arctic, the specific objectives of the ArcticNet research strategy, and the IRIS approach and the iterative roadmap that has guided ArcticNet research and synthesis. A key element of this approach has been frequent and meaningful exchange with stakeholders, and this has been implemented at all levels within ArcticNet, from its governance structure (e.g. full Inuit representation on the Board of Directors as well as on the Research Management Committee) to the many liaison and consultation activities of individual researchers.

Long-term stewardship and accessibility of all data were priorities from the very beginning of ArcticNet, and the critical importance of these objectives was stressed numerous times by evaluators, partners and end-users of ArcticNet research, including Inuit community representatives. Chapter 2 of this compendium describes the approach to data archiving and access that was initiated to meet these expectations. Building on the partnerships developed during the Canadian Arctic Shelf Exchange Study (CASES, funded by the Natural Sciences and Engineering Research Council of Canada), a keyword-based cataloguing system was developed to organize data sets that could be linked to international databases via a standardized metadata format. In partnership with the Canadian Cryospheric Information Network (CCIN), and with support from Fisheries and Oceans Canada, Environment Canada, and more recently Indian and Northern Affairs Canada (the Canadian IPY program office), this culminated in the Polar Data Catalogue (PDC: www.polardata.ca). This data archiving and discovery resource describes, via a public-access, map-based interface, all data collected by ArcticNet researchers in the natural, health and social sciences, and includes contact details for full data access. This multi-sector database could not have been developed without ArcticNet's remarkable breadth of coverage and its long-term vision for polar research and application. One of the measures of success of this ArcticNet product is that it is now adopted by federal and international programs to meet their own needs, notably the Canadian International Polar Year program, the Northern Contaminants Program, and the Arctic Council's Circumpolar Biodiversity Monitoring Program.

Phase I of ArcticNet was organized as 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. Chapter 3 provides an overview of each of these themes, with a brief outline of their component projects, achievements and contributions to the long-term legacy of ArcticNet. The following two chapters then illustrate the project approach by providing detailed information and approaches and achievements within two themes: the East-West transect Theme 1 (Chapter 4), which placed emphasis on marine systems, and the North-South transect Theme 2 (Chapter 5), which placed emphasis on terrestrial systems, including northern communities.

The preparation of this Compendium was aided by many people and organisations. We especially thank Carl Barrette, Marie-Ève Garneau, Sylvain Tougas, Annie Simard, Leslie Coates, Jay Anderson, Dan Leitch, Jean-Luc Bernier, Philippe Leblanc, Martin Fortier, Louis Fortier, and all ArcticNet researchers and research partners for their contributions to this document.



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MANITOBA
ONTARIO
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NEW BRUNSWICK
PEI
NOVA SCOTIA
Arctic Ocean
Beaufort Sea
Baffin Bay
Labrador Sea
Hudson Bay
Arctic Circle
Sachs Harbour
Tuktoyaktuk
Inuvik
Aklavik
Paulatuk
Holman
Kugluktuk
Cambridge Bay
Taloyoak
Gjoa Haven
Kugaaruk
Umingmaktok
Bathurst Inlet
Resolute
Grise Fjord
Arctic Bay
Pond Inlet
Clyde River
Qikiqtarjuaq
Pangnirtung
Igloolik
Hall Beach
IQALUIT
Cape Dorset
Kimmirut
Repulse Bay
Coral Harbour
Baker Lake
Chesterfield Inlet
Rankin Inlet
Whale Cove
Arviat
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Quebec
2007-2009 ArcticNet Research Effort
Marine Observatory
Terrestrial Observatory
Research Location
Inuit Community
CCGS Amundsen Cruise Tracks
Inuit Health Survey
ArcticNet
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Part I: Approach

This section describes the strategic framework of ArcticNet, including its mission, scope and objectives. The approach based on Integrated Regional Impact Studies is introduced, and background information is provided on the data management strategy of ArcticNet, including development of the online Polar Data Catalogue.

1. Strategic Framework

Scientific Director

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This chapter describes the key elements of the ArcticNet strategic plan. First the ArcticNet mission and geographic scope are defined, followed by the eight strategic objectives targeted by ArcticNet Phase I. An overarching, long-term aim of ArcticNet is to develop Integrated Regional Impact Studies (IRISes) for the Canadian coastal Arctic, and the rationale and nature of this approach are also described, including the iterative ArcticNet roadmap for the implementation of an IRIS.

1.1 ArcticNet Mission

The ArcticNet mission is defined as: 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 (see Frontispiece map for study sites and cruise tracks). These regions comprise the East-West environmental and societal gradient of the coastal marine Canadian High Arctic (Theme 1); the North-South gradient of terrestrial ecosystems in the Eastern Arctic (Theme 2); and the land-ocean interaction zone in Hudson Bay (Theme 3). Each of these IRISes will contribute the knowledge needed to formulate policies and adaptation strategies for the Canadian coastal Arctic (Theme 4), that address concerns of users such as the rate of change of the Arctic environment; reducing human vulnerability to hazardous events; adapting the public health system to change; protecting key animal species; managing shipping in a seasonally ice-covered Canadian sector of the Arctic Ocean; and the socio-economic impacts of environmental change and globalization in the Arctic.

1.2 ArcticNet Scope

Geographically, ArcticNet focuses on the coastal Canadian Arctic for several reasons. First, the largest fraction of Arctic and sub-Arctic Canada is primarily a maritime territory. Second, Canadian Inuit are a coastal maritime people. Third, while continental regions of Arctic Canada (e.g. Mackenzie Basin, Northern Quebec) are relatively well studied, the coastal Canadian Arctic encompasses some of the least studied regions of the Canadian Arctic (e.g. Northern Climate Exchange-GAP Assessment 2001). Fourth, the logistic support provided by the research icebreaker CCGS Amundsen, the central infrastructure of the Network, is limited to coastal marine and terrestrial regions.

Temporally, ArcticNet addresses the present state of the coastal Canadian Arctic, and tries to anticipate the nature and magnitude of the impacts of climate warming on this region at the horizons of 2025, 2050 and 2100. Paleoclimatic studies and Regional Climate Models reconstruct conditions in the coastal Canadian Arctic over the last several millennia to help cast present observations in a long-term perspective. However, ArcticNet also focuses on the short term evolution of the coastal Canadian Arctic environment and the strategies to adapt communities and industries to the impacts of incoming warming and modernization.

Culturally, ArcticNet focuses on the impacts of environmental and societal changes on Inuit societies. Inuit form the dominant national group (>98%, numerically) within the boundaries of ArcticNet's geographical domain of research activity.

1.3 ArcticNet Objectives

The ArcticNet Research Strategy targets eight objectives:

(1) To develop the Network infrastructure needed to support and steer the scientific program of ArcticNet.

(2) To build synergy among existing Canadian centres of excellence in the natural, health and social Arctic sciences.

The holistic, ecosystem-level, issues raised by environmental and societal change in the Arctic, and the need to develop

policies and strategies to adapt to its impacts, require that research results and knowledge be merged among the natural, health and social sciences. Specialists of the natural sciences need to scale down their observations and model predictions of environmental change to the scale of the region and the community. These are the scales at which social scientists and epidemiologists can assess the impacts of environmental changes on social systems and individuals. ArcticNet is creating this cross-sector synergy and thereby increasing the value of sectorial research efforts.

(3) To provide Network Investigators and their national and international collaborators with coordinated access to the coastal Canadian Arctic and to Inuit communities.

As demonstrated by projects such as NOW, CASES and Tundra 99, a dedicated research icebreaker is an efficient way to support large-team, multidisciplinary efforts in both the marine and terrestrial Canadian Arctic. However, the deployment of a research icebreaker is costly and necessitates intense planning and co-ordination to maximize the scientific yield of ship operations. The examples of Germany and the USA clearly show that long-term planning of icebreaker operations at the national level is a necessary condition for the development of a well-coordinated national Polar program. The long-term stability (7 and eventually 14 years) in the funding of icebreaker operations for ArcticNet forms the backbone of the academic contribution to the development of a Canadian-led international program in the Canadian Arctic. The guaranteed annual charter of a predictable number of days by ArcticNet facilitates the long-term planning of ship operations to ensure that the CCGS Amundsen is used at full capacity for a maximum number of days per year. This coordination of the deployment of the CCGS Amundsen has been particularly relevant in the context of the International Polar Year (2007/8).

(4) To engage Northerners in the scientific process through bilateral exchange of knowledge, training and technology.

The case for the direct involvement of Northerners in the study of the impacts of climate change in the Arctic is clear. First, people living in the Arctic have a lot of information (traditional, local and recent) to contribute to the research process. Second, they are, of course, in the best position to identify research priorities towards adapting to the impacts of climate change in the North. Third, the training of Northerners is necessary for Northern communities and governance bodies to achieve full self-reliance in the scientific study, management and stewardship of a changing Arctic.

The meaningful partnerships in ArcticNet between academic and government scientists, international, national and regional Inuit organizations and Inuit communities signal a change in the mantra of science methodology to one that is enriched by the knowledge of Inuit and their land. Inuit have millennia of observations about the changes in their environment. Over the last decades, observations of environmental change and resulting impacts have become worrisome to community residents and many questions have arisen regarding observations that are new to the culture. ArcticNet provides a unique opportunity to merge western and traditional science to determine together how the Arctic environment is changing and what this means to its peoples and in turn the Canadian and global population.

(5) To train the young experts (including Northerners) needed to study, model, manage and ensure the stewardship of the changing Canadian Arctic.

Understanding the present transformation of the Arctic environment and anticipating its consequences is one of the greatest challenges faced by the international scientific community. Unfortunately, after 20 years of downsizing its scientific effort in the Arctic, Canada is missing a complete generation of the field scientists acutely needed to study and monitor the present transformation of the North. ArcticNet and its central infrastructure provide a unique scientific environment for the training of young Arctic specialists. Students are exposed to the multidisciplinary, cross-sectorial and international science needed to address the ecosystem-level, holistic issues arising from the on-going transformation of the Arctic.

(6) To implement Integrated Regional Impact Studies (IRIS) of key regions of the Canadian Arctic.

This approach is described in detail in Section 1.4 below.

(7) To contribute to the formulation of adaptation strategies and policies for the Canadian North.

Communities throughout the Canadian Arctic are experiencing significant changes in environmental conditions. These changes, occurring in the context of rapid social, economic, and political change, are posing significant risks to the culture, livelihood and health of northerners. Governments, communities, and individuals of the Canadian Arctic facing these changes need access to directly relevant information for the development of policies and adaptation strategies. Theme 4 was the core component of ArcticNet Phase I that focused on investigating and integrating cross-Arctic issues and connecting projects and disciplines with the ultimate goal of providing directly relevant information as input to the development of policies and strategies.

(8) To communicate the rationale, objectives and achievements of ArcticNet to the Canadian public, stakeholders North and South, and internationally.

To meet its objectives, ArcticNet requires communication with a wide-range of audiences, including the general public, stakeholders in the North and South and the international community. To avoid re-inventing the wheel and duplicating communication channels in the North, ArcticNet builds on the best practices and networks of other institutions and programs that have successfully establish bilateral communications with Northern communities (e.g. the Northern Contaminants Program and the Canadian Wildlife Service).

1.4 Integrated Regional Impact Assessment

To anticipate the impacts and socio-economic costs of climate warming in the Arctic, national and international strategies advocate an approach based on Integrated Regional Impact Studies (IRIS). In a nutshell, an IRIS summarizes and combines knowledge and models of relevant aspects of the ecosystems of a region affected by change, with the objective of producing a prognosis of the magnitude and socio-economic costs of the impacts of change (example in Figure 1).

The resolution of GCMs (typically 400x400 km) is too coarse to provide the regional and community-level information that policy-makers in Northern governments and Federal agencies need. ArcticNet will significantly augment and update the present observational base on which to develop regional models of change in the Canadian Arctic. The Integrated Regional Impact Studies described in the Research Plan of

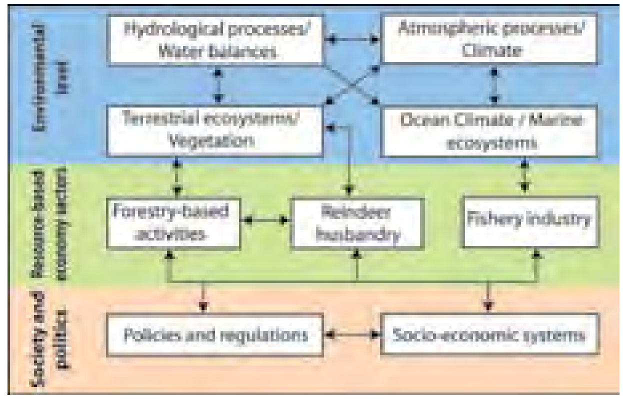

Figure 1. *The general IRIS approach used to assess the impacts of climate change in the Barents Sea region (BALANCE Network), showing the interactions between different models (modified from Lange, M., The BASIS Consortium (2003). The Barents Sea impact study (BASIS): methodology and first results, Continental Shelf Research 23, 1673-1694).*

ArcticNet lays the ground for the development of regional models for the Mackenzie Shelf region, the Canadian Archipelago, the North Water, the terrestrial Eastern Canadian Arctic from Ellesmere Island to James Bay, and for Hudson Bay as a whole. These regional models of climate change impacts will ultimately provide the spatio-temporal resolution necessary to downscale knowledge of the impacts of change to the level of the community.

The iterative roadmap for the implementation of an IRIS includes the following steps:

a) With the input of stakeholders, identify indicators of environmental, health and societal vulnerability;

b) Document past and present changes in climate and different components of the regional environment;

c) With the input of stakeholders, identify present environmental, health and societal vulnerabilities, vulnerability being defined as [(sensibility – adaptability) * exposure];

d) Based on observations and experimental studies of processes, develop impact models that describe the response of an exposure unit (i.e. a natural component/

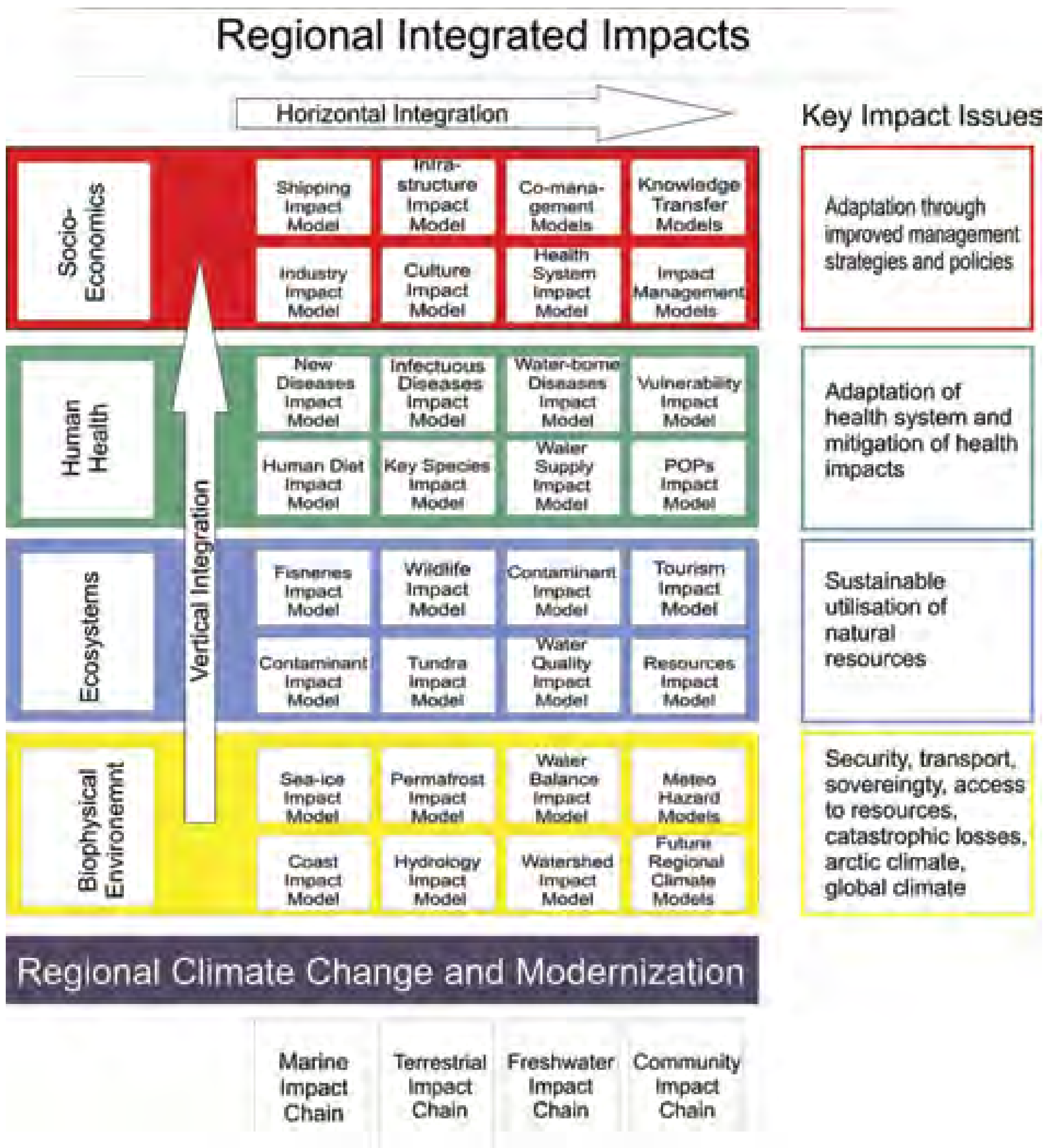

Figure 2. *The basic structure of an idealized Integrated Regional Impact Study (IRIS), an approach that is being implemented by ArcticNet for specific regions of the Canadian Arctic.*

ecosystem, a component of human health or a societal/economical sector) to external changes (climate and non-climate determinants). These models range in complexity from simple conceptual models or statistical relationships to sophisticated numerical simulations;

e) Identify linkages (including feedbacks) between environmental change and health/societal impacts;

f) Assemble the Impact Models into an Integrated Assessment Model through the linkage of individual impact models along predefined vertical "Impact Chains" and the horizontal integration of the vertical chains (Figure 2);

g) Downscale General Circulation Models (GCMs) to Regional Climate Models (RCMs);

h) Force the Integrated Assessment Models with the scenarios produced by the RCM to provide insights into future environmental, health and societal vulnerabilities;

i) Analyse the prognosis with stakeholders.

The structure of the IRIS is summarized in Figure 2. In the context of ArcticNet, columns (Impact Chains) can be removed/added/modified in this IRIS scheme (e.g. a "Land-Ocean Interface Impact Chain" a "Modernisation Impact Chain").

2. Data Management

ArcticNet Data Management Team

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Phase I of ArcticNet comprised 30 projects distributed among four themes (details in Part II), with more than 100 Network Investigators and their teams of graduate students, partners and support personnel. Given this massive quantity and scope of research, an early priority for ArcticNet Phase I was to put into place a comprehensive data management system. A key objective for this system was to facilitate data access for collaboration and synthesis, and to meet the information needs of researchers as well as partners and stakeholders. The latter included addressing the comment that was often heard in our formal and informal consultations with northern communities: researchers come to the North but it is difficult for northerners to know when and where they went, what information they collected, why they collected it, and whom to contact to get that information.

ArcticNet addressed these multiple concerns and needs by first forming the ArcticNet Data Management Committee (ADMC) that reported to the Research Management Committee of ArcticNet. ADMC was charged with developing the ArcticNet Data Management Strategy in consultation with Network Investigators and partners, culminating in the ArcticNet Data Policy, available online at: http://www.polardata.ca/pdc/public/data-policy.pdf. The ADMC identified the following principles that subsequently guided the evolution of ArcticNet's data archiving and access systems:

- Respect confidentiality requirements and researcher rights to publication.
- Recognize that human health and sociological studies will have specialised issues when it comes to data and privacy.
- Ensure that the databases are widely and easily accessible to a variety of users.
- Ensure the long-term preservation of ArcticNet data sets.
- Ensure that there are strong linkages to Canadian and international IPY data management processes.
- Use existing knowledge and infrastructure, wherever appropriate; i.e., ensure connectivity of data, but not duplication of systems.
- Develop the ArcticNet approach as a "system of systems".
- Encourage excellence in data collection, management and accessibility.

In order to make full use of existing systems and accelerate progress, ArcticNet initiated a partnership with the Canadian Cryospheric Information Network (CCIN) at the University of Waterloo to jointly develop an ArcticNet data cataloguing and archiving system. This database was initially designed for metadata and the eventual uploading of raw data, and by 2005 a pilot keyword interface was operational. Collaborators from the Department of Fisheries and Oceans (DFO) and the Canadian Arctic Shelf Exchange Study (CASES) were also actively involved in the metadatabase development. After several modifications and updates resulting from workshops and feedback from Network Investigators, coordinators, end-users and students, the online ArcticNet Metadatabase, renamed the Polar Data Catalogue, was launched in July 2007. The ADMC, with guidance from legal counsel, also formulated a Terms of Use Agreement (Appendix A of the Data Policy), which addresses the use of the ArcticNet Database for uploading metadata and data, and for information-searching within the databases.

The Polar Data Catalogue (www.polardata.ca) is now a data centre that describes and provides access to diverse Arctic and Antarctic datasets, with emphasis on the Canadian North. The

Figure 1. *Screenshot of the opening page of the Polar Data Catalogue website: www.polardata.ca*

records cover a wide range of disciplines from natural sciences and policy, to health and social sciences. The catalogue hosts metadata from research institutions, centres, and programs across Canada and abroad, including the Northern Contaminants Program, the Circumpolar Biodiversity Monitoring Program, and the 2007/08 International Polar Year Program. A geospatial search tool is available to the public and researchers alike and allows users to search for data using a web-based mapping interface, in combination with other search parameters (keywords, date, research group, etc.). Metadata are entered via a streamlined portal, are subjected to quality control and approval, and are then stored as xml files in standard FGDC format to allow exchange with other international databases. The Polar Data Catalogue is overseen by the Polar Data Management Committee composed of representatives from academia, ArcticNet, CEN and the Canadian federal government.

A major feature of this catalogue that directly addresses the stated Inuit needs is that it is online and publicly accessible, including from community computer centers, libraries, schools and other internet access points across northern Canada. The Polar Data Catalogue plays a pivotal role as

Figure 2. *The online interface for the Polar Data Catalogue search facility.*

a tool for the integration and collection of data for the development of the IRISes. This metadatabase and associated data management initiatives have generated considerable interest among researchers, northern communities and government agencies at the national and international levels.

2.1 Acknowledgements

We are grateful to Ellsworth LeDrew, Director of the Canadian Cryospheric Information Network, for his expert guidance in international data management issues and for ensuring the success of our very productive ArcticNet-CCIN collaboration on the Polar Data Catalogue; Leah Braithwaite, for her ongoing advice and encouragement on data issues, and for helping catalyze the rapid evolution of best data management practices in CASES and ArcticNet; Doug Bancroft, inaugural co-chair of the ArcticNet data management committee for helping set this work in motion; the staff at Noetix, Peter Yoon, and his colleagues including the computer science coop students at CCIN who helped design, implement and improve the Polar Data Catalogue; and the multiple funding sources including GeoConnections, the NCE ArcticNet program, CEN, DFO, the Canada Research Chair program, and the IPY Federal Office (INAC) that supported this work.

Part II: Themes and Legacy

This section introduces each of the four themes of ArcticNet Phase I, and concludes with a brief outline of the long term legacy of this research and training program.

3. Theme Overviews



This chapter describes the four themes of ArcticNet Phase I. The background for each theme and its geographical scope are firstly introduced, followed by a description of research projects and objectives. The integration of the theme is described, and each overview then ends with a summary of achievements. More detailed information on the research projects in Themes 1 and 2 is given in Part III of this Compendium.

3.1 Climate Change Impacts in the Canadian High Arctic: a Comparative Study Along the East-West Gradient in Physical and Societal Conditions (Theme 1)

Theme Leaders

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3.1.1 Introduction

Recent warming trends in the Arctic over the last several decades suggest significant future impacts to northern coastal and marine environments, including the communities and infrastructure of these areas. From 2004-2008, Phase I of ArcticNet, Theme 1 initiated studies investigating the causes, impacts, and adaptation strategies to climate change affecting oceans and coastlines. The geographic scope of Theme 1 included the Beaufort Sea in the western Canadian Arctic and extended eastward to Ungava Bay in the eastern Arctic. The dual focus of Theme 1 looked at both the physical environment and societal conditions while still including aspects of the biological and health sciences.

Theme 1 research subjects covered a variety of subjects in the environmental and social sciences. Focus areas included the long-term trends of climate change and ice conditions, the variations in environmental carbon and contaminant cycling, marine resource productivity and their sustainable exploitation, and the changes in Inuit dietary habits, their general health and the emergence of chronic diseases. Theme 1 projects also studied the impact of climate warming on the coastal erosion, permafrost melting, and Inuit coastal community infrastructure vulnerability and resilience. The opening of the Northwest Passage and subsequent consequences were also addressed, as was the legal weight of Canada's claim to the Northwest Passage. Other projects mapped the Arctic seabed to improve navigational charting and the assessment of potential geohazards.

Understanding climate history is essential to predict potential implications of a changing sea ice regime. To plan adaptation strategies, the prediction of future climatic responses and their consequences must be achieved. During Phase I of ArcticNet, Theme 1 worked towards developing an Integrated Regional Impact Study (IRIS) to achieve these goals effectively.

3.1.2 IRIS Region

Theme 1 research projects monitored changes across the Canadian Arctic, from the North Water in northern Baffin Bay and the Nunavik communities, to the Mackenzie Shelf in the Beaufort Sea through the Northwest Passage. Thus the research program of Theme 1 followed an East-West gradient from approximately 60°W-140°W (Figure 1), comparing the fast warming Western Arctic to the more stable Eastern Arctic. The majority of Theme 1 research activities were ship-based, and the land research activities were mainly restricted to coastal areas and river deltas.

While communities in the central Arctic generally experience colder temperatures on average per year than those situated in the coastal outskirts (Figure 2), according to climate change

Figure 1. *The Theme 1 study region.*

models, all regions may undergo increased summer temperatures by 1-2°C throughout the Canadian Arctic within the next 40 years. Models also depict that year-round precipitation will increase by 1-2 cm. The influence of both higher temperatures and greater precipitation will likely make coastlines more vulnerable to erosion through the consequences of higher sea level (from greater ice melt) and greater runoff from land masses. Regions of lower elevation (Figure 2) face the greatest risk to rises in sea level.

Winter temperatures are predicted to undergo greater increases, in the order of 3-5°C by 2050. Within the last 20 years, both the Beaufort Sea and Baffin Bay have experienced declining ice coverage (Figure 3). Baffin Bay averages 30% less ice coverage and its rate of decline is greater than that for the Beaufort Sea. However, models estimate longer ice-free seasons in the Beaufort Sea relative to changes in Baffin Bay during the next few decades.

Paleoceanographic records dating 5000 years link the opening of the Arctic channels with oceanographic changes in regions as far away as Nova Scotia. Reconstruction of sea surface conditions indicates large changes, especially around ~4000 years BP, when the sea surface was warmer by ~2°C and the duration of sea ice cover lessened by 1.5 months per year. This warmer period was followed by a gradual cooling of surface water up until recently. These warming and cooling trends did not occur abruptly, but rather via a series of warm/cold intervals with a cycle of about 1800 years. The mechanistic basis of this cycle is still unknown. Conservative models

Community	Tuktoyaktuk	Holman	Cambridge Bay	Resolute	Kugaaruk	Pond Inlet	Cape Dorset	Iqaluit
Latitude (°N)	69.25	70.45	69.66	74.43	68.32	72.40	64.13	63.45
Longitude (°W)	133.10	117.48	105.84	94.59	89.48	77.58	76.31	68.33
Years with recorded temperature	1973-2006	1979-2006	1930-2007	1947-2007	1984-2006	1975-2006	1963-2006	1946-2006
Average maximum temperature (°C)	-12.2	-12.1	-13.9	-16.3	-19.0	-13.5	-4.8	-5.8
Average minimum temperature (°C)	-18.4	-18.1	-21.3	-23.1	-21.0	-20.8	-9.9	-11.8

Figure 2. *Topographic map and temperature ranges for eight communities in Theme 1. Source: map from GeoBase®; temperature data from Environment Canada.*

estimate a seasonally ice-free Arctic between the years 2030 and 2050 based on observed trends since 1978. Based on field observations, an ice-free Arctic summer may likely occur sooner than previously estimated.

3.1.3 Research Projects and Objectives of Theme 1

The seven projects in Theme 1 generated environmental knowledge to contribute to the analyses of human health and socio-economic impacts of climate change on local communities along the contrasted East-West gradient of the Canadian High Arctic. In initiating and pursuing the North Water Polynya (NOW) and Mackenzie Shelf (Canadian Arctic Shelf Exchange Study; CASES) programs, Theme 1 extended and improved the long-term time series of sea ice cover, ocean properties, plankton production, contaminant loads, fish and mammal abundance, and health and socio-economics to track present variability and future change in Arctic ecosystems. The massive data sets produced by Theme 1 projects contribute to

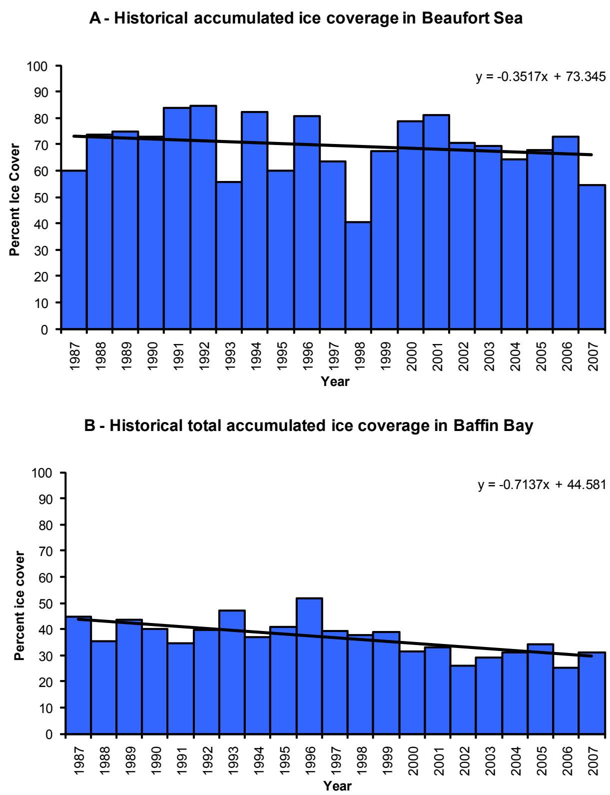

Figure 3. *Temporal trends of ice thickness in the western Arctic (Beaufort Sea) and eastern Arctic (Baffin Bay), 1987-2007. Source: Canadian Ice Service, Environment Canada.*

the formulation of policies and adaptation strategies to help answer the specific needs of stakeholders. The specific objectives of each Theme 1 projects were as follows:

Project 1.1 – Warming Coastal Seas and Shrinking Sea Ice – this project provided long-term observations of the ocean–sea ice–atmosphere coupling in the Canadian High Arctic and baseline physical information for the biological, geochemical and contaminant studies. This project also identified the oceanic processes underlying the changes in the observations mentioned above and aimed to correlate sub-surface ocean properties measured by moored instruments to satellite records of surface temperature, chlorophyll, suspended sediment, sea ice and thermodynamic state.

Project 1.2 – Coastal Vulnerability in a Warming Arctic – this project aimed to improve the understanding and predictive capacity of sea-level change, vertical crustal motion, and flooding hazards affecting erosion and coastal sensitivity. This project also sought to better understand the vulnerability of communities and habitats as well as develop methods for increasing adaptive capacity and resilience.

Project 1.3 – Contaminant Cycling in the Coastal Environment – this project examined the sources and processes leading to the high mercury levels observed in Beaufort Sea's marine mammals. Activities included estimating the relative importance of mercury from the Mackenzie River and permafrost melt, examining coastal erosion as a potential source of mercury, determining the concentration and hot spots of mercury in the Mackenzie River Basin and in the Beaufort marine ecosystem, and studying beluga habitat use and foraging behaviour to examine their dietary sources of mercury.

Project 1.4 – Marine Productivity and Sustainable Exploitation of Emerging Fisheries – this project assessed how changes in sea ice cover, water temperatures and ocean circulation affect microalgal production, fisheries' resources and marine mammal habitat use of the coastal Canadian High Arctic. Research was undertaken by examining key indices of ecosystem maturity (i.e. nutrient drawdown, microbial stocks, phyto- and zooplankton species composition and larval fish growth), microbial dynamics and the availability of fish and marine mammal resources.

Project 1.5 – Changes in Dietary Pattern and Impacts on Chronic Diseases Emergence (New Diseases) – this project investigated the impact of the modernization of diet on the emergence of chronic diseases such as cardiovascular diseases and diabetes among Canadian Inuit. In doing this, it sought to better characterize the role of marine fatty acids in cardiovascular disease protection as

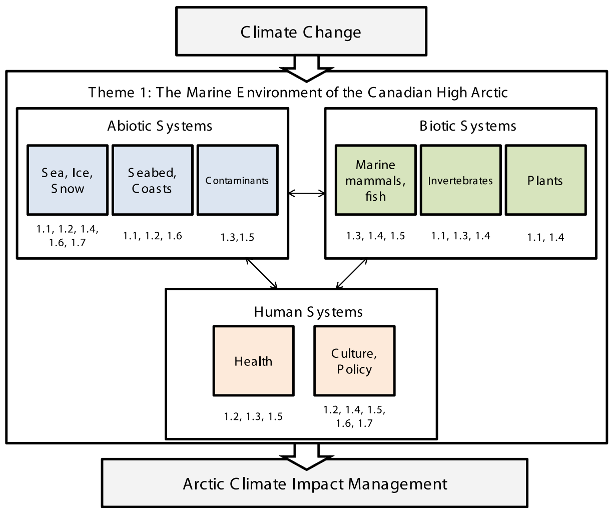

Figure 4. *Flowchart of the Integrated Regional Impact Study (IRIS) for Theme 1.*

well as the impact of climate change on their profiles and Arctic distribution.

Project 1.6 – The Opening of the Northwest Passage: Resources, Navigation, Sovereignty and Security – this project contributed invaluable information to assess the economic, sovereignty and security implications of an ice-free Northwest Passage. The bottom topography, geological structures and geohazards of the Canadian Archipelago were mapped by incorporating high resolution bathymetry, seabed geomorphology and paleoceanographic Holocene sediment records. Data from the project will prove useful for the management of increased intercontinental ship traffic and resource exploration.

Project 1.7 – Canada's Arctic Waters in International Law and Diplomacy – this project assessed the legal weight of Canada's claim regarding the status of the Northwest Passage. It considered the effects of changing ice conditions on the possibility of navigation through the Northwest Passage in the context of a public approach based on risk; it analyzed the potential for persuading other countries to support Canada's claim or cooperate in regulating the use of the Northwest Passage; it developed the outlines of a draft bilateral agreement between Canada and the U.S. on the Northwest Passage; and the project made recommendations to improving policies, search-and-rescue and navigation-assistance capabilities.

3.1.4 Project Integration within the ArcticNet Strategic Framework

The multidisciplinary aspect of all ArcticNet projects is important for implementing an Integrated Regional Impact Studies structure for research. ArcticNet's strategic framework used this structure to render the impacts of climate warming on environmental and socio-economic conditions in the Arctic. Theme 1 participated in the development of the IRIS structure in which each project investigated multiple disciplines with the goal of complete, holistic understanding of environmental dynamics in response to a changing climate. A flowchart of Theme 1's IRIS model is illustrated in Figure 4. The research projects in Theme 1 were categorized into "abiotic systems", "biotic systems", and "human systems".

Theme 1 research activities focussed on climate change impacts of physical and societal conditions of the Canadian High Arctic and, as all the other Themes, provided essential information needed for the "Adaptation, knowledge transfer and policy" aspects of Theme 4. Although Theme 1 mainly worked on marine and coastal environments, the majority of the research projects worked in partnership with Hudson Bay ecosystem projects, land-based projects, and more societal focused projects.

3.1.5 Project Achievements

During the first phase of ArcticNet, Theme 1 projects gathered a wide range of spatial and temporal data sets, providing sound documentation on the ongoing climate change impacts in the Canadian High Arctic. Although ArcticNet's initial phase focussed on data analysis and diagnostic elaboration, some research aspects of Theme 1, aided by multiple inter-project collaborations, were able to discriminate sources of climate change in the High Arctic for the purpose of preparing prognosis, recommendations and adaptation strategies for stakeholders. A summary of the achievements and deliverables for each of the three environmental systems is given below.

Abiotic Systems: Measurements of sea ice, snow, ocean properties, seabed, coastline, and mercury distribution were the focal points in the investigation of the physical, abiotic environment of the Canadian High Arctic.

The Canadian Arctic is losing a significant amount of sea ice, especially in the Pacific sector of the Arctic. Later formation of sea ice and earlier spring break-ups are now observed in Amundsen Gulf. Models based on the observation of climate trends estimate a seasonal ice-free Arctic by 2030-2050. This observed sea ice reduction is a key element in impact assessments of global warming on Arctic climate. Changes in oceanic and atmospheric annual cycles significantly affect the sea ice by disrupting its yearly cycle. Simultaneous changes in snow-cover were also measured. Snow-cover plays a role in radiative transfer to the base of the ice and insulates the growth of the sea ice by thermodynamic control. With the reversal of the Beaufort Sea Ice, increased frequency of cyclonic rotation throughout the year creates positive feedback on sea ice reduction. This reversal is also considered a key factor in the observed ice loss in the central Arctic ice pack.

The stability of the Nares Strait ice bridge in the North Water polynya is apparently affected by thinner sea ice seeding bridge formations coming from the Lincoln Sea, thus reducing the duration of the North Water polynya opening. One of the advances Theme 1 made in this field was an improvement of a dynamic model simulating the formation of ice bridges. After the model was put to test on the Nares Strait ice bridge, it showed that ice bridge location depends on ice thickness, wind and coastline geometry. These results suggested that thinner ice exported from the Arctic basin would eventually prevent the formation of the ice bridge.

Modelling also determined that dynamic and thermodynamic processes are important for the maintenance of the North Water polynya. The thermodynamic process determined the onset of ice formation and melt. The analysis of current meter data from the Mackenzie Shelf uncovered the existence of strong yearly current pulses in January or early February. Their strength and occurrence varied, and their origin is unclear.

Other research in Theme 1 explored the seabed topography. An unprecedented area of seabed throughout the Canadian Arctic Archipelago was mapped to represent timely and critical data for Arctic navigation, resource extraction, climate science and asserting sovereignty. For example, the new multibeam data gathered through the southern side of Coronation Gulf, which was previously uncharted, represents the first step in establishing a new shipping route. New engineering and research techniques were developed to face the challenges of Arctic offshore mapping; these included tidal modelling, high-latitude GPS analysis, sound speed compensation and ice-window beam pattern corrections. All bathymetric, backscatter and sub-bottom data are now maintained on a publicly accessible web based server: www.omg.unb.ca/projects/Arctic/basemaps/index.html.

Mapping the seabed topography also revealed the locations and characteristics of large underwater structures (i.e. 14 km wide slope failure on Beaufort Shelf break, multiple ice keel scours and active gas escape pockmarks). This work represents valuable information to stakeholders concerned with natural resource extraction from the Arctic seabed. Since there are numerous seabed-related constraints for resource development in the Arctic, knowing whether geohazards are inactive or contemporary is of utmost importance for the extraction of these resources.

Canada's Arctic coastlines, totalling more than 155 000 km, are vulnerable to sea-level rise and reduced sea ice cover. These impacts of climate change alter the wave energy regime at the coast, causing flooding, enhanced erosion and shoreline retreat. It also means increased hazard risks for community infrastructures, coastal benthic habitats and resources. Increased permafrost thaw and deterioration of land masses adjacent to coastlines in the southern Beaufort Sea have been observed. The north-west facing shorelines are most susceptible to erosion and retreat. Preliminary model estimates suggested that higher temperatures, rising sea levels, more open water and higher wave impacts may contribute to more rapid coastal erosion and could lead to unprecedented rapid coastal change.

Land mass erosion also results in mercury (Hg) release to water bodies. The identification of mercury sources to the marine ecosystem, including atmospheric deposition, river discharge, coastal erosion and oceanic transport, led to a first partial mass balance model for mercury in Beaufort Sea and the Arctic Ocean. The Mackenzie River is the largest known source of Hg to the Beaufort Sea, followed by permafrost melting and coastal erosion. Theme 1 found that the Mackenzie River contributed about 2.2 tonnes of Hg annually, with permafrost melting and coastal erosion contributing another 0.6 tonnes/year. Mercury from the Mackenzie River becomes bio-available in offshore environments downstream from the outflow plume. Organisms locally exposed to high levels of Hg in the Mackenzie River outflow had the lowest Hg concentrations; for example, beluga feeding offshore (pelagic and epibenthic food) were exposed to higher dietary sources of Hg than those feeding near shore (estuarine prey). Beluga trophic position has not changed over the past 60 years, thus the recent Hg increases in tissue are due to environmental variation in Hg pathways rather than shifts in trophic position. Researchers made a new discovery demonstrating that food web Hg bio-magnification processes drive muscle Hg levels rather than Hg bioaccumulation over time. Monitoring mercury and other contaminants in country foods such as beluga and other marine mammals and fish has important implications in influencing consumption guidelines to sustain healthy living in communities.

Biotic Systems: Theme 1 examined the status and changes in ecosystem productivity in the Arctic by studying polynyas, phytoplankton growth, nutrient dynamics, life cycles, and the biomass stocks of marine food web components.

Considerable spatial-temporal variability in all indicators of biological productivity may be linked to sea-ice dynamics, ocean physics and the variable inflow/outflow of Atlantic, Pacific and river waters. Lower trophic levels (i.e. invertebrates) and upper trophic levels (i.e. marine mammals and fish) congregate at hot spots implying that food web productivity is linked to physical phenomena promoting primary productivity through algae and phytoplankton. Marine plants and, indirectly through the food web, all trophic levels are susceptible to climate-driven alterations of the environment. The highest seasonal estimates of new production were associated with polynyas with low to moderate amounts of Pacific waters. An association between regional maxima of seasonal nitrate drawdown and phytoplankton productivity was noted in late summer suggesting that hot spots are not transient phenomena, but persist throughout the ice-free season. Because Cape Bathurst is prone to frequent wind and tidal upwelling which redistributes nutrients from the seabed to the water column, it is one of the region's greatest centres of ecological productivity.

Arctic cod are an abundant marine fish species in the Arctic, and their survival is also linked to physical parameters influenced by climate change. Results showed that winter temperature at the ice–water interface dictates the hatching season of Arctic cod by limiting the early survival of its larvae. Changes in this species' population structure may affect the survival of its marine mammal predators.

Models revealed that ecosystem shifts from an algal to a detrital mode depended on the relative importance of fresh versus old particulate organic carbon supplies during each season. Remote sensing and records of vertical particle flux at moorings were promising tools for the detection of climate-driven changes in ecosystem productivity and inputs of terrestrial carbon to the Arctic Ocean. Ecosystems of the southeastern Beaufort Sea and Laptev Sea may evolve toward a less productive equilibrium dominated by sediment re-suspension in response to ongoing reduction of the ice cover and increased river discharges. Ecosystems less dominated by river inputs of terrestrial sediments like Baffin Bay could become more productive as the ice regresses, especially in areas where increased wind mixing and upwelling will break stratification and recharge the surface layer with nutrients.

Human Systems: Studies concentrated on the status of health conditions in several Inuit populations and Canada's sovereignty of the North West passage.

The modernization of the Inuit society and particularly changes in their dietary habits may compromise the inherited benefit of traditional food protecting Inuit against chronic diseases. Two cohort studies, part of the Inuit Health in Transition Study, began in Canada: the Nunavik Qanuippitaa? survey and a Nunavut-based survey. These cohort studies focussed on Inuit chronic diseases and their associated risk factors with a particular emphasis on marine lipids (i.e. omega-3 fatty acids). The projects were developed with the purpose of leaving a legacy for the future. Every seven years the projects were updated regarding the information on potential risk factors, the identification of newly diagnosed cases of cardiovascular diseases, diabetes and other illnesses, and social and environmental changes observed in the communities. The surveys also documented dietary patterns to evaluate contaminant exposure.

After completion of the Qanuippitaa? Survey, the final results were presented to the Nunavik population. The survey indicated that Nunavik Inuit were relatively well protected from cardiovascular disease and its related risk factors. Cases of high blood pressure and high cholesterol levels were fewer than in the rest of Québec but other risk factors for cardiovascular disease had worsened or were still a cause of concern (i.e. smoking, obesity and lack of physical activity). Diabetes levels were similar to those of the general Canadian population. Inuit women over 45 years old also had the highest cases of diabetes and showed a prevalence of risk factor related to diabetes (i.e. obesity and hyperinsulinemia) compared to other Canadian communities. Studies of heart rate variability showed no influence of mercury exposure, however subtle negative influences of mercury on adult blood pressure were observed. Omega-3 fatty acid blood concentrations remained high in Nunavik Inuit, although young Inuit had much lower omega-3 blood concentrations and much higher trans-fat levels compared to older adults.

In addition to assessing health and cultural aspects, Theme 1 also examined Canadian policies regarding the Northwest Passage. Canada asserted its claim on sovereignty over the straits and channels in the Canadian Arctic Archipelago, stating they are internal waters. This claim has not been officially disputed, but with the rapid melting of the sea ice, especially in the Northwest Passage, Canada's sovereignty over the Northwest Passage could soon be challenged by other countries. The tacit Canada-U.S. "agreement to disagree" over the status of the Northwest Passage is now put to the test as the ice cover is disappearing and international shipping pressures are increasing. The Canadian claim is legally defensible, but pro-active diplomacy is urgently required to obtain recognition and acceptance of Canada's position on the Northwest Passage. In an effort to prove that a diplomatic solution is possible, we developed the outlines of a draft bilateral agreement between Canada and the U.S. regarding the Northwest Passage, where the U.S. recognizes Canada's claim in return for American and reputable shipping companies' access to the Northwest Passage. The draft also enforced a serious enhancement of Canadian policy (risk approach) and search-and-rescue and navigation-assistance capabilities. Numerous exploratory meetings with national and international experts on sovereignty and international law (i.e. the President of the United Nations Law of the Sea Tribunal) are needed to support Canada's claim over the waters of the Canadian Archipelago.

3.2 Food, Water and Resources in the Shifting North-South Thermal Gradient of the Terrestrial Eastern Canadian Arctic (Theme 2)

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3.2.1 Introduction

The 4-year research program of ArcticNet Theme 2 focused on laying the foundation for an Integrated Regional Impact Study (IRIS) of the eastern Canadian SubArctic and Arctic. This region spans a pronounced North-South gradient in ecological and societal conditions (see IRIS region, below) and it is home to many Canadians, with Inuit communities located along the coasts of Nunavik, Nunatsiavut, and Nunavut as far north as Grise Fjord (Aujuittuq; latitude 76.48 °N). Given the diversity of this region and the potential for substantial environmental change in the future, there is a fundamental need to understand the pattern and impacts of climate warming. Theme 2 researchers studied terrestrial systems, including coastal landforms, glaciers, wetlands, lakes, and tundra. Emphasis was placed on human activities and environmental concerns in the region, and on the development of management tools for improved monitoring, information exchange and policy development.

The breadth of topics covered by the natural sciences included the melting and erosion of coastal permafrost soils, changes in animal populations including birds and small mammals, shifts in tundra vegetation and wetlands, and climate impacts on lakes, rivers and drinking water supplies. The consequences of future warming of the tundra were addressed, including an analysis of the stores of soil carbon that may be released as greenhouse gases. The human health sector examined concerns about the shifts in the diversity of food supplies from hunting, the nutritional quality of that food, changes in water supply, quality and contaminant loading, and climate-related changes in infectious diseases such as brucellosis, Q fever, hepatitis A and botulism. In addition to studies on these health issues by medical researchers, studies by social scientists focused on cultural self-determination in the face of environmental change, Inuit perspectives on environmental impacts (including the development of a new database on this topic) and ways to improve the integration of scientific knowledge and Inuit traditional knowledge.

3.2.2 IRIS region

The Theme 2 study region encompasses diverse environments over 30 degrees of latitude, from 53 to 83°N (Figure 1). Research was conducted at about 50 sites, extending from the northern edge of the boreal forest, to shrub tundra, through herb tundra and high Arctic polar desert. This gradient spans a broad range of climate regimes from a mean annual temperature of -4.3 °C at Kuujjuarapik (Québec, Nunavik) to -19.9°C at Ward Hunt Island (in Quttinirpaaq National Park, northern Ellesmere Island, Nunavut).

An analysis of demographic data for the Theme 2 IRIS region shows how the resident population size decreases precipitously above latitude 55ºN, with a further rapid decline above 65ºN (Figure 2A). The highest population densities occur in each of the territorial capitals, and population growth rates are mostly high (Table 1). This increasing population will likely affect the Arctic and the health of northern communities by increasing local sources and concentrations of air pollutants, for example atmospheric mercury emanating from diesel generators. The eastern Canadian Arctic also receives pollutants from long range sources, notably Eurasia, and source and sink processes may result in a latitudinal gradient of these contaminants.

Satellite analyses of the eastern Canadian sector show that there is a linear decrease in vegetation cover with latitude North (Figure 2B). The composition and biomass of plant communities change drastically, from high boreal forest at the southern extremity of the IRIS region, to High Arctic polar desert at the northern extremity (Figure 3). The trend of decreasing vegetation cover as a function of increasing latitude

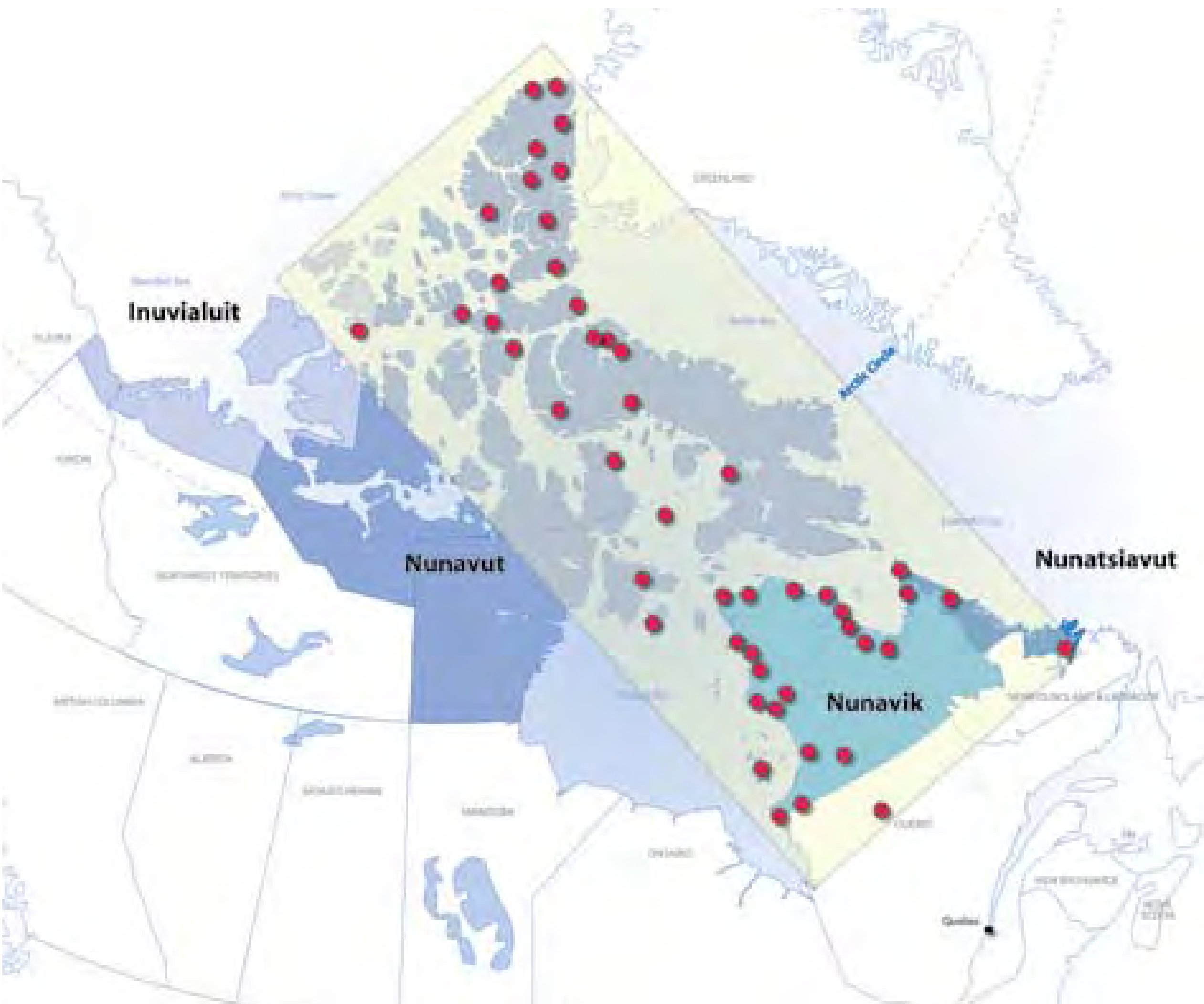

Figure 1. *The Theme 2 IRIS region in the eastern Canadian Arctic and Subarctic. The dots represent the main study sites.*

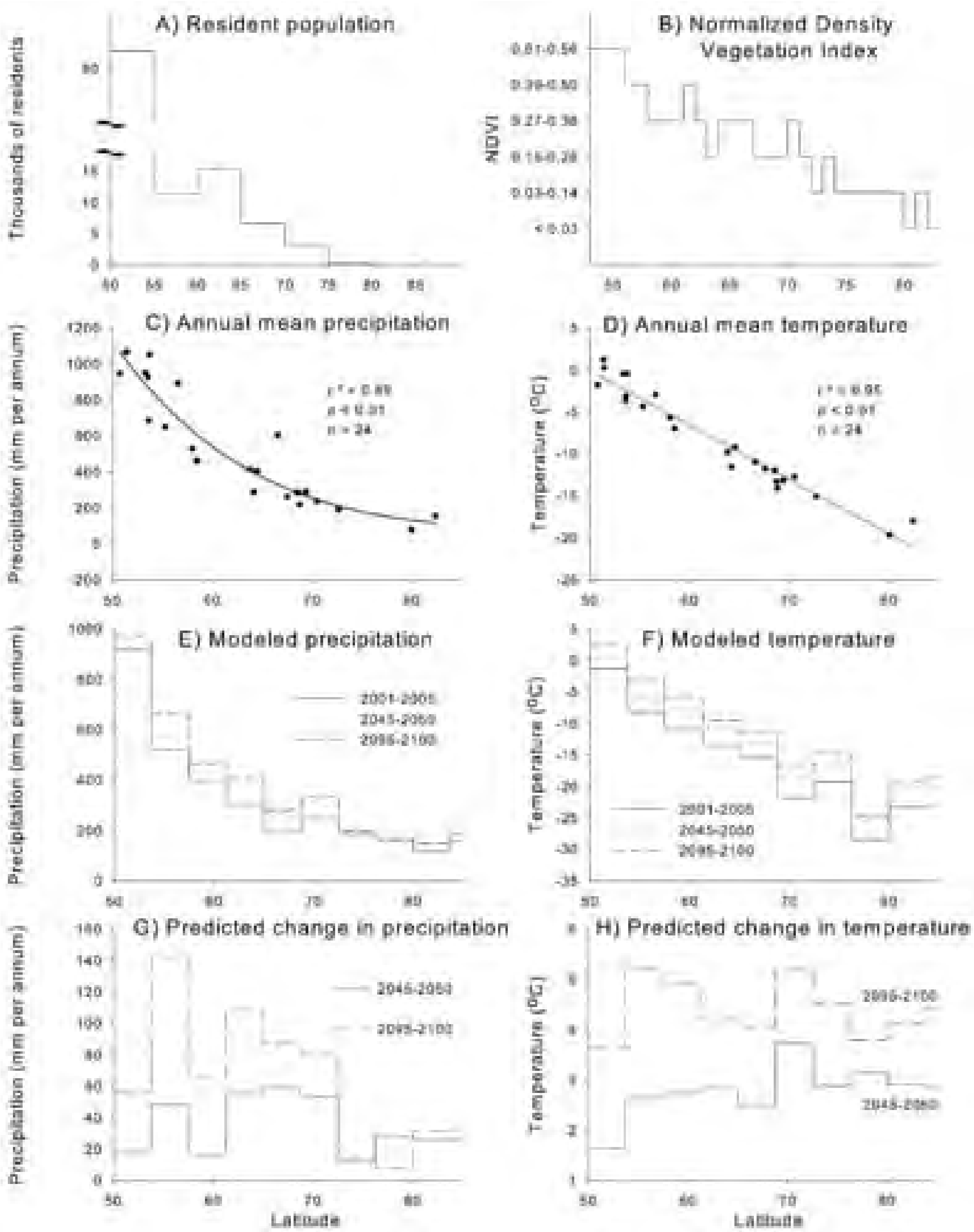

Figure 2. *Latitudinal gradients in the Theme 2 IRIS region. A) Resident population size, from Statistics Canada, 2006; B) Normalized Density Vegetation Index (NDVI), extrapolated from maps provided by the Geographic Information Network of Alaska; C) annual mean precipitation, and D) annual mean temperature, both from Environment Canada; E) modelled precipitation; F) modelled surface air temperatures for three different periods; G) predicted changes in precipitation and H) surface air temperatures for the middle and end of the century. The modelled data (E-H) obtained from the CCCma site, from the CGCM3.1T47 model using the SRES A1B scenario.*

Figure 3. *Vegetation, landscapes and water at extremes of the Theme 2 IRIS region. Top: the High Arctic polar desert landscape at Ward Hunt Lake, Nunavut (lat. 83°N; photo: W.F. Vincent). Bottom: thermokarst lakes at the edge of the forest tundra zone, near Kuujjuarapik, Nunavik (lat. 55°N; photo: I. Laurion).*

is also reflected in a northward decrease of biodiversity across the different ecoclimatic zones that span the IRIS region; see for example:

http://www.eoearth.org/article/Latitudinal_gradients_in_species_diversity_in_the_Arctic

The decrease in plant cover, as described by the Normalized Density Vegetation Index (NDVI, Figure 2B) is strongly related to the decrease in mean annual precipitation ($r = 0.93$, $p < 0.001$) and temperature ($r = 0.94$, $p < 0.001$), which are also strongly correlated ($r = 0.95$, $p < 0.001$).

Precipitation and mean annual temperature both decline markedly with increasing latitude (Figs 2C, 2D). Modeled precipitation shows an exponential decrease with latitude (Figure 2E) while the modeled temperature shows a more linear decrease (Figure 2F). The climate model analyses (from the CGCM3.1T47 model using the SRES A1B scenario, CCCma) indicate that this IRIS region will undergo substantial changes in precipitation and temperature in the future, but that the changes will vary irregularly across this latitudinal range. Precipitation increase may be greatest in the range 53-73°N, with little predicted change at the highest latitudes (Figure 2G). Temperature is predicted to change dramatically (up to 5°C warming by the end of this century) at all latitudes (Figure 2H). For the 2045-50 period, the magnitude of predicted warming increases linearly with latitude ($r = 0.63$, $p = 0.036$), but this latitudinal trend appears to be lost by the end of the century, according to the output for this scenario.

3.2.3 Research Projects and Objectives of Theme 2

Climate change issues in natural, human health and social sciences were addressed across eight projects that aimed to fill knowledge gaps, to anticipate the future coastal Canadian Arctic environment in the study sector, and to provide advice

Table 1

TERRITORY	CAPITAL	LATITUDE	POPULATION	GROWTH RATE
Nunatsiavut			10538	-6.0%
	Hopedale (legislative)	55° 27’	530	-5.2%
	Nain (administrative)	56° 32’	1034	-10.8%
Nunavik			10784	10.5%
	Kuujjuaq	58° 6’	2132	10.4%
Nunavut			29474	10.2%
	Iqaluit	63° 45’	6184	18.1%
Inuvialuit			5762	9.7%
	Inuvik	68° 20’	3484	20.4%
Northwest Territories			41464	11%
	Yellowknife	62° 30’	18700	13.1%
Yukon Territory			30372	5.9%
	Whitehorse	60° 41’	20461	7.4%
OVERALL GROWTH RATE FOR CANADA IN THE SAME PERIOD: 5.4%				

Table 1. *Population data for 2006 for the capitals of each of the Inuit and northern territories. The population growth rate was calculated as the net percentage change from 2001 to 2006 (from Statistics Canada, http://www.statcan.ca/).*

and assessments that will facilitate the formulation of policies and adaptation strategies. The specific objectives of each project were the following:

Project 2.1 – Changing Food Diversity, Wildlife Patterns and Exploitation – this project aimed to assess the effects of climate change on the phenology of animal populations, the distribution of species and the food web dynamics of wildlife communities. A subsequent aim of this work was to consider the effects of changing wildlife patterns on the diet and health of Inuit communities.

Project 2.2 – Water Quality, Supply and Indicators of Change – this project aimed to develop an integrated environmental and health framework for water supplies such as safe drinking water, freshwater habitats for aquatic wildlife and water resources for industrial needs, notably hydro-power generation. Another component of this work examined a variety of paleoclimate indicators of temperature and water supply within the IRIS sector, including diatoms in lake sediments, temperature profiles in perennially ice-capped lakes, tree rings at the northern edge of the boreal forest, and the geochemistry of ice cores from High Arctic glaciers.

Project 2.3 – Emerging New Infectious Diseases in Humans and Wildlife – this project focused on the identification, survey and prevention of health risks associated with infectious diseases in northern Canada, with special emphasis on the appearance and the extent of zoonoses (infectious diseases found in animal hosts and transmissible to humans) and other diseases transmitted via food and water.

Project 2.4 – Climate and Coastal-Landscape Instability: Socio-economic and Ecological Impacts – this project aimed to quantify permafrost, erosion, sedimentation and coastal retreat around communities and in areas of traditional land use, to compare anticipated climate and landscape change with the Holocene paleoclimatic record and oral histories, and to evaluate the impact of landscape change on the activities of northern people, communities and resource development.

Project 2.5 – Cultural Self-determination, Endogenous Development, and Environmental Changes – this project aimed to produce an enhanced understanding of the extent of the environmental issues and challenges faced by indigenous peoples in a rapidly changing milieu, including transformations in the political arena, social structures, economic diversification, approaches to land occupancy, land use, resource use, and diet, as well as to examine Inuit perspectives on environmental impacts, and to foster the exchange between scientific and Inuit traditional knowledge.

Project 2.6 – Warming the Tundra: Health, Biodiversity, and Greenhouse Gas Implications – this project aimed to reconstruct climate variability from dendrochronological analyses of long-lived woody plants as well as from the sequential analysis and dating of organic and mineral layers of permafrost, and to address the implications of changes in permafrost temperature and melting in tundra vegetation, greenhouse gas fluxes and transfer of carbon and optically active materials to waterbodies along moisture and nutrient gradients.

Project 2.7 – Climate Impacts on the Sentinel Species Arctic char – this was a spinoff project from Project 2.2 and aimed to determine if Arctic char (*Salvelinus alpinus*) populations will continue to exist with abundance levels suitable for local exploitation as climate change begins to affect the Arctic, to evaluate if existing populations can be enhanced, and to define linkages between climate change and the contaminant burden of Arctic char.

Project 2.8 – Climate Change in Nunavik: Access to Territory and Resources – this project aimed to help Nunavik communities develop adaptation strategies based on traditional and scientific knowledge of the climate and environmental change and to provide tools which will help the communities face increasing challenges associated with accessing local territories and resources while ensuring human safety.

3.2.4 Project Integration within the ArcticNet Strategic Framework

ArcticNet developed its strategic framework centered on Integrated Regional Impact Studies (IRIS) as a tool to identify and manage the impacts and socio-economic costs of climate warming in the Arctic. The Theme 2 vision of IRIS development is summarized in Figure 4, and involved a two-pronged approach: 1) research questions are driven from below by user "impact management" needs; 2) research questions are driven from above by climate scenarios. Each project is situated within one of three component systems (Abiotic, Biotic and Human Systems), with interactions among and within the systems. The research projects conducted under Theme 2 evaluated how climate change affects resources, health and society, and provided output that fed into Theme 4 – Adaptation, Knowledge Transfer and Policy. Although the focus of Theme 2 was on terrestrial environments, there were close links with several marine-based projects (Theme 1) and with other research in Hudson Bay (Theme 3).

3.2.5 Project Achievements

During the Phase I of ArcticNet, Theme 2 generated a wealth of data, covering a broad sweep of subjects and disciplines, and providing a solid basis to document the ongoing changes in the eastern Canadian SubArctic and Arctic. Although the Phase I of ArcticNet mainly focused on new observations and data acquisition, the convergence of disciplines allowed Theme 2 scientists to produce novel insights into the impacts of climate change on northern lands, ecosystems and society, and the results have already led towards the formulation of societal adaptation strategies and policy recommendations. The main achievements and contributions of Theme 2 are presented below according to the three IRIS component systems (Abiotic, Biotic and Human Systems; Figure 4).

Abiotic Systems: Many approaches were adopted to assess regional patterns of environmental change throughout the

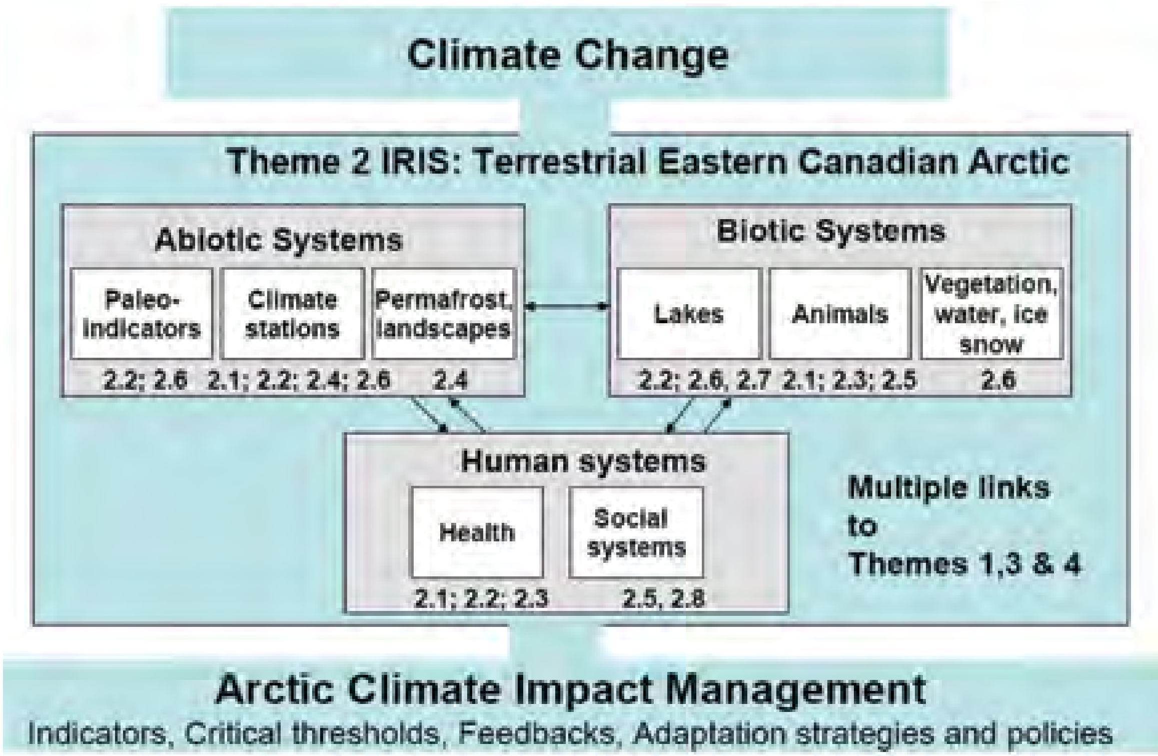

Figure 4. *Conceptual diagram for the Theme 2 IRIS framework.*

vast, north-south range of the eastern Canadian Arctic. These included the establishment of new climate monitoring stations, monitoring of lake and fiord ice by Radarsat-1, and the paleo-analysis of ice cores, lake sediments and tree-rings. New approaches were also developed such as the use of lake and fiord profiles as climate indicators, the application of DNA-based techniques to assess aquatic biodiversity, the analysis of fossil bacterial pigments as paleo-indicators of lake ice and snow cover, and the use of buried dead trees in lake sediment to extend the dendrochronological series to the millennial scale for climate reconstruction. The results from northern Ellesmere Island showed that the northern limit of Nunavut is a region that is already experiencing severe climate change. Further south in the transect, dendrochronological analyses indicated that climate has generally been warming since the end of the 1800s, with accelerated warming since 1980. Evidence of this recent and abrupt onset of warming that was unparalleled relative to previous millennia was also revealed by the analyses of lake sediments. Modelling of lake water profiles and analysis of ice shelf dynamics indicated that the region was strongly affected by climate warming in the 1930s and 40s. Monitoring of ice-related features along the coastline showed evidence of accelerated change over the last five years, including the break-up and ongoing loss of the Ward Hunt Ice Shelf and its associated ecosystems, and the complete break-out and loss of the Ayles Ice Shelf during record minimum sea ice conditions and record maximum air temperatures.

Many of the ongoing changes in Arctic and SubArctic landscapes appear to be related to climate change. For example, a reduction of permafrost area by over 35% occurred in the discontinuous permafrost zone east of Hudson Bay between 1957 and 2005, leading to the generation of hundreds of thermokarst lakes and shrubby hollows. The impacts of this process on ecosystems are extensive, including changes in greenhouse gas fluxes to the atmosphere, and changes in landscape geomorphology.

Biotic Systems: In addition to the impacts of permafrost erosion on ecosystems, the analyses indicated that climate warming could directly affect SubArctic and Arctic ecosystems. Warming experiments and monitoring confirmed that an increase in woody shrub species is expected in most tundra areas, with increased potential for northward migration of the treeline. Moreover, warming will result in improved tree reproduction at the southern limit of the Arctic and in increased potential for higher tree density in the forest-tundra. An increased tree and shrub density in the forest-tundra will alter albedo and the regional energy balance, which could result in warming of the same order as a doubling of atmospheric CO_2 concentrations. This has the potential to change the structure of the systems and could ultimately affect wildlife and other resources used by northerners.

The monitoring of wildlife species revealed that a general northward movement of animals is already underway and will likely accelerate over the next few decades. The consequences of climate warming on wildlife are variable, but could lead to major shifts in the structure of the animal community. Changes in key species are expected in many parts of the Arctic, which could affect the health of ecosystems and influence ecosystem services such as provision of food to human communities. For instance, the monitoring data collected from Arctic char management projects, including the compilation of information from Inuit participants, indicated that a shift in the abundance of zooplankton and chironomid midges due to greater open water could affect mercury concentrations in the char. Monitoring key wildlife species will be essential to assess the magnitude and pace of ecosystem changes and to provide Canada with an important warning system regarding changes in the Arctic. Given the importance of ecosystem services such as wildlife supply to hunters, this information is also required to assess the vulnerability of human communities in the North.

Human Systems: Changes in climate, landscapes and ecosystems affect northern communities in many ways. For example, the access to territory and to resources by Inuit communities, and consequently their safety, is directly affected by changing ice and climate conditions. River mouths and new areas of open water were identified as key hazards for travel and hunting, and changes in the nearshore sea ice environment were mentioned as potentially the greatest life-threatening hazard under the new climate conditions. New quantitative indicators associated with environmental conditions and lake and sea ice formation are now being identified through a convergence of Inuit knowledge and science, and new online maps of safe travel routes are being produced through this ongoing research. Northern infrastructures are also affected by increasing temperatures. Despite the fact that some tracts of land are unsuitable for construction due to adverse terrain conditions, space for expansion on low sensitivity permafrost does exist and is currently being exploited in some communities.

Environmental changes have major repercussions on the supply of freshwater, a vital resource for northern communities in terms of safe drinking supplies, freshwater habitats for aquatic wildlife and water resources for industrial needs, including mining and hydro-power generation. The analyses of drinking water underscored the urgency of setting up both an effective environmental monitoring system and an effective health monitoring system to detect and rapidly deal with health problems related to water quality. Approximately one third of the population of Nunavik consumes untreated water, and our research identified associated problems in domestic water storage prior to consumption.

Emerging infectious diseases in humans and wildlife are among the most serious consequences of climate change, and such effects have been increasingly observed in the North. A portion of the Nunavik Inuit population has been exposed to pathogenic microorganisms responsible for certain zoonotic diseases, notably to *Toxoplasma gondii*. Further investigation is needed to identify the sources of exposure to this pathogen. In the context of climate change, it is important to continue supplying information on zoonoses and safe procedures for handling animals (population, hunters and trappers), and to support clinicians and medical staff in their identification, prevention and treatment of zoonoses.

The ability of Inuit communities to respond and cope with these changes, mainly by adjusting subsistence activities may not be a reliable indication of ability to adapt in the future. Furthermore, the effectiveness of local adaptive strategies is uneven across the Arctic and there are large gaps in knowledge as to why some Arctic communities do remarkably well, while others are more vulnerable and exposed to drivers of change, despite their use of similar resources and ecological settings. Modernization is a pervasive source of change in the Arctic that will continue to interact with climate impacts in complex ways to affect the lifestyle of people and their capacity to adapt. Further research and the integration of traditional ecological knowledge and scientific knowledge at different spatial and temporal scales are needed to understand the extent of change that can be accommodated by the existing ways of life of indigenous peoples.

3.3 Managing the Largest Canadian Watershed in a New Climate: Land-Ocean Interactions in Sub-Arctic Hudson Bay (Theme 3)

Theme leader

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3.3.1 Introduction

The larger scientific community has largely overlooked Hudson Bay until recent years – an oversight that currently is being rectified by the ArcticNet consortium. The ArcticNet Theme 3 research agenda focused on physical, chemical and social aspects of environment and life around the 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 fjords of Atlantic Labrador. To this end, several land- and water-based research projects were carried out to define the background physical state of the 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 the Bay, defining, for example, the annual cycles of salinity, temperature, ice formation and melt, and 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 models to predict that state.

3.3.2 IRIS Region

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. The Bay is the site of considerable hydroelectric development in recent decades, with large power-generation projects moderating fresh-water 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.

Annual average air temperature around the Bay is heavily influenced by the presence of ice. Figure 2(a) and 2(b) illustrate the cooling effect of the Bay and shows the average temperatures

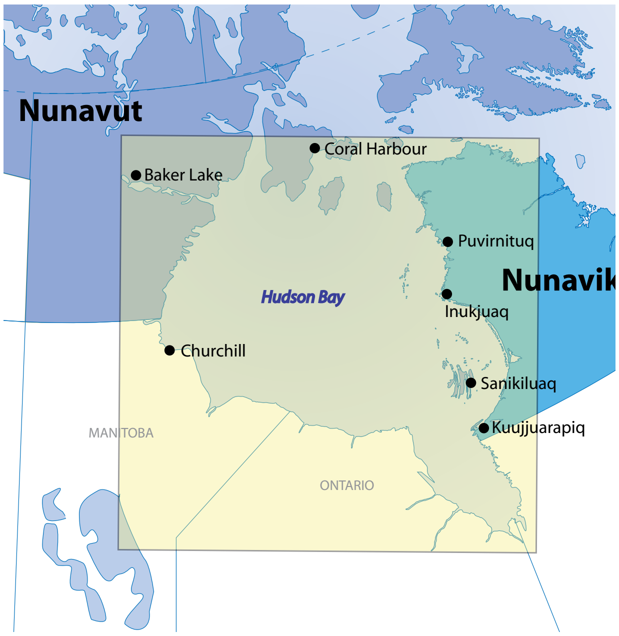

Figure 1. *The Hudson Bay (Theme 3) study region. Source: Atlas of Canada.*

for January and July. Temperatures in January range between -16°C and -27°C, decreasing 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 -30°C in January. Air over the Bay itself remains cool (5-10°C) 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 the Bay (Figure 3).

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 the Bay. The majority of precipitation reaches the southern bowl of the Bay during the summer months. While the regions around the 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 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 Bay harbours an active ecosystem. The Bay 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 the 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 the Bay's shorelines (Figure 5). The Hudson Bay coastal area is known to be a large store of methane, an effective greenhouse gas. Warmer temperatures in the region have allowed a portion of the permafrost layer to begin to melt, not only allowing for the release of methane, but also the deterioration of social infrastructure and natural habitat.

3.3.3 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 were among the key objectives

(a)

(b)

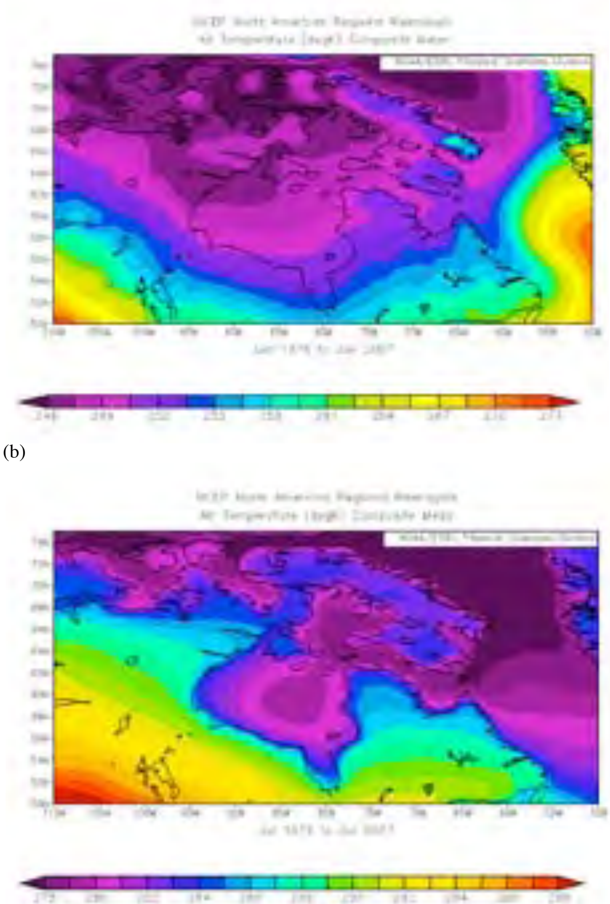

Figure 2. *Temperature distribution for January (a) and July (b) over Hudson Bay, averaged between 1979 and 2007. Source: NCEP NARR.*

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 in Hudson Bay – the goal of Project 3.1 was to investigate 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 – the objectives of this project were two fold. 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 the 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, Climate Change, and Marine Ecosystem Resources in Hudson Bay – this project 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 the Bay. Water characteristics in Hudson Bay reflect inputs from the Pacific by way of Foxe Basin, from the Atlantic, through Hudson Strait, and from fresh-water rivers that represent one of the largest drainage basins in North America. These three sources, plus the addition of significant inputs of fresh water from the melting of ice, give Hudson Bay a unique marine character.

Project 3.4 –Mercury Assessment of the Hudson Bay Marine Ecosystem – the main objective of this project was to produce 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 on the Arctic and subArctic marine food webs often contain elevated levels of methyl mercury (MeHg), a potent neurotoxin, which accumulates in top predators by the process of bioaccumulation.

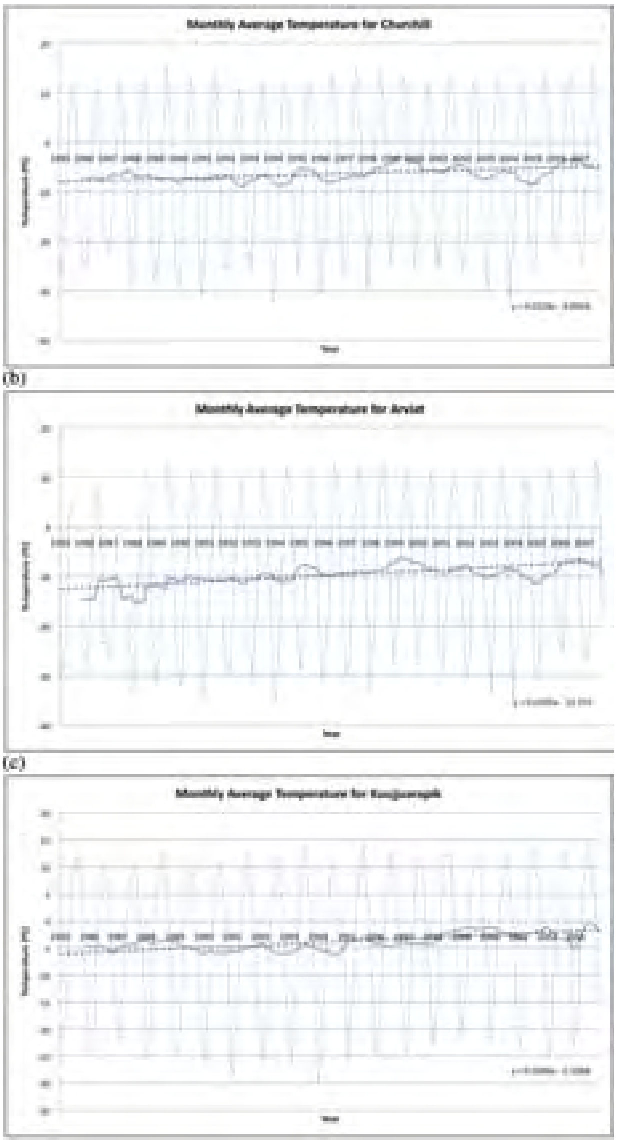

Figure 3. *Times series of monthly temperature for three Hudson Bay communities [(a) Churchill, Manitoba; (b) Arviat, Nunavut; (c) Kuujjuarapik, Quebec (Nunavik)]. A plot of moving average (t=12) and a linear trend has been overlaid. Positive trend lines indicate an overall warming trend at each of the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

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 – this project 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, 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 – research in Project 3.6 attempted to document 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 Fjord-Based Marine Ecosystems – Understanding the Effects of Climate Change and Modernization in a Northern Marine Environment – the goal of this project was to use three marine ecosystems in the fjords of Atlantic Labrador (Anaktalak Bay, Saglek Bay and Nachvak Fjord) to collect baseline data that will help address

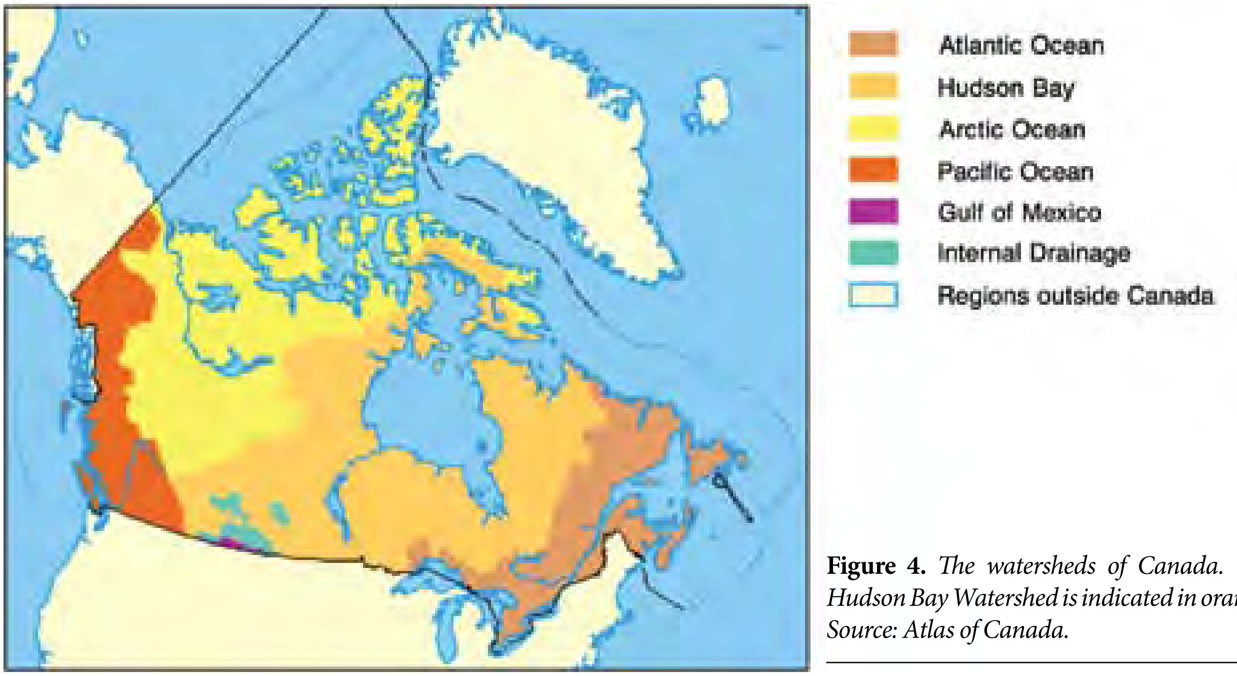

Figure 4. *The watersheds of Canada. The Hudson Bay Watershed is indicated in orange. Source: Atlas of Canada.*

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.

3.3.4 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 the 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 multi-disciplinary research effort that incorporates scientists and managers in the natural, human health, and social sciences with their partners in Inuit organizations, 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 fully a part of the Canadian geographical scene. To further the awareness of the 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 the Bay over the course of the next few of 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

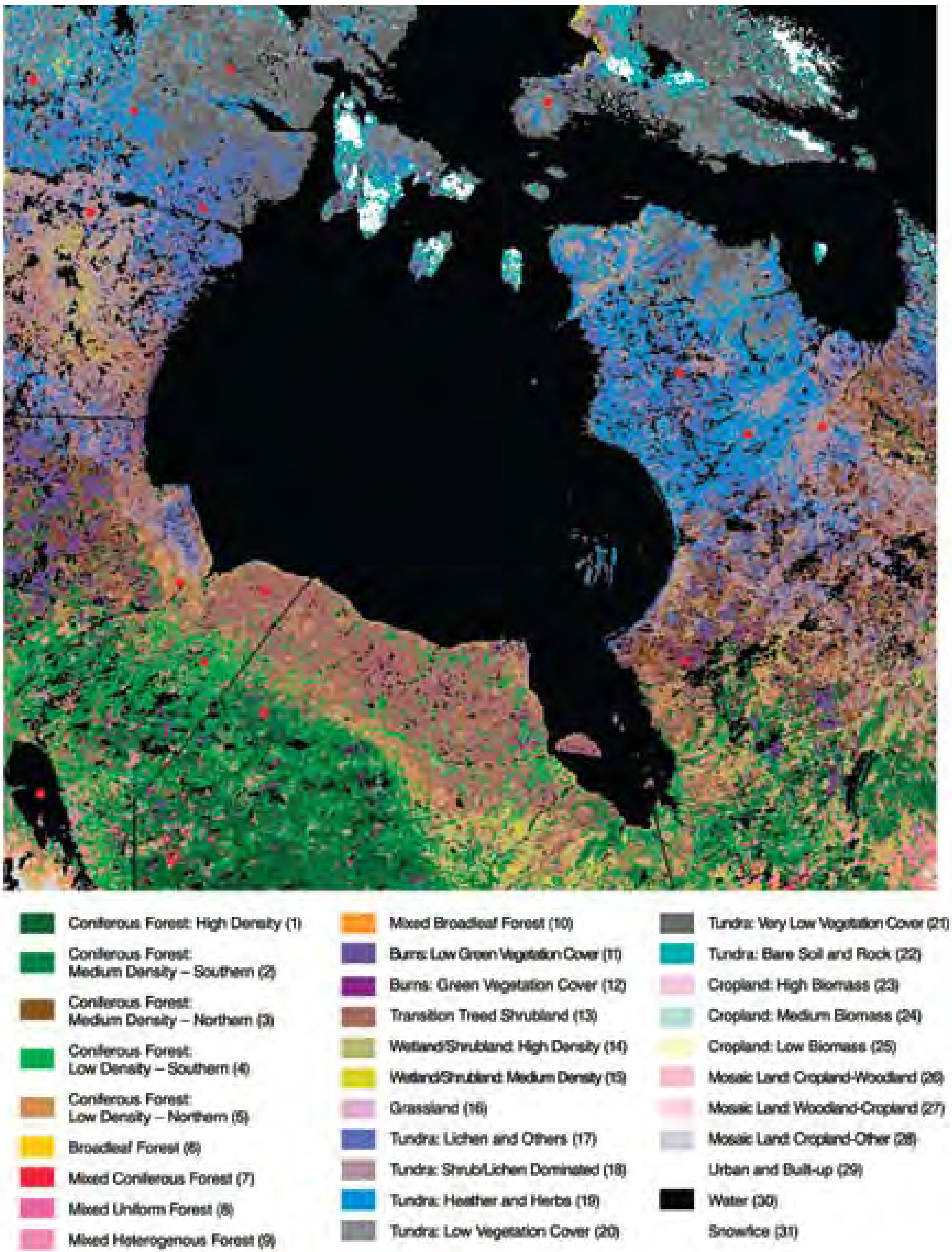

Figure 5. *Vegetation and landscape types in the Hudson Bay region. Source: Atlas of Canada.*

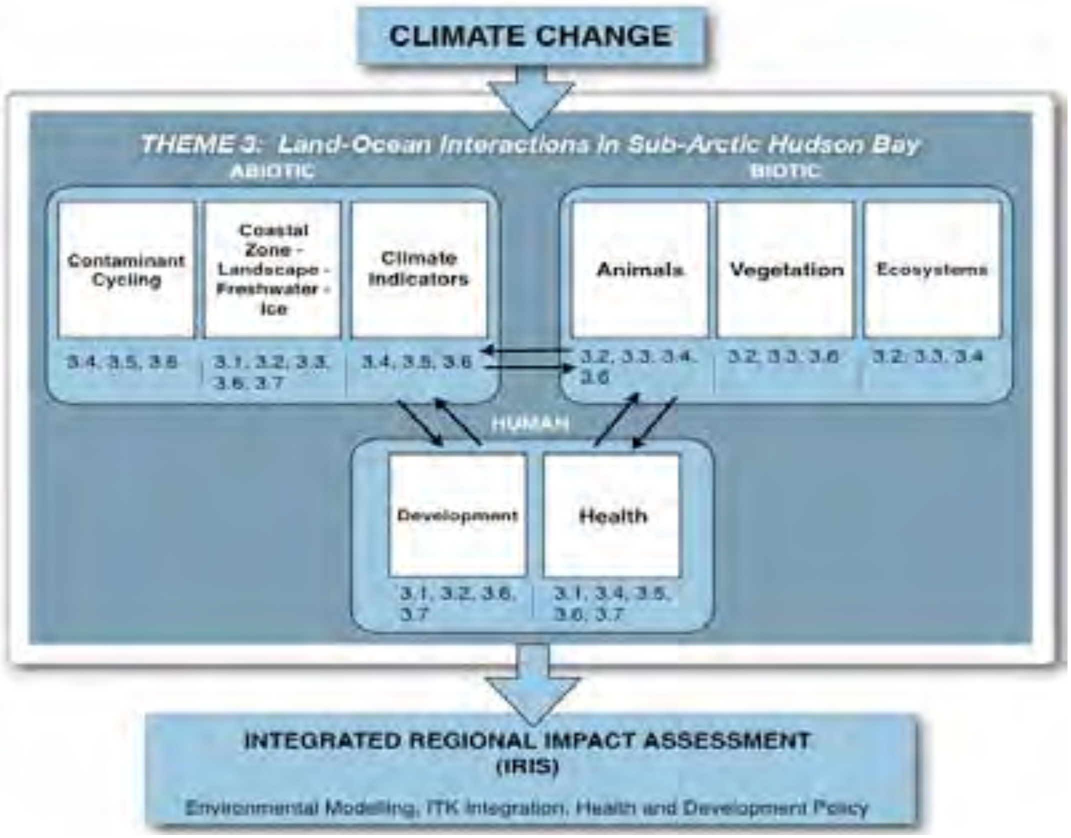

Figure 6. *Theme 3 flowchart and Integrated Regional Impact Study (IRIS) framework.*

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, and Table 1 shows linkages.

3.3.5 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 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 the Bay, the Nelson River, has been characterized in terms of turbidity and sediment flux, as well as CDOM (coloured dissolved organic matter) into the Bay. Late under-ice and early break-up processes in the estuary at the Churchill ice camp were modeled, using 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,

Table 1

THEME 3 PROJECTS	ARCTICNET PROJECT ASSOCIATIONS
Project 3.1 – Ocean-Ice-Atmosphere Coupling and Climate Variability	1.1, 1.2, 2.4, 2.8, 4.1, 4.3, 4.5
Project 3.2 – The Hudson Bay Coastal Zone in a Changing Climate System	1.2, 2.4, 3.1, 4.1, 4.2, 4.5
Project 3.3 – Climate Variability, Climate Change, and Marine Ecosystem Resources in Hudson Bay	1.4, 2.4, 2.7, 3.2, 4.1, 4.4
Project 3.4 – Mercury Assessment of the Hudson Bay Marine Ecosystem	1.3, 1.5, 2.2, 3.5, 3.6, 4.1, 4.2, 4.4
Project 3.5 – Persistent Organic Pollutants (POPs) and Human Health	1.3, 1.5, 2.2, 2.3, 3.4, 4.1, 4.2
Project 3.6 – People and Environmental Change: Linking Traditional and Scientific Knowledge	1.1, 1.2, 1.3, 2.1, 2.2, 2.3, 2.4, 3.1, 3.2, 3.3, 3.4, 3.5, 4.1, 4.2, 4.3, 4.4, 4.5
Project 3.7 – Nunatsiavut Nuluak: Baseline Inventory and Comparative Assessment of Three Northern Labrador Fjord-based Marine Ecosystems	1.2, 1.3, 1.4, 1.7, 2.2, 2.4, 2.5, 3.5, 3.6, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.6, 4.8

Table 1. *Theme 3 project linkages within the ArcticNet framework.*

aiding the breakup of the land-fast ice as spring advances. In winter, conditions in the estuary are highly variable, with the physical interaction of the river plume, overlying land-fast ice, and the rubble zone along the margin of the land-fast ice. Less-dense fresh water flowing into the estuary creates a brackish zone on the water surface, under the ice, and impounded by the rubble zone. This brackish zone is rich in nutrients, and sponsors 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 breakup of the land-fast ice. Once the rubble zone is breached, the river plume disperses quickly into the 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 greenhouse gases. 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 Lowland responds 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 the 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 the 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 the 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 the 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 the Bay and Strait. Larger mammals reflect eastern Arctic origins, with seals, beluga, 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 the 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 the 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 the 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 middle of the 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 the Bay between September and November, wintering 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 diphenyl 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 Fjord and Anaktalak Bay are relatively pristine environments, but Saglek Fjord 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, which is a trend 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 greenhouse gases 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 and 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 a 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 recent 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, energetics, 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.

3.4 Science to Policy-Makers and People (Theme 4)

Theme leader

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Theme Coordinators

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3.4.1 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 was to provide relevant information to aid decision makers in 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 was to allow for the identification and discussion of key issues, knowledge gaps and priorities related to adapting to climate changes in the coastal Canadian Arctic.

3.4.2 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 said, certain projects focused on a specific region in a given year.

3.4.3 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, to determine how they impact local communities and how these hazards will 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 government departments (e.g. Meteorological Service of Canada, DFAIT, DFO, EC, INAC) 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 breadth of 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 – this project aimed to verify climate models in order to make safe predictions of future weather and sea ice conditions by improving on 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 – this project 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 – this project 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 meteoro-logists. 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 – this project addressed the impacts of climate change on traditional food security associated with alterations in animal, fish and plant populations, and ice and snow conditions. Impact on the availability and access by Northerners 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 – this project 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 – this project 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 to Policy-Makers – this project sought to under-stand 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 affect change. The project aimed to create an open dialogue between scientists and decision makers.

Figure 1. *The Theme 4 research area.*

Project 4.8 – Strengthening Climate Cooperation, Compliance & Coherence – this project undertook 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; and in inter-national sovereignty and diplomacy.

3.4.4 Project Integration within the ArcticNet Strategic Framework

The overlapping interests and complementary 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, other 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 categorized by three subject areas, each contributing to a vision of IRIS: climate science scenarios; health science; and policy research. Each project sat within 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.

3.4.5 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 multiplicity of stressors on people and the ecosystem. During the first phase of ArcticNet, Theme 4 undertook 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 categories in 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 conducted 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 component from oceanic movements. 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 north-eastern 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 2040-2061 epoch. In the climate-forced future scenario, mid-century maximum ice concentrations were less than current minimums. 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 2041-60 period. In the interval 2081-2100, there was a further decline in ice thickness of 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, 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 2041-60.

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, if any comparisons with other studies have been possible due to this lack of information, but comparisons now have been started 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 determined that some of the greatest impacts of regional strong storms and their effect on the community scale, are linked with sustained periods of strong winds enhanced in the Arctic by topographic conditions. Persistent high wind situations are often linked with slowing down 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 normally wind speed increases from the surface to the top of the troposphere, strong surface winds at many locations, 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's strength down to small spatial scales.

Snow and Freezing Rain: It was 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, than in more southern locations. A result is that the effects of freezing precipitation persist longer in the Arctic than in the South. Freezing precipitation events may increase in the future and lead to 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 in country/traditional food (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, the Arctic char appear up river earlier, snow geese stay longer in fall, yet the closer presence of polar bears around shorelines restricts camping for long-term hunting and fishing. Collectively, the observations lead to descriptions of change in environmental conditions, and impact on traditional/country food security and nutrient intake.

The comparison of traditional food consumption levels against benchmark nutrient requirements led to 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 programmes 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 concern in particular 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 potable 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 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 assessing 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 detailed and comprehensive comparisons of challenges and advantages in the different public health systems possible.

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 examined the role of relevant climate stresses in the context of other stresses. Relevant stresses or "exposures" that affect (positively or negatively) some component of the community's livelihood, health and safety were 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 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 in place at the local and regional level, and by formal and information institutions. There is a need to "scale up" case studies for them to integrate with and inform regional policies and institutions, and to ensure 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 were 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, has 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 Integrated Regional Impact Assessments (IRISes) 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 upon 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 theories dominant 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 IRIS 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 conceive of 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 lead 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 taking place in, or otherwise 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, by environmental groups, 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 bears 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 and 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 list server 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 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 IQ 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.

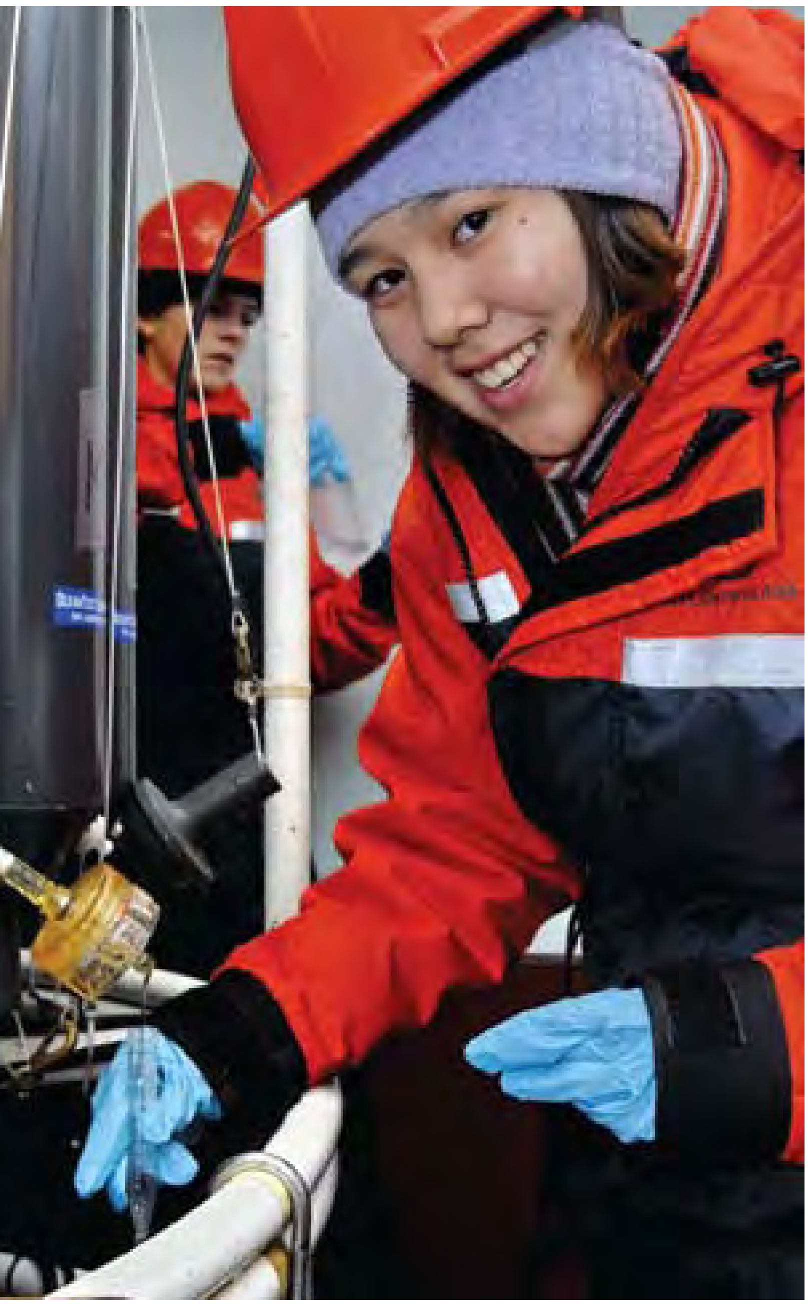
Exploration of new policy approaches to polar bear sustainable use, conservation and management in the Canadian Arctic is required. Research seeks a way forward for a management situation challenged by science-based wildlife management orthodoxy of a growing Inuit political influence and new decision-making 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 ought to 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. The justice claims that the Inuit formulate around the global problem of climate change trade on a whole constellation of claims they have with respect to an economy and society that is both impinging upon them and part of who they now are. Put in this way, 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 the fact is that climate change is perhaps the most overwhelming symptom of patterns of economic and social behaviour that have had adverse effects on Inuit and other indigenous communities for decades.

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. Should the courts and arbitration tribunals fail to recognize and take into consideration this perception, conflicts concerning land claims 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.

3.5 Legacy of ArcticNet Phase I

The ArcticNet Network of Centres of Excellence has profoundly transformed and accelerated the evolution of Canadian northern science. Phase I of this program launched a coordinated suite of new approaches that are beginning to yield long term benefits in six key areas – knowledge and communication, partnerships, training and expertise, capacity development in the North, international participation, and multi-sector integration.



Knowledge and Communication:

The quality, originality and value of ArcticNet Phase I research is reflected by the many publications in the world's best scientific book series and journals, and the new data, insights and knowledge that they disseminate (see Section IV of this volume). In addition, and because of its broad scope, diverse partnerships and multidisciplinarity, ArcticNet has achieved a legacy of research, training and knowledge transfer than extends well beyond this scientific output.

One of ArcticNet's central goals was to improve the observational database for the Canadian Arctic, and Phase I projects made substantial progress in all three research sectors. These included the creation of new marine and terrestrial observatories in the Natural Sciences, new survey approaches in the Health Sciences (notably Qanuippitaa? and Qanuippitali?, the ship-based health surveys of Inuit villages in Nunavik and Nunavut), and new analyses and observations in the Social Sciences, ranging from local vulnerability assessment to international policy analysis. This research now provides important baselines and protocols for ongoing observations, modelling and prediction, and it provides the core knowledge resources for synthesis within the Integrated Regional Impact Studies.

Communication of this knowledge was an especially noteworthy success of ArcticNet, raising the profile of the Arctic within Canada, and Canada's Arctic internationally. Over the course of Phase I, there was a significant increase in national and international media inquiries and coverage regarding research activities due to intense public interest in many of

the ArcticNet observations, such as the opening up of the Northwest Passage, the collapse of Nunavut's ancient ice shelves, the findings from the Inuit health studies, the evaluation of sovereignty issues for Canadian Archipelago waters, and the general state of the Arctic environment. The development of the ArcticNet/CCIN Polar Data Catalogue (described in Chapter 2 of this volume) will ensure the longevity of ArcticNet and other northern data sets, and it provides a powerful new online tool for information discovery, sharing and outreach.

The ArcticNet Annual Science Meeting is the largest annual Arctic research gathering held in Canada and is an important legacy of the Network. It has grown to become the premier venue for the presentation of research results from all fields of Arctic research, stimulating both networking and partnership activities. This conference brings together researchers, students, policy makers and stakeholders not only to hear the latest in northern research but also to participate in workshops addressing the challenges and opportunities brought by climate change and modernization in the Arctic. It is a unique gathering, which addresses a significant gap prior to ArcticNet that had resulted in like-minded Canadian Arctic researchers and stakeholders meeting only on an ad hoc basis, usually at discipline-specific conferences internationally and without a Canadian context.

Partnerships:

By creating a pan-Canadian network of Arctic research groups, ArcticNet Phase I catalyzed an unprecedented synergy in and about the North involving partnerships, collaboration and knowledge exchange among academic institutions, communities, all levels of government, industry and a diversity of other stakeholders. ArcticNet brought together northern stakeholders who previously had no regularised forum for communication, and the Network itself became an "Arctic agora". In particular, ArcticNet provided researchers and stakeholders, who previously had little or no opportunity for interaction with Northerners, the chance to work directly and meaningfully with northern communities. This capacity has created lasting connections and ensures that Inuit concerns and priorities become a driving force in shaping Arctic research programs and projects. A further testament to ArcticNet's partnering ability was the development of successful and substantial long-term commitments from private sector partners and government agencies. These were a direct result of ArcticNet's networking capacity, and they continue to flourish during ArcticNet's ongoing program.

Training and Expertise:

An exceptional training environment was created for the next generation of Canadian scientists. Student researchers, postdoctoral fellows and technical staff were provided with a unique opportunity for education and skill development across the Arctic sciences, and all within a new framework of interdisciplinary exchange and close liaison with Inuit communities. Literally hundreds of young researchers have been part of ArcticNet and exposed to the "network approach" to northern research, and this has had an enduring effect on their view of how to conduct science. Their contact with both northern communities and government/private sector stakeholders gave them a broad perspective and context for their research projects. Many ArcticNet students have achieved excellence in their fields of endeavour and have graduated to a variety of professions and some have gone on to become ArcticNet researchers in their own right. The success of the ArcticNet Student Association in the development of student leadership and initiative became a model to other Networks of Centres of Excellence. Notably, many students from the North were also mentored within ArcticNet-associated programs, including via the highly successful Schools on Board program.

An illustration of the excellence and long-lasting expertise that ArcticNet developed and brought together can be seen in the number of Canada Research Chairs within the Network. Additionally, the mature linkages forged through ArcticNet, both nationally and internationally, allowed full advantage to be taken of the new Canada Excellence Research Chairs program. As a result, two of these very significant Chairs will be contributing directly to ArcticNet goals and will play a substantial, long-term role in integrated Canadian northern research.

Capacity Development in the North:

Inuit communities have become enthusiastic partners in the gathering of data and in knowledge exchange. Researchers from all ArcticNet projects have developed close working relationships with northern communities and have provided diverse knowledge products for use in the North, integrating both traditional and science-based knowledge. In the science policy and management arena, the strengthening of existing educational facilities in northern institutes represents another substantial contribution that will facilitate capacity building research by local residents for Inuit and northern communities. The upgrading of existing field observatories and the development of new observatories, some also in a network context and with Inuit partnerships, represent another substantial contribution that will facilitate ongoing research and collaboration in the SubArctic and Arctic.

International Participation:

ArcticNet has both stimulated and benefited from international collaboration in the Canadian North. ArcticNet researchers were well placed to be fully involved in the International Polar Year (2007-2008), and led, co-led and participated in a number of IPY projects involving many international collaborators including Arctic Wildlife Observatories Linking Vulnerable EcoSystems (ArcticWOLVES), the Circumpolar Flaw Lead System Study (CFL), and Micro-biological and Ecological Responses to Global Environmental change in the polar regions (MERGE). ArcticNet participated as a full partner in many other international programs including the Inuit Health in Transition study, the International Tundra Experiment (ITEX), and the Nansen and Amundsen Basins Observational System (NABOS) that was co-led with the University of Alaska Fairbanks, USA, the Arctic and Antarctic Research Institute, Russia, Universität Kiel, Germany, and the Scottish Association for Marine Science, UK. These international collaborations are also allowing results from the Canadian Arctic to be placed in a broad circumpolar context.

Multi-sector Integration:

Finally, ArcticNet Phase I achieved the first step towards communication among Arctic science disciplines, via its Integrated Regional Impact Study (IRIS) strategy (described in Chapter 1). This approach encouraged linkages between natural science specialists, networks of expertise in northern health sciences, and specialists in societal issues such as cultural change and adaptation, all within a framework of respect and integration of Inuit perspectives. This new ArcticNet IRIS structure provides an exciting opportunity to collaborate with and build experience among northern residents, industry, regulatory agencies, policy-makers and managers. The results will help strengthen the resilience of Arctic communities and will enhance Canada's ability to contend with accelerating change in the North.

Part III: Projects

To illustrate in more detail the activities and results of ArcticNet Phase I, this section provides information on the projects within Theme 1 (the east-west, largely marine theme) and Theme 2 (the north-south, largely terrestrial theme). Each project is summarized with a brief abstract, key messages and objectives. These are followed by an overview of the project, its activities during Phase I, main results and discussion.

4. Theme 1 Project Compendium

Theme I was entitled "Climate change impacts in the Canadian High Arctic: a comparative study along the east-west gradient in physical and societal conditions". It was composed of seven projects, extending from the Mackenzie Shelf-Beaufort Sea region in the west, through the Northwest Passage, to the North Water Polynya and Baffin Bay in the east.

4.1 Warming Coastal Seas and Shrinking Sea Ice (Project 1.1)

Project Leaders

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4.1.1 Abstract

Project 1.1 measured and studied the fundamental relationships between sea ice, snow cover, meteorological variables, ocean properties, and the energy fluxes that tie them together. To this end, a series of five Arctic cruises were conducted from 2004 to 2008 in which a suite of surface and sub-ocean instruments were deployed and in-transit measurements collected from Baffin Bay to the Beaufort Sea, through the Northwest Passage. Long-term observatories (i.e. moorings) were also deployed in key locations in Baffin Bay and the Beaufort Sea. Project 1.1 provided baseline physical information for all the ArcticNet Network Investigators. This work, in addition to establishing fundamental scientific relationships between the components of the Arctic environment, also provided baseline climatological records for the measurement of future climate change and datasets that could be incorporated into global climate models.

The work has revealed that sea ice in the Pacific sector (Beaufort and Chuckchi Seas) of the Arctic is being lost at an alarming rate. The occurrence of the reversal of the Beaufort Sea Ice Gyre has increased over the past several decades and this change is creating a positive feedback on sea ice loss. It was also determined that the fall sea ice season begins later in this region and ends earlier. The Gyre also plays an important role in 'seeding' sea ice into the Amundsen Gulf. In the North Water Polynya (NOW) region, it was discovered that the Nares Strait ice bridge is no longer as stable as it once was, and this is actually reducing the amount of time that the NOW polynya is open. The formation and shape of the ice bridge was successfully modeled for the first time and the impacts of the ice bridge on the local km-scale circulation were determined. The seasonal properties of snow cover, deposition, and melt were characterized, and some of the relationships with algal growth were established.

It was observed that stratification, mixed layer depth and mixing regimes vary between Northern Baffin Bay, Northwest Passage, Amundsen Gulf and Southern Beaufort Sea. The most surprising result was that, outside of storms and with the exception of the first 5-10 m, wind generated mixing was not the major source of mechanical turbulence, i.e. turbulence related to the velocity shear. Results also uncovered the existence of strong (0.4-1.0 m s-1) current pulses on the Mackenzie shelf in January or early February of each year.

4.1.2 Key Messages

- A significant amount of sea ice in the Pacific sector of the Arctic is being lost. A seasonally ice-free Arctic is becoming increasingly likely in the near future, based on observed trends since 1978.
- The reversal of the Beaufort Sea Gyre has changed over the last 30 years with an increased frequency of cyclonic rotation throughout the year.
- Sea-ice dynamic processes are forced by the atmosphere through a range of scales, including surface insulation through cloud forcing, to the stratosphere.
- Sea ice in the Amundsen Gulf is beginning to form several weeks later and breaking up several weeks earlier than shown in historical climatology.
- The NOW polynya exists because of the ice bridge in Nares Strait. The stability of this bridge appears to be affected by thinner sea ice 'seeding' bridge formation from the Lincoln Sea.
- The Nares Strait ice bridge behaviour has been successfully numerically simulated for the first time.
- A new AVHRR algorithm can now distinguish between ice, water, and ice-water mixtures in northern Baffin Bay.
- Pronounced East-West gradients in stratification and mixing conditions in the Canadian High Arctic were observed.

4.1.3 Objectives

- To provide long-term detailed observations of the ocean–sea ice–atmosphere coupling in the Canadian High Arctic.
- To identify the oceanic processes underlying changes in the ocean-ice-atmosphere variables.
- To provide baseline physical information for biological, geochemical and contaminant studies (i.e. Projects 1.2, 1.3 and 1.4).
- To correlate sub-surface ocean properties recorded by moored instruments to satellite records of surface temperature, chlorophyll, suspended sediments and sea ice type, and thermodynamic state.

4.1.4 Introduction

The mandate of ArcticNet Theme 1 was to study the climate change impacts in the Canadian High Arctic by performing a comparative study along the East-West gradient in physical and societal conditions. Project 1.1 examined the ocean-sea ice-atmosphere interface. The area of Arctic sea ice has dramatically declined during the past decades, in 2007 reaching the lowest values since measurements began in 1979 (Figure 1). In the late summer of 2007, the legendary Northwest Passage was completely open to shipping, a development that earned international headlines. Unprecedented changes in our climate system have occurred in the past few decades. Computer simulations predict an "ice-free" ocean in the Arctic, at least during the summer months, in the near future (Barber and Massom 2007). These changes in sea ice have a direct impact on the life of Northern communities, and marine and terrestrial ecosystems.

Except for the Barrow Strait, very little was known about the physical oceanography of the Northwest Passage. In the early 1980's, personnel from the Department of Fisheries and Oceans (Burlington, Ontario) monitored the mixing of the Arctic Surface Water masses in Barrow Strait and estimated from year-long current meter array the transport of Arctic Surface water passing through Barrow Strait (Prinsenberg and Bennett 1987). The most recent reviews of the Northwest Passage (Ingram et al. 2006; McLaughlin et al. 2006) reported very little recent results since the early 1980's on the physical oceanography of the system. In fact, the advances came from three recent research programs: an ArcticNet collaborator from the Bedford Institute of Oceanography (DFO) monitored

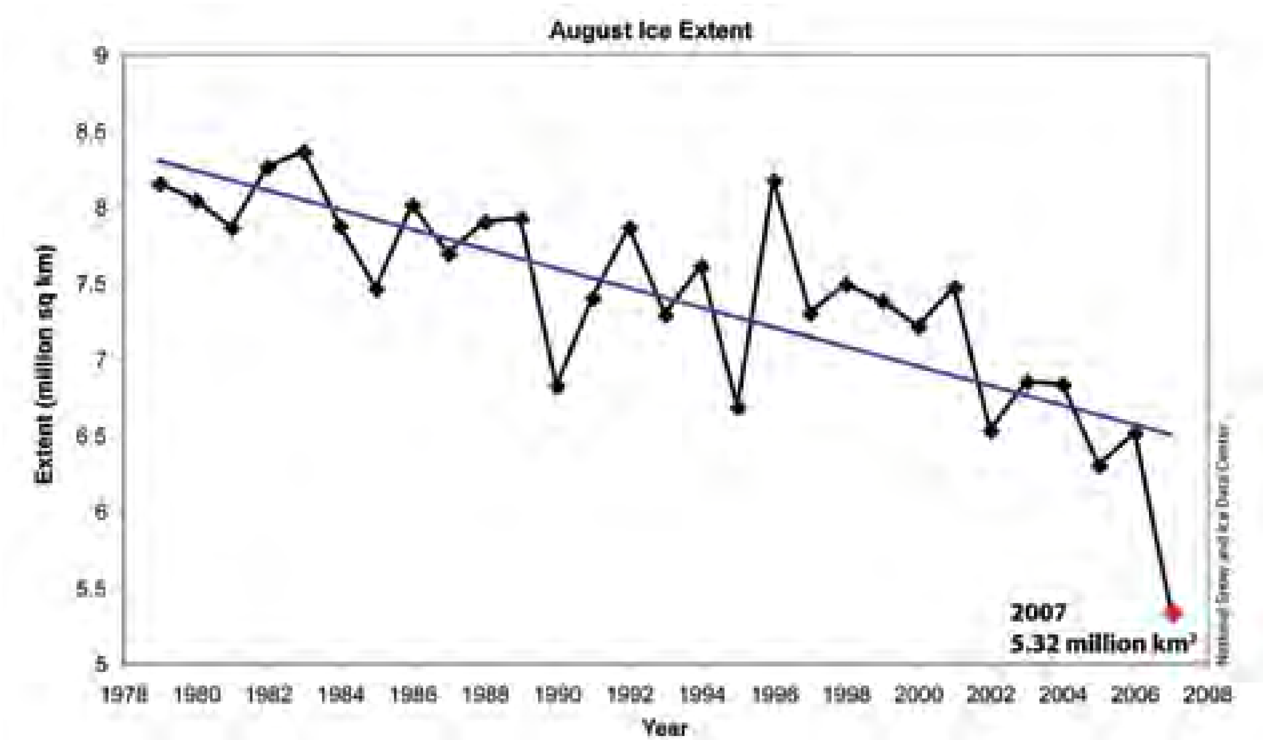

Figure 1. *Time-series of monthly average sea-ice extent from August 1979 to August 2007. The low ice extent for 2007 contrasts sharply with all previous Augusts. The August 2007 ice extent was 31% below the long-term average of 7.67 million square kilometres. Graph courtesy National Snow and Ice Data Center.*

the volume, heat, and freshwater fluxes that pass through Lancaster Sound (Prinsenberg and Hamilton, 2005); another Project 1.1 collaborator from the Institute of Ocean Sciences (DFO), monitored, with U.S. partners, the freshwater fluxes from the Arctic Ocean to the Atlantic through a set of shallows straits; the third research program was this ArcticNet project.

Project 1.1 studied how the changing climate affects Arctic sea ice in Smith Sound, the Canadian Arctic Archipelago (CAA), and the southern Beaufort Sea (SBS). In SBS, a flaw lead polynya occurs each year. Its seasonal evolution is forced by both atmospheric and oceanic processes (such as air temperature, winds, ocean currents, etc.). Dynamic processes become important when the ice is thin or weak, allowing ocean and atmospheric circulations to advect ice out of the Arctic. This combination of dynamic and thermodynamic forcing allows for increased mass and energy exchanges between atmosphere and ocean through the sea ice. Understanding these interactions were the principal research questions explored in Project 1.1 and its partnerships with other ArcticNet Theme 1 projects. Fundamental physical parameters and the associated relationships between the Arctic sea, ice, and atmospheric variables discovered during Project 1.1 and other ArcticNet themes provided critical details for global climate models and our ability to predict the future evolution of the Arctic.

4.1.5 Activities

Time frame and study area: Field work involved intense and repeated sampling over the 2004-2008 period. Scientific cruises were conducted annually throughout Theme 1 study area aboard the CCGS Amundsen. The study area spanned from Greenland to the Beaufort Sea, through the Canadian Arctic Archipelago. Instruments were also deployed under the ice and retrieved one year later.

Research: Field work was carried out and modelling simulations, historical data analysis and satellite remote sensing studies were also performed. Project 1.1 focused on coupling through the ocean-sea ice-atmosphere (OSA) interface and resulted in the following investigations:

- Studies on the role of the Beaufort Sea Gyre on the sea ice climatology of the Canadian Arctic Archipelago and the Southern Beaufort Sea.
- Investigations on the role of meteorological forcing on sea ice dynamic processes in all three study regions.
- Investigations into the role of atmospheric forcing of sea ice from the surface to the stratosphere.
- Collection and analysis of data on cloud physics and surface forcing.
- Collection and analysis of data on circulation and ice formation in the NOW polynya.
- Collection and analysis of data on circulation and water mass formation in all three study regions.
- Investigations into the connections between sea ice melt and the formation of the ocean surface mixed layer.
- The first-ever measurements of coupled geophysical and radiative transfer at the base of landfast sea ice were obtained.
- The first-ever coupled measurements of sub-ice primary production and detailed geophysics and radiative transfer through landfast ice were obtained.
- The first-ever turbulence measurements in the Canadian Arctic were obtained.
- A dynamical model of the NOW ice bridge formation was developed.
- A thermodynamic model of ice formation and ice melt in the NOW polynya was developed.

4.1.6 Results

The atmosphere is a major driver of physical and biological processes operating over and under the ocean-ice-atmosphere interface. Most of the research efforts were dedicated to atmosphere and ice studies.

The Atmosphere:

Clouds are critical in the Arctic climate system due to their control on radiative exchange with the surface. A comparison of surface-based observations with satellite and model-derived cloud fractions conducted through winter and spring showed that the average CF (the fraction of sky covered in cloud) quickly increases from around 0.4 to > 0.7 with the major shift occurring between late April and early May. By comparing CFs from the ceilometer (a skyward-looking laser profiling system), it was observed that high clouds occur more frequently between mid-January to mid-April than over other periods in the time series. This phenomenon may simply be due to high clouds not being visible from the surface when low or mid-cloud becomes more extensive. According to the small values of CF from the surface observations, cloudless or slightly cloudy skies are common during the winter to early spring period. Further details of the cloud fraction and comparison with various datasets from the CASES study region are available in Jin et al. (2006; 2007).

The Beaufort Gyre:

The motion of sea ice in the Beaufort Sea follows a circular rotation around the pole, which in the southern Beaufort Sea, is known as the Beaufort Sea Ice Gyre. It generally rotates anti-cyclonically due to the persistence of a high-pressure system over the pack ice in the northern hemisphere (i.e., atmospheric flow associated with the high-pressure pattern moves the sea ice). The Gyre has been known to reverse direction, particularly in the summer, when, on occasion, the high-pressure is replaced by low-pressure systems that settle in over the sea ice. Our recent work on the dynamics of the Beaufort Sea Ice Gyre (Lukovich and Barber 2005) showed that the relative motion of the Gyre has been changing in recent times. Ice-relative vorticity computed from week 25 (June), for 1979 – 2000, showed that sea ice motion in the Beaufort Gyre is characterized by predominantly anti-cyclonic activity throughout the year (Figure 2:

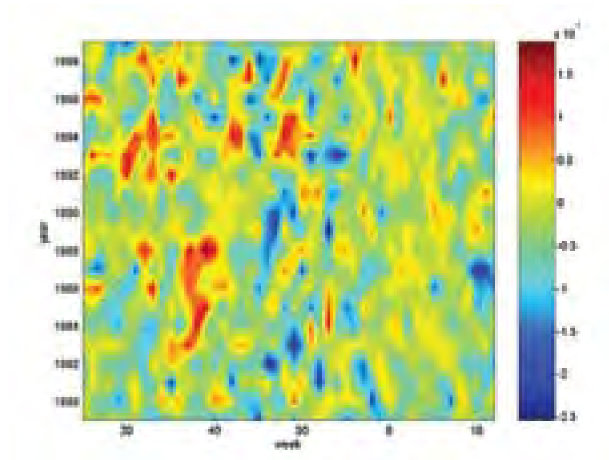

Figure 2. *Mean relative vorticity from weeks 25 to week 20 of following year (x-axis), from 1979 to 2001 (y-axis). Red (Blue) shades denote cyclonic (anticyclonic) activity. (From Lukovich and Barber 2006).*

colder colours: blue/green) with episodic reversals of the Gyre to a dominant cyclonic flow (Figure 2: warmer colours: red/yellow). Examples of the weekly sea ice motion vector and relative vorticity fields during the fall season (weeks 32 and 36 in 1983) illustrate the transition from the anti-cyclonic to the cyclonic regime in the Beaufort Sea region. (see Figure 3 in Lukovich and Barber 2007). It is interesting to note that the dominant reversal of cyclonic flow in the 1980s most often occurred in weeks 35-40 (August/September), contrasting with the 1990s with its more periodic shifts in cyclonic flow over a much wider temporal range (weeks 30-50).

Sea Ice:

Galley et al. (2008) reported on the spatial and temporal trends in sea ice types (e.g., multi-year, first-year, young, etc.) using the Canadian Ice Service digital database. Several findings of this work support the earlier work of Barber and Hanesiak (2004). One particularly interesting feature was that the timing and duration of break-up within the Amundsen Gulf is widely variable in comparison with freeze-up. The duration of break-up, open water, and freeze-up depends to some degree on the presence of old sea ice within the region (re-circulation from the Gyre back into the Gulf). Break–up within the Amundsen Gulf is dynamically forced, while freeze-up is almost exclusively thermodynamically forced; break-up occurring much earlier on average during 1980-2004 than during 1964-1974.

Young ice forms along the pack ice margin in early October and by October 15 (Figure 3) the new ice meeting the forming young ice in sheltered bays, then progressing northwards. Both dynamic and thermodynamic processes will give rise to an increase in ice volume during this period. By the end of October, high concentrations of ice are present along the Mackenzie Shelf (October 29) and by November 12, the land-fast ice has begun to grow in Franklin Bay and along the coast of Cape Parry. Over the December and January period, the fast ice regions continue to grow outwards from the coasts. These growth periods result in shear zone features where the mobile pack ice and the landfast ice meet.

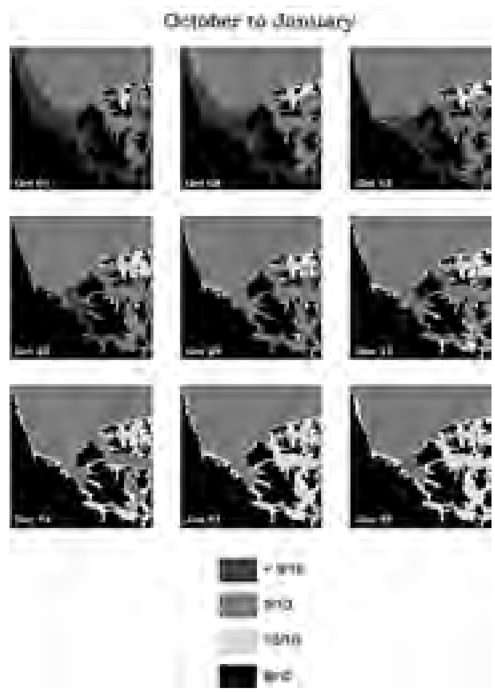

Figure 3. *Sea ice concentrations for selected weeks from the Canadian Ice Service Digital ice chart products showing the median ice concentration (expressed in tenths) for mobile and landfast sea ice during freeze-up (formation).*

In the North Water (NOW) polynya region, the results showed that the Nares Strait ice bridge is no longer as stable as it once was and this is actually reducing the amount of time that the NOW polynya is open. Vincent (2006) produced a very interesting study of the ice bridge area in Nares Strait and its impact on the local km-scale circulation. The most interesting contribution of this work is a new calibration for the NOAA AVHRR satellites for Northern Baffin Bay that can distinguish between ice, water and ice-water mixtures. Vincent (2006) also showed that ice fog often hides warm water upwelling.

A mixed layer parameterization (April 2006) was added to Hanesiak's landfast ice model (Hanesiak et al. 1999). This work suggested that dynamical and thermodynamic processes were both important for the maintenance of the North Water Polynya in Northern Baffin Bay, with the thermodynamic processes determining the onset of ice formation and melt.

Modelling work was carried out first to test the ability of a large-scale dynamical sea-ice model to simulate regional features such as the ice bridge that forms in Nares Strait each year and allows the North Water Polynya to open. Current models used in climate studies do not adequately simulate the formation of the ice bridge. Dumont et al. (2008) used a modified elastic-viscous-plastic elliptical rheology dynamic sea ice model leading to the correct simulation of the ice bridge location, form and ability to impede the drainage of sea ice from the Arctic basin (Figure 4). The improved model, applied to a high resolution domain of the North Water area, showed that the ice bridge location depends on ice thickness, wind and current conditions, suggesting that thinner ice exported from the Arctic basin would eventually prevent the ice bridge from forming. Dumont et al. (2008) focused on modelling the ice bridge with a dynamical sea ice model widely used for Arctic

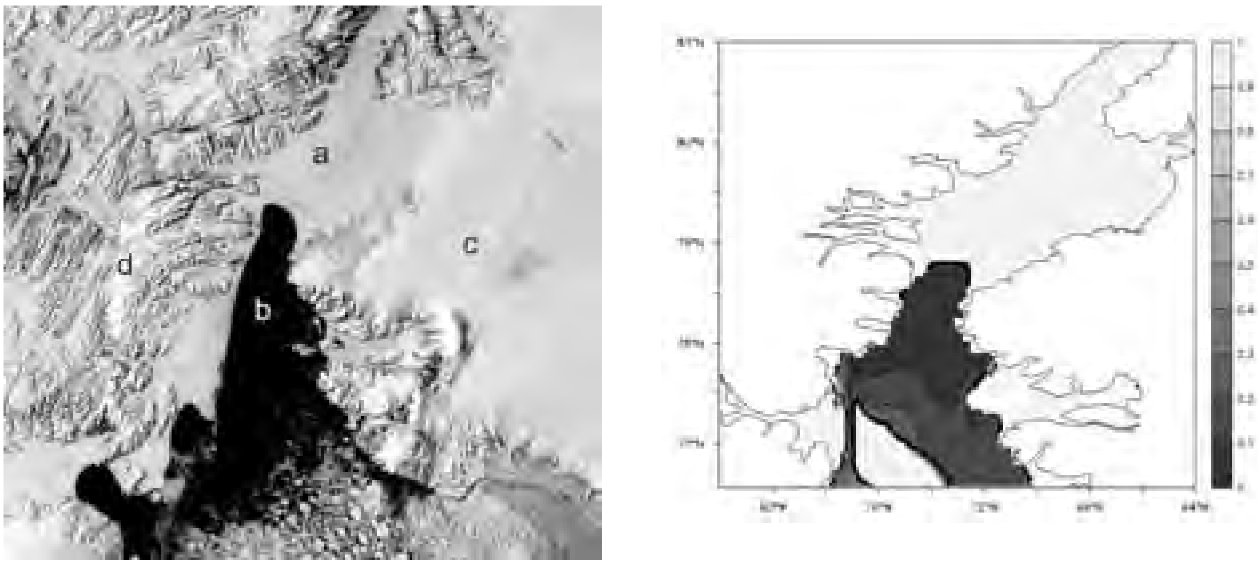

Figure 4. *Nares Strait ice bridge after 45 days of simulation with MOM4 (Modular Ocean Model). Left: MODIS image of the North Water Polynya fully opened by May 25, 2001. a: Kane Basin; b: Smith Sound; c: Greenland, d: Ellesmere Island. Right: Ice concentration simulated with MOM4 (Modular Ocean Model). The model uses a modified version of the elastic-viscous-plastic sea ice model of Hunke and Dukowicz (1997) and reproduces the location and shape of the actual ice bridge.*

climate studies (Kattsov et al. 2005; as shown in Figure 4). This work has greatly improved the capacity of the model to simulate the main dynamical characteristics of the ice bridge by changing sea ice rheology, i.e. the relation between internal stresses and strain.

Snow on Sea Ice:

Snow-covered sea ice plays a critical role in the ocean-sea ice-atmosphere interface. Due to its low thermal conductivity and high albedo, the snow-sea ice layer acts as a barrier between the ocean and atmosphere, limiting mass and energy flow between these two systems. Snow-covered sea ice is also a major controlling factor in Arctic ecosystems. During the spring period, the distribution of snow-covered sea ice controls the spatial variability of photosynthetically active radiation (PAR) reaching the underlying ocean (Welch and Bergmann 1989; Iacozza and Barber 1999; Mundy et al. 2005). PAR plays an important role in algal production and provides nutrients for copepods, an important food source for Arctic cod and other Arctic fish species. In order to enhance our knowledge of physical-biological coupling, the primary objective of Project 1.1 research in this area was to investigate the relationship between ice surface roughness and snow distribution for different classes of first-year sea ice — including smooth, rough and ridged ice — at the meter to tens of kilometres scale.

The pattern of snow distribution is controlled primarily by the ice-surface topography (Iacozza and Barber 1999; Eicken et al. 1994). In general, sea ice with large variations in surface topography (i.e. large ridges associated with rough sea ice and hummocks associated with multi-year sea ice) tends to have a large variation in snow distribution, producing a pattern that mirrors the surface topography and prevailing wind (Iacozza and Barber 1999; Sturm et al. 2002). For first-year sea ice with small topographic features (i.e. smooth first-year sea ice), the prevailing winds produce an undulating snow distribution pattern, with snow dunes forming at regular intervals, these snow dunes exhibiting small variability in depth.

After examining several statistical relationships, a statistically significant relationship was found between snow depth and the average surface roughness measured along a transect. The candidate algorithm is defined as:

$$x_{(SD)} = 59.6 + 19.7 * \ln(x_{(SR)})$$

where $x_{(SD)}$ is the mean snow depth and $\ln(x_{(SR)})$ is the log of the mean surface roughness. This relationship explained nearly 80% of the variability in average snow depth for the sites tested.

Micro-scale properties of sea ice and snow:

To fully understand the thermodynamic processes of sea ice, it is important to investigate the micro-scale structure of sea ice and its snow cover. In a study of landfast first-year sea ice, it was found that the bottom layers typically consisted of columnar ice with the bottom-most 0.01-0.02 m having a porous skeletal structure. Visible coloration was apparent towards the bottom of the skeletal layer due to the presence of ice algae. Analysis of ice core sections taken in early May revealed that the sea ice near the ice-water interface was composed of jagged crystals with a distinct platelet substructure. The combination of crystal size and circularity, platelet width and brine volume gives a measure of border surface area between interstitial brine and ice and could potentially be used to quantify scattering properties of sea ice. The mean crystal size decreased with distance from the ice-water interface, with the exception of the bottom-most 0.05 m layer. Within this newly formed layer, smaller grains developed with a lesser degree of horizontal C-axis alignment. The mean (and maximum) horizontal cross-sectional crystal areas observed from the ice–water interface upwards to 0.39 m (Figure 5) were 18 mm^2 (155 mm^2), 60 mm^2 (480 mm^2), 32 mm^2 (350 mm^2), 24 mm^2 (670 mm^2) and 20 mm^2 (490 mm^2), respectively.

Ice temperatures, salinities, density, and the partial fractions of brine ice and air are presented in Figure 5 from Ehn et al. (2008). This paper provided summary statistics on the microstructure of sea ice in the spring period. Other work by these authors provided the same information for ice formation during the fall period (Ehn et al. 2007).

Snow on sea ice is also a critical issue that requires measurement at the micro-scale. One of the most complete datasets on snow metamorphism (change in grain size and shape due to temperature variations within the snow), on characterizing the fall-to-winter vertical profile evolution of thin and thick snow pack physical properties, and on associated meteorological forcing over landfast first-year sea ice was collected. From these data, results showed that snow physical and thermal properties evolve according to whether the system was categorized as being in 'cooling' or 'warming' periods. During the cooling period, only very small changes in the geophysical characteristics of the snow-pack except for salinity were observed and these decreased throughout the period. This snow desalination was stronger at the bottom of thin snow packs: a rate of –0.12 ppt×day^{-1} with an R^2 of 0.52. Net shortwave and longwave radiation did not appear to have a significant influence on

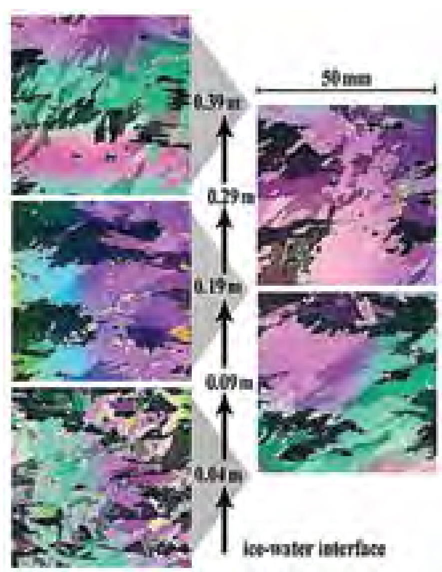

Figure 5. *One mm-thick thin sections showing the columnar ice structure immediately above the ice-water interface when the ice thickness was 1.87 m.*

either thin or thick snow covers with high variability in L↑ and L↓ and low values for K↑ and K↓. Warming periods initiated significant changes in the morphology of the snow grains for both thin and thick snow packs (see Figure 5 in Langlois et al. 2006). The rate of growth was stronger for thick snow-packs (0.25 and 0.48 mm day^{-1} for thin and thick snow respectively) where $\delta T/\delta_L$ and $\delta e_{si}/\delta_L$ were larger (i.e. stronger vapour flow) and Q* values near 0. The vapour flow acted as the main vehicle for brine volume to move upward in the snow pack and this mass movement created significant changes in snow grain morphology (see Figures 6 and 7 in Langlois et al. 2006), affecting snow density and therefore snow thermal properties. Hence, it is necessary to distinguish between thin and thick snow when analyzing snow physical variability as winter progresses.

Radiative Transfer:

Irradiance spectra measured at increments within the bottom layers of landfast sea ice in Franklin Bay during early spring allowed the estimation of the "Inherent Optical Properties" (IOPs) of sea ice using the DISORT radiative transfer code (Ehn et al. 2008). The inverse modelling approach adopted by this group appears to be its first use in a sea ice environment. In the model, the scattering coefficient, b, was assumed to be wavelength-independent for visible wavelengths, while any wavelength dependence was accounted for by the absorption coefficient atot (λ). The calculated IOPs can be described in terms of observed physical properties (temperature, salinity, and density) and biological properties (algal spectral absorption) of the 1.8 m thick first-year sea ice cover. These physical properties are typical of sea ice close to the ice-water interface.

Ice-core sampling and irradiance measurements revealed very low concentrations of ice algae above the bottom 0.05 m of the sea ice. For the bottom layer, chlorophyll a concentrations ranged from 16.6 to 242 mg m^{-3}. They were more than an order of magnitude less in overlying layers. This bottom algal layer has a marked effect on the spectral distribution and magnitude of transmitted irradiance beneath the ice. Particulate absorption spectra, $a_p(\lambda)$, from melted ice samples showed that the chloroplastic pigments may have been degraded in the period between sampling and measurement; the spectral shape of $K_d(\lambda)$ could not be explained by the measured $a_p(\lambda)$ for the bottom-most ice algae layer. Interior ice layers did show similar spectral shapes in absorption to measurements made from melted samples, providing evidence of pigment degradation within these layers. Iterations of DISORT to match the in situ $K_d(\lambda)$ resulted in reasonably shaped estimates of $a_p(\lambda)$. Based on the spectral shape of the modeled $a_p(\lambda)$, it was suggested that the ice algae within the bottom-most layer were healthy, while pigment degradation increasingly modified the spectral absorption with distance from the ice-water interface. Further details of this work are available in Ehn et al. (2008) and Ehn et al. (2007).

Energy Fluxes:

The nature and properties of the evolving surface and atmosphere dynamics are strong determinates of energy and mass exchange over sea ice. These relationships underlay strong climate feedback processes in the Arctic, such as the ice-albedo feedback effect, and exert considerable influence on climate over a wide range of spatial scales (IPCC 2001). Because of these linkages, the Arctic is an important and sensitive component in the climate system. In particular, results found that the surface energy balance strongly influences the annual cycle of sea ice throughout the study region but that dynamic forcing of the sea ice is equally as important as thermodynamic forcing (Lukovich and Barber 2006). Low-pressure systems have an impact on the geophysics of the snow-sea ice system and leave an 'imprint' on the snow metamorphism (Langlois et al. 2008). Cyclones remain an important variable for study as preliminary research suggests that cyclone frequency is increasing in the Pacific sector of the Arctic and may be changing in the Baffin Bay region and NOW polynya. Cyclones appear to play a role in coupling across the ocean-sea ice-atmosphere interface through their control on mass and energy fluxes.

The surface energy balance changes throughout the annual cycle, with long-wave radiation exchange dominating the net radiation to the surface over the fall and winter period. The average hourly net long-wave loss was typically 41 W m^{-2}, with peak values exceeding 95 W m^{-2}. In contrast, hourly net solar radiation to the surface averaged 21 W m^{-2}, peaking at 258 W m^{-2}. Monthly median albedo fluctuates around 0.83, although the range varied widely among the months. The evolution of the heat budget shows characteristics typical of the winter to spring transition: winter and early spring (January to March) radiative losses at the snow surface are largely offset by conductive gains to the snow layer from the underlying sea ice and ocean with solar radiation exerting increasingly strong influence on net radiation during April and May. The snow flips from a state of net energy loss to gain in early spring (April). The atmospheric latent heat flux was ineffective at removing/supplying heat. On average, 50% of the energy lost through net radiation was offset by conductive heat and sensible heat input to the snow prior to the end of April, while surplus net radiation approximately equalled heat gain by the snow thereafter.

The temperature structure of the snow and sea ice (Figure 6) showed a strong response to changing boundary heating, particularly in January and February, and after mid-March (beyond day 75). Cloud cover and the increasing atmospheric heat content associated with migrating low-pressure systems affects surface heat loss largely by increasing down-directed long-wave radiation, although on occasion significant sensible heat transfer to the surface is observed. During these periods when lows are present, noticeable increases in substrate temperature occur, as less of the conductive heat input from below is lost to the atmosphere. Volume heating promotes short-term variation in snow morphological, optical, and electrical properties (e.g., Hanesiak et al. 1999; Hwang et al. 2007; Langlois et al. 2008). A rapid and prolonged rise in net solar radiation usually follows a sensible heating event. Events such as these effectively promote the rapid onset of snow melt (Barber and Thomas 1998). The timing and frequency of low-pressure systems in the springtime is therefore critically important in determining the timing of in-situ spring melt and break-up.

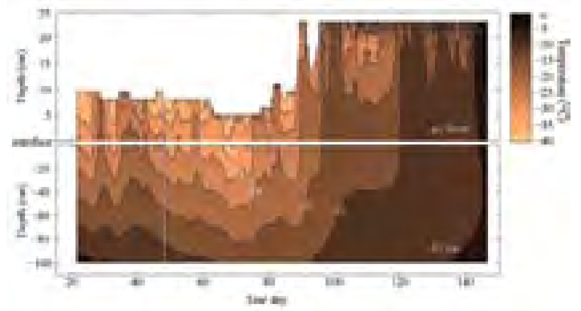

Figure 6. *Evolution of the snow (a) and ice (b) temperature structure.*

Water Masses, Mixed Layer, Mixing Processes and Biology:

Tables 1 and 2 summarize the ship-based CTD (conductivity, temperature and depth) and mooring operations, respectively. The CTD-rosette is the workhorse of all chemical, biological and physical oceanography sampling (see Tremblay et al. 2006 and 2008, for example). The CTD produces continuous profiles (1 m resolution, after processing) of pressure (depth), temperature, conductivity (salinity), photosynthetically available radiation (PAR), pH, dissolved oxygen, turbidity, fluorescence and nitrates. (see Table 1 and their locations in Figures 7 and 8). The 2004-2008 datasets were rapidly made available to the ArcticNet community.

The project also studied the East-West gradient in physical properties and examined the differences in stratification, mixed layer depth and mixing regimes between Northern Baffin Bay, Northwest Passage, Amundsen Gulf and Southern

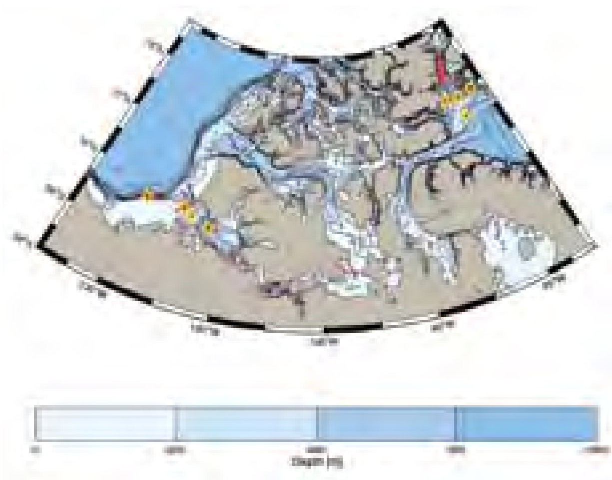

Figure 7. *Location of the CTD-rosette casts in 2005 (red dots). Also shown is the location of the moorings (yellow diamonds).*

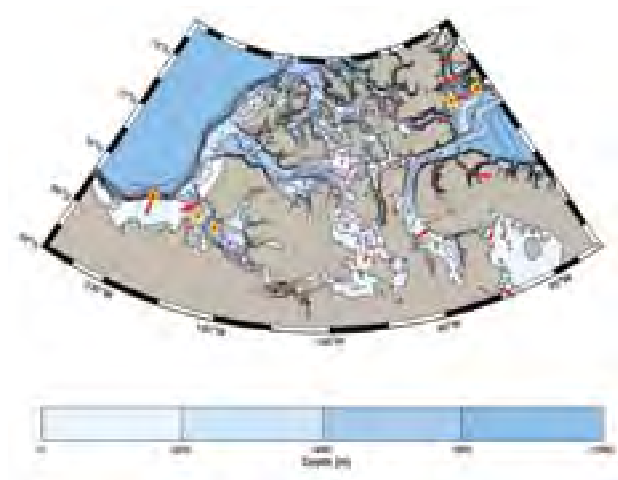

Figure 8. *Location of the CTD-rosette casts in 2006 (red dots). Also shown is the location of the moorings (yellow diamonds).*

Beaufort Sea (Sévigny, in preparation). The most surprising result was that, outside of storms and with the exception of the first 5-10 m, wind generated mixing is not the major source of mechanical turbulence, i.e. turbulence related to the velocity shear. Each region seems to be characterized by different mixing regimes. An example from central Amundsen Gulf is shown in panel (a) of Figure 9. The mixing below the thermocline is characterized by mechanical turbulence while mixing in the surface layer is characterized by double diffusion (DD), i.e. the difference in mixing rates between salt and temperature. Interestingly, the fluorescence maximum is located exactly between the two regions. This suggests that the mixing regime has a major impact on the localisation of the fluorescence and nutrients maxima. It has also been shown (Lovejoy et al. 2002) that DD processes can have a major impact on the distribution of protist communities and bacteria.

Pulses and Hot Spots:

Analysis of the 2004-2006 current meter data from the Mackenzie shelf (Figure 10) uncovered the existence of strong (0.4-1.0 m s^{-1}) current pulses in January or early February of each year. This strong current was observed simultaneously at each mooring shown on Figure 10 (yellow dots) and lasted on the order of five days. The strength of the pulses and the date of occurrence vary from year to year. Their origin is still unclear. Mooring data also shows that the Cape Bathurst area is prone to frequent wind and tidally-driven upwelling events making it a regional 'hot spot'.

4.1.7 Discussion and Conclusions

The observed reduction in sea ice minimum extent is one of the key pieces of evidence in the assessment of global warming on Arctic climate variability and change. Changes in oceanic and atmospheric forcing of the annual cycle disrupt the annual cycle of sea ice. Because of the close connection between snow and sea ice, the corresponding changes in snow distribution are significant, and these physical changes also affect most elements of the marine ecosystem.

The current projects (from both observations and modelling perspectives) predict a seasonally ice-free Arctic around 2050 (±20 yrs). A seasonally ice-free Arctic on our planet has not been observed for at least 1.1 million years (Barber et al. 2005). Organisms will have to adapt to changes in timing, presence,

LEG NUMBER	DATE		NUMBER OF CASTS	NUMBER OF STATIONS	NUMBER OF SCAMP PROFILES
	STARTS	ENDS			
0406	5 August 2004	26 August	24	8	0
0501	5 August 2005	15 September	137	80	44
0502	26 July 2007	27 October	126	90	40
0602	18 August 2006	26 September	115	61	29
0603	26 September 2006	9 November	138	99	52
0705	26 July 2007	14 September	40	31	0
TOTAL			580	369	165

Table 1. *Ship-based sampling between August 2004 and September 2007. A cast is the process of lowering the CTD-rosette in the water. There may be more than one cast at each station. The SCAMP (Self Contained Autonomous Micro Profiler) is a high resolution (1 mm) CTD-profiler deployed from the ship's zodiac. All the 2004, 2005 and 2006 CTD data have already been distributed to the Network Investigators.*

YEAR	MOORINGS (INSTRUMENTS)	DEPLOYMENT MONTH	LOCATION	AVAILABLE TIME SERIES
2004	7 (24)	August	Beaufort Sea	21
2005	4 (16)	September	Beaufort Sea	4
	4 (13)	August	Baffin Bay	7
	4 (18)	September	Hudson Bay	16
2006	3 (14)	September	Beaufort Sea	N.A.
	2 (8)	October	Baffin Bay	N.A.
	3 (8)	September	Hudson Bay	N.A
2007	4 (10)	August	Hudson Bay	N.A.

Table 2. *Long-term ArcticNet observatories (moorings) and data availability. "Raw data available" means that the instruments were recovered and raw data could be extracted. "N.A." means that no information is available at this time.*

and geophysical conditions of sea ice in a time span that is unprecedented in recent geological history. In the Beaufort region, there is also a key link between the sea ice in Amundsen Gulf and the Beaufort Sea Gyre (Galley et al. 2008). The observed reversals of the Gyre may be a key element in the observed reductions in the central Arctic ice-pack (Lukovich and Barber 2006).

Of particular relevance to the marine ecosystem are the concurrent changes in the snow-cover on this sea ice (Langlois et al. 2006; Iacozza et al. 2007). This is due to the control that snow plays on radiative transmission to the base of the sea ice (Ehn et al. 2008) and its insulative control of the thermodynamic growth of the sea ice. Recent work by our team and others has shown that sea ice micro-algae prefer certain habitats at the base of first-year sea ice (Mundy et al. 2007). The micro-scale attraction of these habitats is related to the presence of brine drainage holes at the base of the sea ice, which in turn are controlled by snow and sea ice thermodynamics.

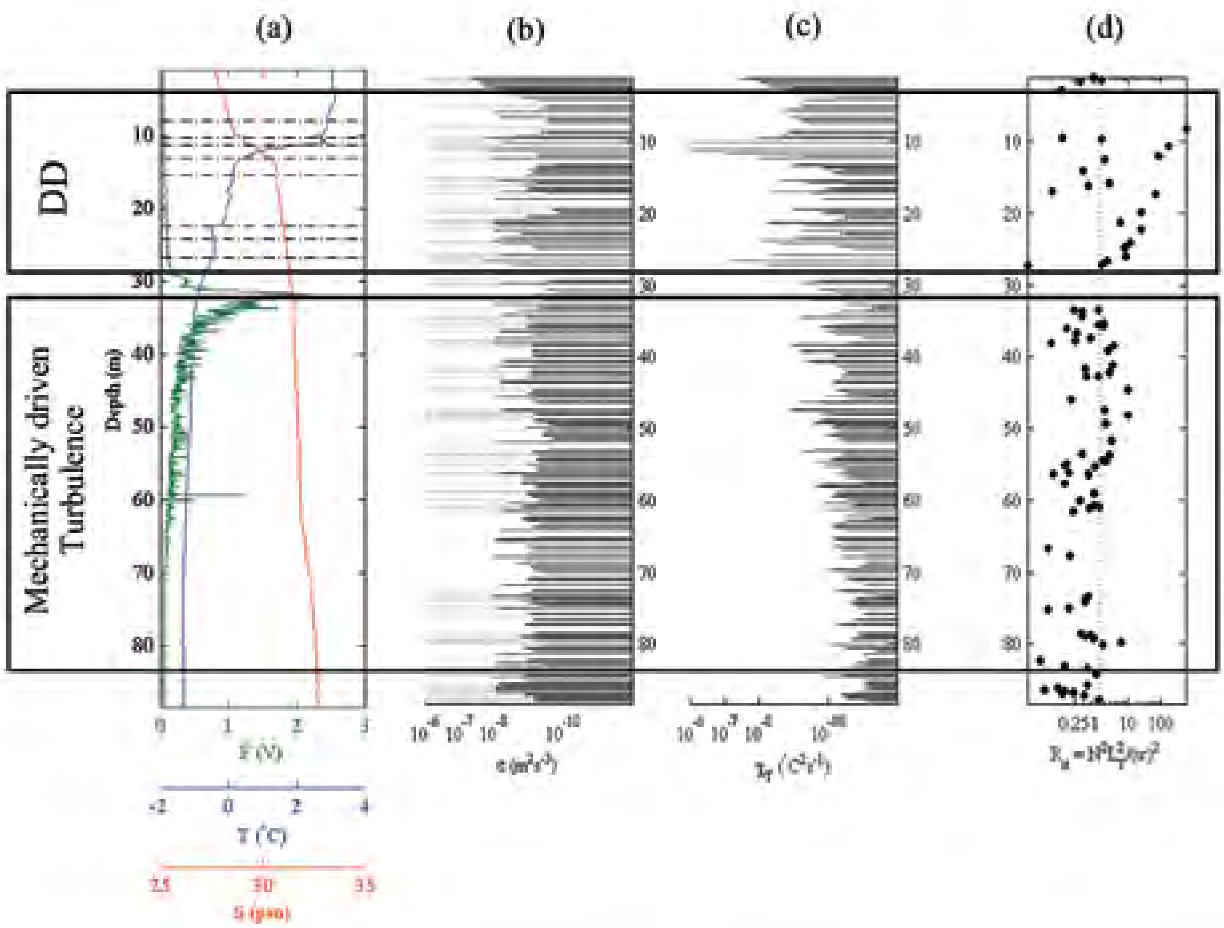

Figure 9. *SCAMP (Self Contained Autonomous Micro Profiler) profile from the middle of the* Amundsen *Gulf. Panel (a) presents the temperature (blue), density (red), fluorescence (green) and PAR (gray) vertical profiles. Of interest is the fact that the fluorescence maximum is located between two different turbulence regimes: double diffusion (DD) and mechanical turbulence. The other panels are (b) the kinetic energy dissipation rate; (c) the thermal variance; and (d) the turbulent Richardson number.*

Higher on the trophic ladder, changes to sub-ice grazers (e.g., copepods) and associated predator-prey relationships through the food chain up to the Arctic cod can be expected. It is known that Arctic cod use the under-ice roughness as a means of avoiding predation. The dynamic processes of ice formation are in a state of flux and the consequences of this to the Arctic cod remain unknown.

The existence of pulses on the Mackenzie shelf has been revealed and this confirmed the status of "hot spots" for the Cape Bathurst and Lancaster Sound mouth areas. Also, results underscored East-West differences not only in the classical physical oceanography indicators, stratification and mixed layer thickness, but also in the nature of the mixing processes in each region. With this information, present research is in a position to study the influence of the ice bridge on the circulation in northern Baffin and to assess the impact of its disappearance. The impact of the Amundsen Gulf ice bridge on the local circulation will also be examined.

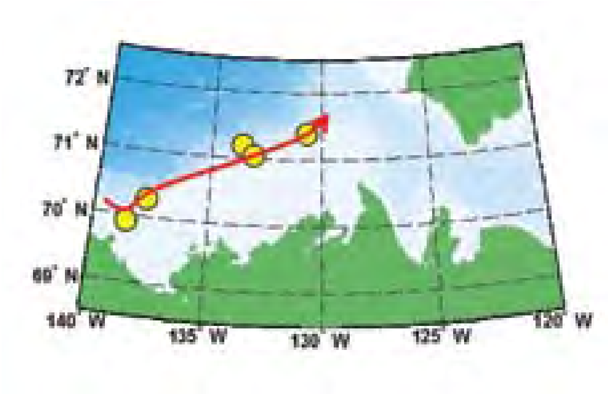

Figure 10. *Locations where January pulses were observed on the Mackenzie Shelf in 2004. The yellow dots represent the mooring locations while the red arrow traces the pulse trajectory. Pulses were also observed in 2005 and 2006*

4.1.8 Acknowledgements

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4.2 Coastal Vulnerability in a Warming Arctic (Project 1.2)

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4.2.1 Abstract

Coastal change in the Arctic has been ongoing for thousands of years and human adaptation has been a constant imperative for Inuit occupying this region. Sea-level rise in the western Arctic is believed to be comparable to the global mean (+1.8 mm/a 1950-2000) and may have accelerated over the past century. Rates of subsidence in the western Arctic and along the eastern fringe of Baffin Island enhance rates of relative sea-level rise (+3.5 mm/a 1961-2006 at Tuktoyaktuk). Co-located continuous GPS and tide-gauge stations were established over five years in the eastern Arctic, but the lengths of records were too short to derive meaningful estimates of relative sea-level rise in this region. Increased coastal instability is a concern in many areas, from the Yukon coast to Foxe Basin. Accelerated coastal erosion has been documented on the Yukon coast and in northern Alaska but not in the Mackenzie Delta region. Contributing factors include higher temperatures and thaw subsidence in ice-rich terrain; rising relative sea level; and diminished sea-ice cover, resulting in higher wave energy and more damaging storms. A key goal of the project was to build understanding of climate-change impacts in Arctic coastal communities and to strengthen the adaptive capacity of communities to cope with climate change. The work contributed to IRIS objectives in the eastern and western Arctic. Progress was made toward integrating science into the decision-making process in several regions (Inuvialuit Settlement Region in NWT, Kitikmeot and Baffin regions in Nunavut) and communities (Sachs Harbour, Tuktoyaktuk, Gjoa Haven, Arctic Bay, Igloolik, Hall Beach, Clyde River). Research partnerships with the communities of Hall Beach, Clyde River and Iqaluit were initiated as pilot projects under the Government of Nunavut Climate Change Adaptation Plan.

4.2.2 Key Messages

Rates of land uplift in parts of the central Arctic may be overtaken by expected rates of faster sea-level rise in the coming century. Higher mean sea levels at the coast may lead to increased erosion and more frequent storm-surge flooding.

Coastal sensitivity to climate change, including higher temperatures, rising sea level, more open water and resulting higher wave impacts, may be contributing to more rapid coastal erosion. Coastal instability threatens archaeological and other cultural heritage sites in the Inuvialuit Settlement Region and community land and infrastructure in Tuktoyaktuk NWT, Hall Beach NU, and other Arctic communities.

In partnership with several Arctic communities (Sachs Harbour, Tuktoyaktuk, Gjoa Haven, Arctic Bay, Igloolik, Hall Beach, Clyde River) and parks (Aulavik, Ivvavik and Sirmilik National Parks and Qikiqtaruk Territorial Park [Herschel Island]), the team worked toward the integration of science and local knowledge into decision-making and climate-change adaptation planning. This was to help to build capacity and experience among northern residents and territorial policy-makers in approaches that contributed to enhanced resilience in Arctic communities.

4.2.3 Objectives

The project objectives included improved understanding and predictive capacity related to the following issues on an East-West transect across the Canadian Arctic:

- Sea-level change and vertical crustal motion as a basis for projections of erosion and flooding hazards under climate change;
- Coastal sensitivity and response to changes in forcing related to climate variability and change in a warming Arctic;
- Vulnerability of communities and habitats and methods for increasing adaptive capacity and resilience.

Figure 1. *Twin Otter on the beach at Herschel Island, Yukon. Soft sandy storm deposits on the beach caused problems for aircraft landing in summer 2007. Note driftwood scattered near the strip and multi-cyclic retrogressive thaw-flow failures on the ice-rich slope in background. Photo: N. Couture, McGill University, 2007.*

4.2.4 Introduction

Coastal change in the Arctic has been ongoing for thousands of years and human adaptation has been a constant imperative for Inuit occupying this region. The extent of the changes can be seen in prominent raised shorelines and archaeological evidence of former coastal occupation sites landward of the present coast. In marginal areas of the eastern and western Canadian Arctic, former shorelines are submerged below present sea level, coastal retreat is the dominant form of change, and cultural and archaeological resources, as well as community infrastructure, are sometimes at risk of damage or loss (Manson et al. 2005).

ArcticNet Theme 1 addressed issues across an East-West Arctic transect. Project 1.2 extended those issues from the western submergent coastal region of the Beaufort Sea and Amundsen Gulf, through the central Canadian Arctic Archipelago dominated by ongoing postglacial uplift, to the eastern submergent margin in Baffin and Labrador (Forbes et al. 2004). Working along this transect, based primarily from shore and in part aboard the *CCGS Amundsen*, investigated coastal sites were integrated in various geological and ecological settings across a spectrum of rising or falling relative sea levels and wide variations in sea ice, open-water fetch, storm climatology, and wave regime. The work focused, in particular, on coastal communities. Inuit are a coastal people and much of the traditional harvest on which Arctic communities depend is derived from the coast and sea. Coastal habitat is important for many harvest species, including fish, birds, and marine mammals, but knowledge of critical habitat and its sensitivity to climate change in the Arctic is limited. Work in this project addressed coastal habitat and other issues, including hazards to infrastructure that affect the sustaina-bility of northern communities (Ford and Smit 2004).

Coastal change in the Arctic, involving shoreline retreat (through submergence or erosion) or advance (through emergence or progradation), is characterized by distinctive erosion processes sensitive to climate warming (Forbes 2005; Lantuit and Pollard 2005, 2007; Lantuit et al. 2008; Taylor and Atkinson 2008). Sea-level rise and coastal change can affect permafrost and coastal habitats, with erosion and flooding impacts on coastal communities and infrastructure (Figure 1). Coastal change processes are regulated by climate factors such as duration and extent of sea ice, the dynamics of shorefast ice, tides, storm waves and storm surges, and ground surface temperatures. Equally important factors include lithology, ground-ice content, coastal morphodynamics, sediment supply, and sea-level trends. Changes in relative sea level (RSL), as observed at the shoreline, incorporate two components: (i) changes in sea-level; and (ii) changes in land-level (uplift or subsidence). RSL is falling in much of the central Arctic because the rate of residual postglacial isostatic uplift exceeds the rate of regional sea-level rise (Henton et al. 2006). RSL is rising in the Eastern and Western Arctic margins because the crust is nearly stable or subsiding. As climate change leads to accelerated global sea-level rise over coming decades, some areas and communities where RSL has been stable or dropping may begin to see rising sea-level, with serious implications for coastal stability, infrastructure, and coastal habitats. Furthermore, some non-resistant coasts presently in areas of near-permanent sea ice cover may experience unprecedented destabilization through a combination of rising RSL and more open water with waves. Effective planning and adaptation to climate change in coastal communities requires significantly improved understanding and capacity to predict future impacts under various climate change scenarios (Catto and Parewick 2007).

4.2.5 Activities

Study sites and activities: Over the 2004-2007 period, Project 1.2 researchers accomplished numerous research activities.

- Acquired continuous GPS (CGPS) data to measure vertical motion (uplift or subsidence) at 8 sites in NWT, Nunavut, and Labrador (Inuvik, Tuktoyaktuk, Sachs Harbour, Ulukhaktok, Resolute, Alert, Qikiqtarjuaq, Nain). Complementary episodic GPS data were obtained on the Mackenzie Delta and northern Banks Island and in Kugluktuk and Iqaluit.
- Acquired water level data at tide gauges co-located with the CGPS in Tuktoyaktuk, Ulukhaktok, Alert, Qikiqtarjuaq, and Nain.
- Monitored breakup processes and spring flooding across the outer Mackenzie Delta in 2005-2007.
- Acquired LiDAR data to develop high-resolution digital elevation models and flood hazard assessments under climate change for parts of the Mackenzie Delta, the communities of Aklavik and Tuktoyaktuk, NWT, and the seasonal community of Shingle Point, Yukon.
- Undertook studies over several years to investigate coastal permafrost, ground ice, organic carbon, and erosion processes in unlithified ice-rich deposits of the Yukon coast. Detailed geophysical surveys using ground penetrating radar and capacitive coupled resistivity were carried out to determine ground ice distribution. Annual shoreline surveys were conducted along the Yukon coast.

Figure 2. *Erosion undermining houses and sheds along the waterfront at Hall Beach, NU, looking South. Erosion is occurring downdrift of a northward migrating gravel foreland in the background. Note collapsed seawall in middle distance. Local residents report significant reduction in sea ice and much later fall freeze-up, leaving more open water during the fall storm season. This may be contributing to increased erosion, despite a falling relative sea-level trend in Foxe Basin. Photo: D.L. Forbes, Geological Survey of Canada, 17 August 2007.*

- Undertook studies of coastal geomorphology and sedimentology, including coastal profile surveys and mapping, to assess the degree of ongoing geomorphic change and consequent risks and hazards to infrastructure in Sachs Harbour and Gjoa Haven. In 2006, coastal survey sites first established in 2003 on northern Banks Island (including Aulavik National Park), the first ever along this coast, were resurveyed to document the extent of change over the intervening 3 years.
- Investigated shore-zone sensitivity to potential petroleum contamination in Sachs Harbour and Gjoa Haven, and conducted hazard mapping in Gjoa Haven.
- Working from the Heron launch and *CCGS Amundsen* in 2006, undertook seabed surveys (multibeam bathymetry, backscatter, and sub-bottom) at Resolute NU and De Salis Bay and Sachs Harbour NWT. In 2006 and 2007, a total of 17 cores were obtained through ice from a number of submerged basins and breached lakes in the Sachs Harbour area to provide data on former sea levels. Coastal seabed surveys and sampling were completed in various years using small local boats on the Yukon coast, in Tuktoyaktuk, Sachs Harbour, and Ulukhaktok, NWT, and in Kugluktuk, Gjoa Haven, Hall Beach, and Clyde River, NU.
- Undertook benthic surveys to document coastal marine habitat conditions in the vicinity of Sachs Harbour (summer 2005) and Gjoa Haven (summer 2006).
- Completed field studies in 2005, 2006 and 2007 on modern and relict (raised) gravel beaches on Lowther Island, Griffith Island, in the Resolute area (Cornwallis Island), on Bylot Island, and in the vicinity of Cape Charles Yorke and Pond Inlet (Baffin Island).
- Obtained high-resolution (QuickBird) satellite imagery for detailed coastal mapping in the communities of Tuktoyaktuk, Sachs Harbour, Ulukhaktok, Paulatuk, Kugluktuk, Gjoa Haven, Resolute, Arctic Bay, Pond Inlet, Clyde River, Hall Beach, and Iqaluit. High-resolution imagery was also obtained for Lowther Island, Mackenzie Delta, and Herschel Island.
- Undertook detailed studies and consultation in 2004-2006 on adaptive capacity and community resilience in Sachs Harbour, Tuktoyaktuk, and Gjoa Haven. Earlier work in Arctic Bay was supplemented with detailed hazard mapping in 2006. Community consultation and supporting research were undertaken in Hall Beach (Figure 2) and Clyde River in 2007. Additional community-based geoscience surveys were undertaken in Resolute and Pond Inlet in 2006 and 2007. The project contributed to consultations on climate-change adaptation sponsored by the Government of Nunavut in 2006-2007 and to the international dialogue on Arctic coastal zones at risk in Tromsø (Norway) in 2007.
- Continued dialogue with network partners and with a wide range of outside collaborators and stakeholders.

4.2.6 Results

Sea-level change and vertical crustal motion:

Relative sea-level rise or fall is a function of rising or falling regional sea level and land subsidence or uplift. Realistic projections of future relative sea-level rise (change in mean water level relative to the shoreline) are critical for assessing future erosion and flooding impacts, and thus are necessary components of an integrated regional impacts study (IRIS) involving coastal communities and habitats. High variability in rates of isostatic uplift and subsidence across the Canadian Arctic is an ongoing legacy of past glaciation (Henton et al. 2006). Sea-level rise in the western Arctic is believed to be comparable (within ±0.5 mm/a) to the global mean of +1.8 mm/a 1950-2000 (IPCC 2007) and may have accelerated over the past century. Whereas much of the central Arctic is experiencing ongoing uplift and falling relative sea level, rates of subsidence in the western Arctic and along the northern and eastern coast of Baffin Island enhance rates of relative sea-level rise. The trend derived from tide-gauge records at Tuktoyaktuk is +3.5 mm/a over 45 years (1961-2006) (Manson and Solomon 2007), consistent with regional subsidence of approximately 2 mm/a estimated from geophysical models and GPS measurements. Co-located continuous GPS and tide-gauge stations were established at five sites across the Arctic, but the lengths of record are still much too short to derive meaningful estimates of relative sea-level rise at most sites.

Coastal sensitivity and response to changes in forcing related to climate variability and change in a warming Arctic:

One component of the study addressed the impacts of storms and wave activity on Arctic coasts, both under present-day conditions and over the past several thousand years (as recorded in raised beach sequences). Preliminary results were derived from field data bracketing a storm event at Resolute Bay in late July 2007. With negligible sea ice present at the time, maximum open-water fetch occurred and winds generated significant wave activity at the coast. Surveys of the beach before, immediately after, and three weeks after the storm event revealed beach morphological changes during the storm and patterns of subsequent recovery. Beaches with southern and eastern exposure underwent significant erosion, resulting in ice-bonded sediments being exposed in several places along the foreshore. Beaches facing west experienced accretion in the form of berm and beach-ridge development.

Studies of coastal erosion processes on Herschel Island quantified mean annual erosion rates, which ranged from 0.61 m/yr to 0.45 m/yr over a 50-year period (Lantuit and Pollard 2007). These rates were consistent with ones from a similar analysis for the Mackenzie Delta region (Solomon 2005). Shoreline orientation was shown to play a strong role, with the greatest rates occurring on N and NW facing coasts (Figure 3), consistent with the prevalent direction from which storms originated.

Figure 3. *North coast of Herschel Island, Yukon coast, showing rapidly eroding undercut cliffs. Photo: N. Couture, McGill University, 2003.*

The greatest increases, however, occurred on S and SE facing shorelines and appear to be associated with the occurrence ground-ice related features such as retrogressive thaw slumps. The number and the total area of such thaw slumps have dramatically increased (+125% and +160%, respectively) between 1952 and 2000. Volumes of ground ice along the Yukon coast ranged from 5% to 98% and depended to a large extent on surficial materials, being lowest in marine deposits (12.4% on average) and highest in morainic material (76.4% average). Organic carbon in the coastal sediments varied between 21 and 231 kg/m^3, resulting in current fluxes due to erosion of 90,000 tons/year. Future fluxes under changing environmental forcing were also modeled. A mathematical model of block failure mechanisms was developed, which considered the relative influence of thermo-erosional niche and ice wedge occurrence on the block failure process.

Publicized community concern about changing coastal conditions led to Sachs Harbour, NWT, being chosen as

Figure 4. *Mirabilite, a hydrous sodium sulphate salt (Na_2SO_4-$10H_2O$), encountered in cores extracted from basin-floor sediments collected through the ice in a coastal breached lake near Sachs Harbour, Banks Island, NWT (Smith et al. 2006). Scale in centimetres. Photo: K. Jarrett, Geological Survey of Canada, 2006.*

one of the first coastal sites for detailed study in this project (Manson et al. 2005; Belliveau 2007). Ongoing changes in climate including decreased sea-ice extent, increased storm frequency, and sea-level rise were observed in the Sachs Harbour area and the pace of change was expected to increase. Coastal surveys, nearshore bathymetric surveys, and sediment samples were used to determine present coastal processes and rates of change. Aerial photographs and satellite images were used to determine historical change along the coastline and within the community. Sea ice and storm records were analysed from the 1950s to present in order to determine the frequency of events and associated sea-ice conditions (Belliveau 2007; Manson and Solomon 2007). Storm event frequency varied throughout the record and declined since 2000 (cf. Atkinson 2005). Sea ice often limits open-water fetch during storm events, but three major areas of erosion were identified, to the west, to the southeast, and within the community itself. Sediments are reworked alongshore within three major coastal cells, two outer cells to the southeast and west, with net westward sediment transport, and an inner cell moving sediment eastward into the harbour (Belliveau 2007).

Marine surveys using the Heron launch operating from the CCGS Amundsen in 2006 documented submerged basins of glacial kettle-lake origin in De Salis Bay and Sachs Harbour on Banks Island. Submerged nearshore erosional terraces were also observed. Working from the ice in 2006 and 2007, cores of basin-floor sediments were obtained from a number of submerged basins and breached lakes in and around Sachs Harbour. Preliminary analysis suggested that some of the sediments may be annually laminated (varved). Where this occurs in the shallow, marine-transgressed basins, it may help to resolve the time it takes for a basin to become fully inundated, as well as shedding light on the relative stability of sills and catchment sediments during marine transgression. Diatom analysis was used to identify the transgressive contact marking the transition from freshwater to fully marine conditions in each basin. Dating of this contact will help to constrain the history of relative sea level rise and models of vertical motion (subsidence at this site). One breached lake basin was found to contain >1 m of mirabilite salt crystals (Figure 4), tentatively linked to brine exclusion on freezing. Salinities in excess of 80 psu were observed near the bottom of the basin in late August 2006, indicating probable year-round persistence of hypersaline conditions.

Coastal habitat vulnerability:

Description and analysis of nearshore marine biodiversity and habitat mapping was carried out in two of the areas studied to date: Sachs Harbour, NWT, and Gjoa Haven, Nunavut. In Sachs Harbour, the dominant environments were highly mobile shallow sand sheets with low biodiversity, and quiet-water sands and muds in the Sachs estuary, often with algal mats growing on the sediment surface. In Gjoa Haven, the substrates observed in Sachs Harbour were observed, as were rocky bottoms covered with kelp, and gravel and gravelly-sand bottoms. In Gjoa Haven, seaweeds growing on pebbles and cobbles were an important component of the biota in many sand and mud environments, in striking contrast to the homogeneous sand-dominated environment of Sachs Harbour. Species diversity in shallow-water areas was significantly greater in Gjoa Haven than in Sachs Harbour, but there was no difference in species diversity between the two areas in the 20-40 m depth range. Ordination and analysis of similarity showed that the species composition differed significantly between areas, between depth classes, and between equivalent depth classes in the two areas. Species composition differed significantly among substrates, and between equivalent substrates in the two areas, but patterns were weaker than those observed among depth classes. The fauna in Sachs Harbour was generally more tolerant of sedimentation than that observed in Gjoa Haven, where epifauna were more common.

Resilience and adaptive capacity of Arctic coastal communities:

Climate-change adaptation processes in three communities (Sachs Harbour, Tuktoyaktuk, and Gjoa Haven) were analysed using the established mechanism and practices of participatory community planning – a framework which allowed local environmental changes to be assessed and responded to by the people affected (Parewick and Catto 2006). The project aims were to:

- Rethink municipal planning practice in order to support and enhance community resilience;
- Directly support municipal decision-making respecting pressing infrastructure issues arising from climate changes;
- Facilitate interdisciplinary communications to benefit the subject community;
- Facilitate practical applications of scientific findings in a community context.

In each community, the same general work plan was followed: preliminary familiarization visits and local pre-planning; climate change and community data compilation; participatory planning consultations; and adaptation plan preparation with stakeholder review and editing. Given the scale and sensitive nature of local climate-change impacts projected for Tuktoyaktuk, it was apparent that special efforts would be needed to mount an effective planning exercise there. The enhanced planning process allowed Tuktoyaktuk residents to benefit in addition from the Coastal Zone Canada (CZC) conference that the community hosted in August 2006. This multidisciplinary gathering of researchers and policy-makers active in coastal zone studies afforded the community a unique opportunity to meet experts and obtain feedback on their climate change adaptation plans.

Establishing effective working partnerships in the communities was recognized as being essential to the effective pursuit of this project. Relationships were built in the communities that would serve to engage more local people in the participatory planning process. This endeavour was successful in assembling small groups of committed and respected local residents in each community to serve the functions of both a project Steering Committee and the "community editors" for the plan to be produced. An important planning workshop targeting the community elders was conducted with the approval and input of the Tuktoyaktuk Hamlet Council. The feedback on this workshop was very positive with several participants commenting that it had been a long time since the Elders had been formally consulted on matters of such great import to the future of the community.

Information was compiled respecting predicted local climate changes and likely impacts on infrastructure for all three communities. Given the expressed preference for smaller group and individual presentations exhibited by the community to date, key materials were incorporated in a PowerPoint presentation that was, in turn, serially edited by consultation participants. In its current form, the presentation outlines key background information and identified issues to be addressed with this plan review. The compilation of documented and/or

Figure 5. *Travelling to survey site near Hall Beach, NU. L-R: Solomon Qanasiaq, Levi Kannak, and Gavin Manson. Note sidescan sonar and echosounder transducer at left (brought inboard for transit). Photo: D.L. Forbes, Geological Survey of Canada, 2007.*

observed adaptations made by each community to date, and an assessment of critical community infrastructure was begun. The exact form that the final climate change adaptation "plan" for Tuktoyaktuk will take was also discussed. There were a series of drafts of the final project report(s) that were circulated within the Steering Committee and amongst other participating community organizations before being returned to the Hamlet Council for final comment on behalf of the community at-large.

4.2.7 Discussion and Conclusions

Two climate-induced trends that will have a significant impact on the Arctic coastline over coming decades are relative sea-level rise and reduced sea-ice cover (ACIA 2005). Both can alter the wave energy regime at the coast, causing flooding, enhanced erosion and shoreline retreat, with impacts on coastal communities. Such changes represent increased hazard risk for community infrastructure, nearshore benthic habitats, and coastal resources. Projecting the future response of the coastal system to these changes in forcing is a prerequisite for an effective adaptation strategy (Manson et al. 2005, Ford et al. 2007). Project participants quantified a number of important coastal properties that are sensitive to changes in environmental variables. Changes were monitored and the results were used to evaluate the sensitivity of different coastline types to a variety of coastal processes likely to change with a warming climate. Future work will focus on developing and refining numerical models to assist in predicting the extent of these changes. This project documented coastal response to storms in the Beaufort Sea, Barrow Strait, Bylot Island, and Foxe Basin, indicating that modest events can be highly effective agents of change on

Arctic coasts, even where relative sea level is falling (Taylor et al. 2006). This suggested that increased fetch exposure due to climate warming in currently ice-infested areas such as northern Banks Island (including Aulavik National Park) could lead to unprecedented rapid coastal change. The impact could be equally significant in areas where extensive open water occurs today, if the length of the open-water season is extended to include more storms, leading to an increase in damaging wave events. Future work will aim to quantify these effects as input into climate-change risk assessment and adaptation planning in Arctic communities.

The dominant factor affecting benthic biodiversity at two locations in the central and western Arctic (Sachs Harbour and Gjoa Haven) was the over-riding influence of sandy sedimentation in the Sachs Harbour area, where marine transgression and associated coastal erosion has produced a widespread marine sand unit on the floor of Thesiger Bay. More active sea-ice movement and scour in the Sachs Harbour area may also be a factor. The Sachs Harbour estuary contains semi-isolated flooded kettle-lake basins with hypersaline bottom-water and anoxic, methane-laden sediments. Sediments in some basins may be annually varved and two basins were found to be sites of mirabilite precipitation, a phenomenon that was previously unreported in the Arctic.

Due to interest expressed by the Government of Nunavut, the procedures that were developed as a result of work in Tuktoyaktuk were the subject of a workshop in Gjoa Haven, Nunavut. At the same time, other NIs and partners in Project 1.2 were interacting closely with the Climate Change Coordinator for the Government of Nunavut and co-sponsored a community consultation meeting in Iqaluit in December 2006. One outcome of that meeting was the self-selection of two communities (Clyde River and Hall Beach) to serve as pilot projects for development of the territorial adaptation plan. Preliminary consultation with a wide range of community members took place in March 2007 in Clyde River and in August 2007 in Hall Beach. Environmental science research was initiated in partnership with each of the communities in summer 2007 (Figure 5), targeting climate-sensitive issues identified in the consultations. Preliminary results of the research were incorporated in planning consultations to be undertaken by partners from the Canadian Institute of Planners in the winter of 2007-2008. The techniques developed in this ArcticNet project are thus in the process of being applied to a number of communities across the Canadian Arctic. Through international contacts, the applicability of this approach in the wider circum-polar world was also explored.

4.2.8 Acknowledgements

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4.3 Carbon and Contaminant Cycling in the High Arctic (Project 1.3)

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4.3.1 Abstract

Extensive studies were carried out during ArcticNet Phase I (2004-2008) to probe the sources and processes leading to the elevated mercury (Hg) and methylmercury (MeHg) concentrations in marine mammals in the Beaufort Sea region. A re-evaluation of the putative atmospheric Hg record contained in Arctic lake sediments showed that the Hg flux record is strongly influenced by lake productivity trends, and direct atmospheric deposition of Hg is much less important than previously believed. As the Mackenzie River is the largest source of fresh water and sediment to the Beaufort Sea, a major aspect of this study measured both Hg and MeHg concentration over the entire length of the Lower Mackenzie River (from Hay River to the estuary) over 3 consecutive summers. The estuary area was further monitored for 4 consecutive spring freshets. Mercury profiles in permafrost cores were also determined from various sites on the southern coastal line of the Beaufort Sea. The results suggest that the Mackenzie River contributes about 2.2 tonnes of Hg to the estuary on an annual basis, ranking it the largest known source of Hg to the Beaufort Sea. The permafrost melting and coastal erosion contributes another 0.6 tonnes/year of Hg. Further studies in the Mackenzie Basin suggested Hg in the Mackenzie River mainly originates from tributaries flowing through mountainous terrain in the western basin due to increased erosion and leaching. In addition, organic matter and petrological studies suggested the coal seam near Tulita, NWT, is also a considerable source of Hg to the river. In the corresponding southern Beaufort Sea biotic studies, estuarine-shelf prey items were found to have the lowest MeHg levels while the highest levels were measured in fourhorn sculpin (*Myoxocephalus quadricornis*) from the epibenthic food web. With use of diet biomarkers (fatty acids and stable isotopes) along with satellite telemetry, the beluga diet and dietary sources were measured for the summer range of the Beaufort Sea beluga. Beluga diet was found to vary with length, whereby the largest beluga fed predominantly offshore on Arctic cod (*Boreogadus saida*) and medium to smaller sized beluga fed predominantly near shore also on Arctic cod in addition to near shore species (e.g. Pacific herring (*Clupea palasii*)). Belugas feeding offshore were exposed to higher dietary sources of Hg than those feeding near shore. Beluga habitat use of near shore open water regions and offshore regions under heavy sea ice cover resulted in differences in diet and dietary sources of Hg. The estuarine food web had the lowest source of Hg to beluga relative to the offshore pelagic and epibenthic food webs which suggests that the Hg leaving the Mackenzie River only becomes bioavailable and enters the marine ecosystems after leaving the near shore delta region. Annual stable isotope records retrieved from beluga tooth growth layers showed that the average trophic position of the population has not changed over the past 60 years, meaning that the recent tissue Hg increases are due to environmental variation in Hg pathways, rather than shift in trophic position.

4.3.2 Key Messages

The Mackenzie River is the largest known source of mercury to the Beaufort Sea, followed by the permafrost melting and coastal erosion. The relative importance of atmospheric deposition and oceanic transport remains unknown but are currently under investigation. Net atmospheric deposition is likely less important than has previously been reported.

The seaward flux of Hg from the Mackenzie River increases with the water discharge. About 50% of the annual total Hg flux was delivered to the estuary during the spring freshet.

In addition to surface erosion and other non-point sources, the coal seam from the Tulita region of NWT showed localized, high enrichment in Hg, and contributed to the Hg loading of the Mackenzie River.

The majority of the Hg in the Mackenzie River is present in the form of suspended particulates, and appears to be inorganically associated, although near lakes there seems to be a significant correlation with organic matter.

Mercury from the Mackenzie River may only become available for biological uptake in offshore environments downstream from the outflow plume. Organisms locally exposed to high levels of Hg in the Mackenzie River outflow had the lowest Hg concentrations. In contrast, higher Hg levels were found in biota collected from the Amundsen Gulf, Franklin Bay and eastern Beaufort Sea.

Overall, beluga appeared to feed predominantly on marine fish; however, larger sized beluga appeared to prefer offshore Arctic cod associated with their large-scale foraging, whereas the medium and smaller sized beluga incorporated shelf Arctic cod and brackish prey species that had lower Hg levels than the offshore Arctic cod. There is no evidence that the population's feeding behaviour has changed trophically over the last 6 decades.

For the first time, it was demonstrated that food web Hg biomagnification processes drive muscle Hg levels rather than Hg bioaccumulation over time.

4.3.3 Objectives

The overall goal of Project 1.3 was to probe the sources and processes leading to the high Hg concentrations observed in marine mammals in the Beaufort Sea region. The specific objectives of our research during Phase I (2004-2008) were to:

- Estimate the relative importance of the Mackenzie River, and permafrost melt and coastal erosion as potential sources of Hg to the Beaufort Sea;
- Determine the concentration, speciation, and hot spots of Hg in the Mackenzie River Basin;
- Measure the Hg and MeHg concentrations in the Beaufort marine ecosystem;
- Determine beluga habitat use, foraging behaviour and dietary preferences;
- With the use of diet biomarkers measure the dietary sources of Hg to beluga;
- Outreach with the Inuvialuit community.

4.3.4 Introduction

Mercury (Hg) in the form of mono-methylmercury (MeHg) is a known neurotoxin causing reproductive, immunosuppressive, and neurobehavioural risks to biota and the Minamata Disease in humans. Produced mainly by microbial methylation of inorganic mercury (Hg) in the aquatic environment, MeHg bioaccumulates in organisms over time, and biomagnifies at each trophic level (Morel et al. 1998). As a result, Hg concentrations at ultra-trace levels in water can reach toxic levels in top predators. Of particular concern is the recent observation that the current Hg levels in the Beaufort Sea beluga whale (*Delphinapterus leucas*) population were highly elevated compared to other wildlife populations (Lockhart et al. 2005), and were on average 10-fold higher than in Beaufort beluga during the 15th to 17th Centuries (Outridge et al. 2002). Liver Hg concentrations of this population tripled from the early 1980s to the mid-1990s, and were the highest relative to other Canadian Arctic beluga populations. Since then, the Hg concentrations seem to have dropped to a similar level to other Arctic beluga populations, but are still higher than the 1980s and earlier (Lockhart et al. 2005). Elevated Hg concentrations were also reported in ringed seals and other marine mammals from the region (Stern, unpublished data). This has raised serious concerns over the health of marine mammals and Inuvialuit people who consume their tissues as part of their traditional diet.

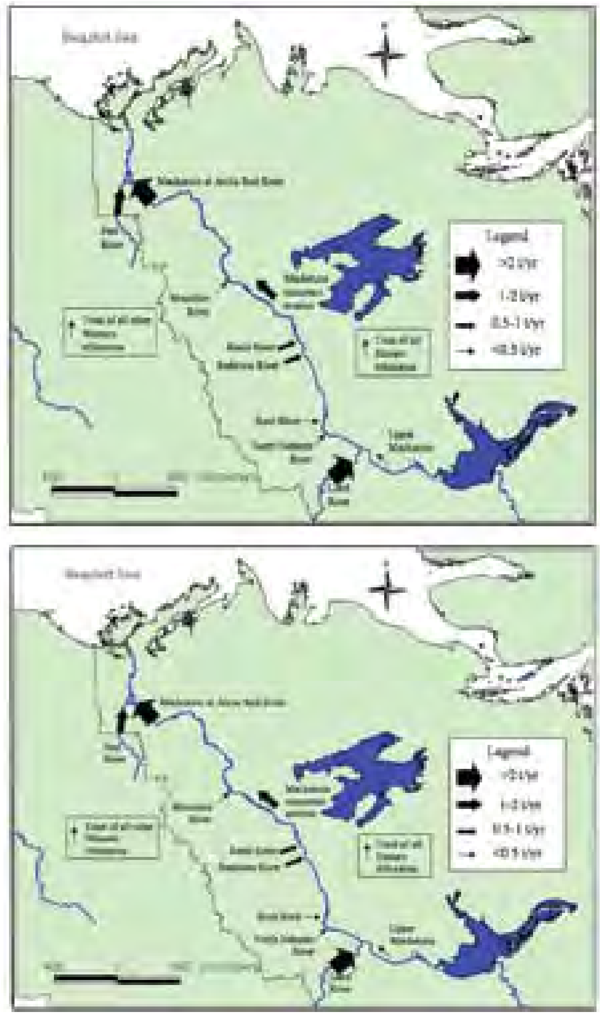

Figure 1. *Dissolved (top) and particulate (bottom) Hg fluxes in the lower Mackenzie Basin (Leitch et al. 2007).*

The cause of such high Hg burdens and large variations in the Beaufort marine mammals remains a mystery. The discovery of the tropospheric mercury depletion events (MDEs) in the Arctic coastal environment in the mid-1990s (Schroeder et al. 1998) provided a potential mechanism of increased atmospheric Hg deposition in Arctic coastal regions after polar sunrise. However, further studies suggested that much of the Hg deposited in snow during MDEs is photo-reduced and re-emitted back to the atmosphere, and may not impinge significantly on the Arctic marine ecosystem (Lalonde et al. 2002; Steffen et al. 2005). Furthermore, median atmospheric Hg concentrations in the Arctic have remained essentially constant for at least the past 10 years (Steffen et al., 2005; Berg et al., 2004). Therefore, other processes likely play a more important role in the Hg distribution and trends in the Beaufort Sea marine ecosystems. Examples of such processes include the riverine Hg discharge, direct terrestrial Hg input from melted permafrost and coastal erosion, oceanic Hg transport (Leitch et al. 2007), sea ice loss, marine mammal habitats, feeding patterns and food web structures (Loseto et al. 2008).

Project 1.3 aimed to investigate these abiotic and biotic processes of Hg in the Beaufort Sea region and their response to the projected climate change in the region. The abiotic processes were focused on the riverine Hg flux from the Mackenzie River and the coastal erosional Hg flux due to the increasing rate of permafrost melting. The Mackenzie River is the dominant source of freshwater and sediment to the Beaufort Sea, and consequently that of Hg (Leitch et al. 2007). Further efforts were undertaken to identify the sources and hot spots of Hg to the Mackenzie River. Tributaries originating from the mountains in the western basin, particularly the Liard River, contribute the vast majority of suspended sediments to the Mackenzie and are expected to deliver Hg in mainly inorganic species (Figure 1). Coal seams near the Tulita area was found to contribute to the inorganic fraction of Hg to the Mackenzie River. Lakes (e.g., the Great Slave and Great Bear Lakes), wetlands and estuaries are likely major sources of organic Hg.

Due to the biomagnifying properties of MeHg, Hg concentrations in predators such as beluga largely reflect the Hg levels in their diet (Mathers et al. 1985). Thus, by establishing the feeding patterns of the belugas, dietary Hg sources from prey could be determined. During the summer, Beaufort Sea beluga habitat use differs with length, sex and reproductive status that reflect social structure (Loseto et al. 2006b). Habitat segregation may reflect differences in energy requirements and survival strategies that vary with age, sex, size, and reproductive stage (Bowyer et al. 2004). Variation in beluga habitat selection suggested that they may have different diets and foraging behaviour (Loseto et al. 2006b). This beluga population summers where several coastal, anadromous and marine fish species occur, in addition to invertebrates, comprising pelagic, benthic and estuarine food webs. Thus, the biotic portion of this project involves determining beluga feeding behaviour in association with their habitat use, which will require measuring Hg contribution from several food webs in the beluga summer region. To provide a historical perspective on beluga diet and feeding behaviour, an annual stable isotopic record was retrieved from the growth layers of tooth dentine from beluga harvested in the 1960s, 80s, 90s and in 2002, through extensive micro-drilling and collection of milligram amounts of dentine powder.

While the focus was on Hg, samples were also collected and analyzed for other trace elements and persistent organic pollutants (POPs). Only the study on mercury will be reported here.

4.3.5 Activities

Study sites, time frame and activities: Over the 2004-2007 period, Project 1.2 researchers accomplished numerous research activities in the following subjects.

1) Hg and MeHg in Arctic rivers and estuaries

Co-funded by the Department of Fisheries and Oceans (DFO) Science Subvention Program, sampling of the Mackenzie Delta during the spring freshet (ice break-up; June 2004) was conducted for the analysis of Hg and MeHg in water and suspended sediment. This marked the first year of a 4-consecutive-year monitoring program of the spring freshet period. From July to September 2004, expedition onboard the *CCGS Dumit* and *Eckaloo* and the sampling of the river water and suspended sediment at more than 60 stations along the lower Mackenzie River (from Hay River to the estuary). This was a follow-up study of a similar sampling program in the summer of 2003 in order to establish the annual variations in Hg concentration, speciation and seaward flux of Hg. In August 2004, collection of permafrost cores from Herschel Island and the southern Beaufort Sea coast which were analyzed for ^{210}Pb and ^{137}Cs to determine depositional processes, and analyzed for total Hg, ice content and various other physical and chemical parameters.

From May 26 to June 6, 2005, sampling of the Mackenzie Delta, for the second consecutive year during the spring freshet. In

August of the same year, expedition onboard the CCGS Dumit and Eckaloo again for the third consecutive year, for sampling of the entire length of the Lower Mackenzie River (from Hay River to Inuvik); sampled water and suspended sediment were taken at more than 60 stations.

Onboard the *CCGS Nahidik* from July 27 to August 20 2005, collection of water and zooplankton samples in the shallow Mackenzie Delta region for Hg analysis.

In May-June 2006, continuation of the sampling of water and suspended sediment in the Mackenzie Delta during the freshet for the third consecutive year. The samples were analyzed for dissolved, particulate and total Hg and MeHg. Collection of 60 coal samples from the Brackett Basin near Tulita, NWT, with the assistance of the Geological Survey of Canada (GSC) – Calgary. The samples were analyzed for Hg and other trace elements to determine whether they are enriched in Hg.

In June 2007, return to the Mackenzie Delta for the fourth consecutive year study of the Hg concentration, speciation and flux during the spring freshet. With the helicopter time provided by the Polar Continental Shelf Project, more water samples, water and sediment samples were also obtained from the central and western channels of the Delta during the freshet. In July 2007, with the assistance of GSC – Calgary, collection of more sediment samples from the Mackenzie River and its tributaries near Fort Simpson, and near the coal seam in the Tulita area. Visit of the GSC – Calgary laboratories in February and August 2007, and training in Rock-Eval and petrological analysis.

2) Beluga dietary source of Hg

In partnership with the Canadian Arctic Shelf Exchange Study (CASES) program, zooplankton and Arctic cod were collected from the Amundsen for analysis of Hg, stable isotopes and fatty acids to determine dietary sources of Hg to beluga. In July 2004, beluga tissue samples were collected at Hendrickson Island, the long-term monitoring site established with the Tuktoyaktuk Hunters and Trappers Committee.

Estuary fish were collected, onboard the *CCGS Nahidik* from July 27 to August 20 2005, for mercury analysis and fatty acid analysis to determine the importance of these fish in Beaufort Beluga diet the *CCGS Nahidik* from July 27 to August 20 2005.

Samples for mercury and diet analysis were collected from the 2005 tagged beluga whales and the harvested whales from the long-term Hendrickson Island monitoring site. In addition beluga tissue samples were collected from Paulatuk to evaluate habitat use and diet variation hypotheses in Loseto et al. (2006b).

Beluga and fish samples that were collected in previous years were analyzed in 2006 for Hg, stable isotopes, and fatty acids.

3) Beluga Tagging Program

On Hendrickson Island, a beluga tagging camp was set up with DFO. The camp included 9 members from the Inuvialuit Settlement Region.

The field camp for the Beaufort Sea Beluga Tagging Program was established on July 1st 2005 at Kendall Island. Only 4 whales were caught for tag deployment as a result of prolonged periods of wind, fewer whales were in the area and the areas for effective herding were limited.

4) Mentoring activities

In 2004, two Fisheries Joint Management Committee (FJMC) students were mentored and worked on the Beluga Tagging Program. Nine beluga whales were fitted with satellite transmitters, one of which lasted over a year, the longest data available for this beluga population. In August of 2004, the FJMC mentoring students traveled to DFO-Winnipeg and were instructed on laboratory techniques such as measuring Hg and fatty acids in fish and beluga samples.

In August 2005, the FJMC mentoring students visited the DFO – Winnipeg laboratory again to be trained on measuring Hg and fatty acids in tissues. One of the students was further trained to prepare for sampling on the *CCGS Sir Wilfred Laurier*. She and A. MacHutchon were then onboard the *CCGS Sir Wilfred Laurier* from September 20 to October 20. Water and zooplankton were sampled along a transect running from the Beaufort Sea to the Chukchi Sea, similar to the Beaufort Beluga migration that occurs in the fall.

5) Hg time trends and archaeology

Community consultations and archaeological site visits around the Delta, to obtain community co-operation and permission to conduct archaeological research at Kittigizuit, so that 19th Century beluga teeth could be obtained. These plans were later abandoned after community consensus could not be reached regarding the project.

Sampling in 2005 of dozens of Beaufort beluga teeth originally collected in 1960-61 and 1977 by Arctic Biological Station scientists and newly-discovered at the Museum of Nature, Ottawa. The samples were analyzed for Hg, age, and stable C and N isotopes. These samples extended the tooth and tissue Hg time trends back another 25 years from the time when tissue sampling started in the mid 1980s. Use of the historical tissue Hg data estimated from trends in teeth, combined with dietary survey information from Inuit communities in the Delta, to determine human intake patterns of Hg from beluga as a traditional food source (Kinghorn et al. 2006).

Recovering in 2006 of Hg and organic carbon profiles from lake sediments on Richards Island in the Mackenzie Delta to reconstruct a Hg and carbon input record for the Mackenzie River over the last 1,000 years. Also, continued working to reconstruct stable isotope histories from the annual growth layers of beluga whale teeth from the Beaufort over the last 60 years, to see if dietary behaviour played a role in changing Hg levels in the animals. RockEval analyses on extant Arctic lake sediment samples were conducted to develop possible relationships between lake productivity and sedimentary Hg trends. Development of retrieval, statistical and graphical software using “R” language, to retrieve and plot meteorological data from Environment Canada archives; the software is lodged on an ArcticNet FTP server, to allow public access.

Stable isotope analyses were completed in 2007 on micro-drilled samples from beluga teeth (Outridge).

6) Hg, MeHg, POPs and PBDEs in environment and organisms

Onboard the *CCGS Amundsen* during ArcticNet Leg 1 cruise (August - September 2005) sampling of water, air, zooplankton, fish larvae, and sediment samples in three high Arctic areas; North Water Polynya, Archipelago and the Beaufort Sea for total Hg, MeHg, POPs and PBDEs.

In August – November 2006, during Legs 1 and 2 of the 2006 ArcticNet cruise onboard the *CCGS Amundsen*, water column samples were taken from 7 sites in the High Arctic Ocean at very high vertical resolutions and were analyzed for Hg, MeHg, POPs, $\delta^{18}O$, DOC, nutrients, among many other in situ measurements (e.g., PAR, salinity). Air samples were collected for POPs analysis. Zooplankton samples were also collected for Hg, MeHg, and POPs analysis. The objective was to obtain high resolution vertical distribution profiles of Hg, MeHg, and POPs in the water column of the High Arctic Ocean.

7) Contaminants and CO2 flux estimations

During Leg 1 of ArcticNet cruise 2005, measurements of the air-surface flux of heat and CO2, bulk meteorology, and surface radiation from sensors mounted on the foredeck tower. Resulting atmospheric information facilitates transfer velocity calculations for contaminant flux estimates. α-hexachlorocyclohexane fluxes have been computed for the Southern Beaufort using contaminant gradient information and stability corrected 10 m winds from CASES data.

Measurements of the air-sea fluxes of heat, water vapour, momentum, CO_2 flux, and bulk meteorology from an instrumented tower on the foredeck of the *CCGS Amundsen* during Legs 1 and 2 of the 2006 ArcticNet cruise, under-way measurements of surface sea water pCO_2 using the ship's sea water intake in the engine room using an infrared gas analyzer, based sensor. The addition of the under-way pCO_2 measurements during this cruise provided the ship with unprecedented coverage of surface water dissolved CO_2, and marks an important forward step from the previous ArcticNet and CASES cruises in the ability to (i) calculate atmospheric fluxes and (ii) better relate measured fluxes to oceanographic processes. The similarity of transport mechanisms among gases allowed this information to facilitate contaminant flux estimates, as outlined above.

8) Near shore permafrost and coastal stability

In April 2005, realization of a series of capacity coupled resistivity surveys of near shore permafrost on Richards Island. Boat-based mapping of coastal exposures was done in August in a variety of terrain units delineated by geomorphology and surficial geology. Cores were collected at 18 additional sites for contaminant analysis. Expansion of a model of coastal stability based on thermo-erosional niche formation and ice wedge distribution. The model provided new insights into the coastal erosion rate which is critical in estimating the Hg flux from permafrost melting and coastal erosion.

In 2006, sampling of bottom sediments along the Yukon coast and analysis of these sediments for $\delta^{13}C$ in order to determine how much organic carbon eroded from the coast was deposited in the near shore zone. Photographic and GPS surveying were carried out on Herschel Island for all retrogressive thaw slump activity. High resolution GPS monitoring of shoreline retreat rates was continued.

9) Development of new instrumentations installed on the *CCGS Amundsen*

Funded by CFI, designing and building a new portable clean room laboratory, the Portable In-situ Mercury Speciation Laboratory (PILMS). PILMS was installed in 2007 on the *CCGS Amundsen* and was on its way to the Beaufort Sea. As a joint effort between our ArcticNet Project 1.3 and the Circumpolar Flaw Lead System Study (CFL), this lab was an unprecedented opportunity to study the net atmospheric deposition of Hg into the Arctic aquatic system, and its uptake by the marine ecosystem. Through this same funding source, facilities for continuous measurement of sea water pCO_2 and temperature were built and installed on the *CCGS Amundsen* to augment the micrometeorological measurement of air-surface fluxes. The addition of this equipment improved our capacity to convert contaminant gradients to fluxes.

4.3.6 Results

The Mackenzie River as a source of mercury to the Beaufort Sea:

A 3-consecutive-year monitoring of the entire river in summer and a 4-consecutive-year monitoring of the delta region were carried out during ArcticNet Phase I. Large seasonal and annual variations were found in Hg concentrations in the river, coincident with the variations in water discharge. The correlation between Hg concentration and river flow suggested additional Hg sources during periods of high water, potentially from increased surface inundation and increased bank erosion. Based on the data from the period 2003-2005, the Hg and MeHg fluxes from the Mackenzie River to the Mackenzie estuary averaged 2.2 tonnes/yr and 15 kg/yr, respectively (Leitch et al. 2007), ranking it the largest known Hg source to the Beaufort Sea. These results, together with the observation that more than half of the Hg fluxes occur during the short spring freshet season which coincides with the fast growth season of marine biota, implied that the

Mackenzie River input may play a major role in the elevated Hg concentrations in marine mammals in the Beaufort Sea. The Hg and MeHg fluxes from the Mackenzie River are expected to further increase with the projected climate warming in the Mackenzie Basin.

Further analysis of the data suggested that the middle reaches of the Mackenzie River are enriched in Hg with respect to the rest of the river, both in the water and the sediments. This region is bounded by the Mackenzie Mountains on the western side; these high energy systems are contributing Hg to the Mackenzie River mainly via erosion (e.g., Milliman and Syvitski 1992). Speciation of organic matter in sediments by Rock-Eval pyrolysis analysis showed no correlation between any of the organic matter fractions and Hg on a basin-wide scale. However, significant correlation between labile, small molecular weight organic matter (S1 fraction) and Hg was found in the tributaries that are lake fed, suggesting that the lakes are acting as an organic source of Hg. Coal samples taken from the Tulita area in NWT showed highly variable Hg levels. Mercury concentrations as high as 2.4 mg/kg were found in some samples. As the coal bed in the region is located close to the river bank, it is likely acting as a source of Hg to the Mackenzie River. This was confirmed by petrological studies which show the highest density of coal particles in the sediments near the coal bed. Petrological studies also revealed the dominance of inertinitic particles (mainly from char) in the sediments from the entire river system, indicating the widespread impact of forest fires, which could be another Hg source to the river.

Permafrost melting and coastal erosion as a mercury source to the Beaufort Sea:

Mercury profiles in most of the permafrost cores taken from the southern Beaufort Sea coast showed a subsurface Hg peak at 2-10 cm below the surface. Using median Hg concentrations and existing estimates of coastal erosion rates, it was estimated that approximately 600 kg of Hg are discharged into the Beaufort Sea from permafrost degradation annually. This equals to 28%, which is as much as estimates from the Mackenzie River and on the same magnitude as estimates of atmospheric deposition, suggesting that permafrost degradation is a significant source of Hg to the coastal marine ecosystem. As permafrost degradation is occurring at rapid rates in the circumpolar Arctic, and is likely to increase dramatically in concert with higher temperatures, increased open water, a wave climate that includes periods with larger waves, more storms, and an increase in sea level, this annual flux could easily increase to over 1000 kg in the next 30 years.

Re-evaluation of Atmospheric Hg Deposition:

Organic geochemical analyses of organic matter in previously sampled Arctic lake sediment cores showed significant relationships between Hg concentrations over the last 1,000 years, and Hg fluxes over the last 150 years, and specific forms of carbon characteristic of algal-produced organic matter (Outridge et al. 2007) (Figure 2). Using these relationships to predict 20th Century Hg fluxes and concentrations, Outridge et al. (2007) found only small amounts of unexplained variance in 20th Century Hg, suggesting that most of the recent sedimentary Hg increase, which was previously attributed to atmospheric Hg pollution, was actually due to increased Hg scavenging associated with co-occurring changes in aquatic primary productivity. Thus, direct atmospheric deposition of Hg into the Arctic surface environment may not be as important as previously believed, and other potential sources such as oceanic transport, riverine input and coastal erosion need to be more intensively investigated.

Food web sources of Mercury and Hypothesized beluga feeding groups:

Significant Hg variability was found within three food webs in the Canadian Western Arctic where Beaufort Sea beluga

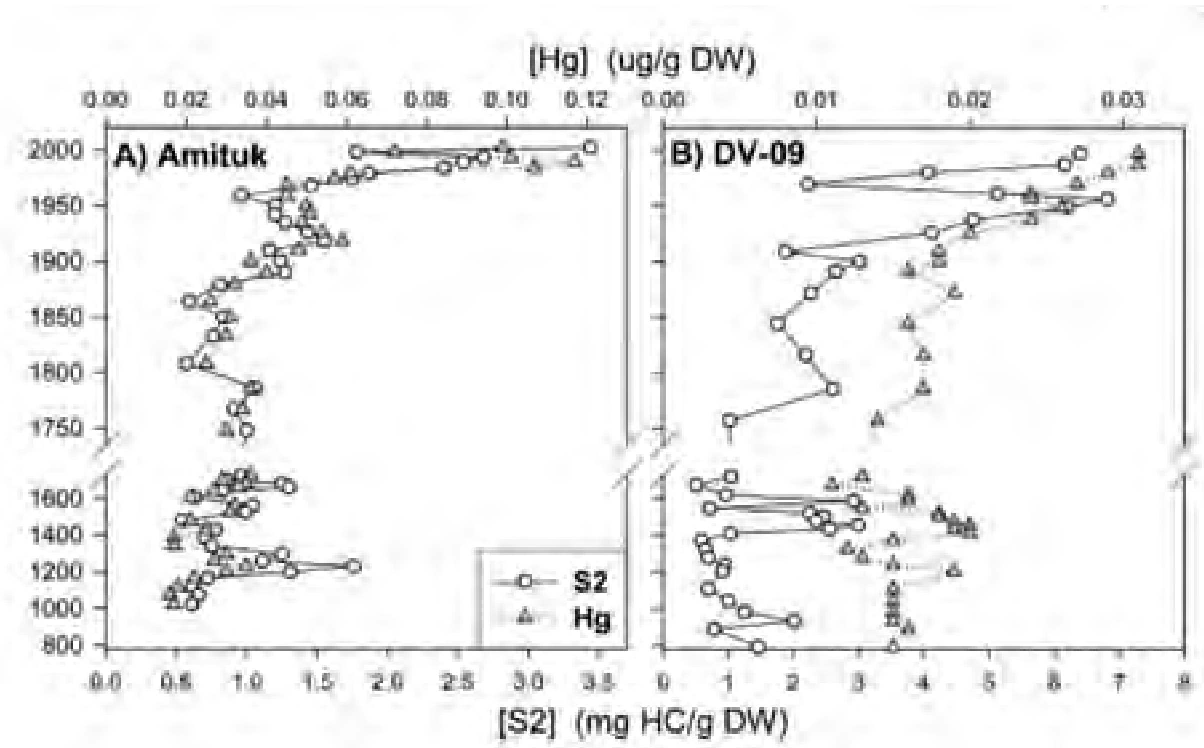

Figure 2. *Sediment Hg and S2 carbon concentrations in (A) Amituk Lake and (B) Lake DV-09 (Outridge et al. 2008).*

spend their summer (Loseto et al. 2008). To our knowledge, this is the first study to report MeHg levels in estuarine fish and epibenthic invertebrates from the Arctic Ocean. Although the Mackenzie River is a large source of Hg, the estuarine-shelf prey items had the lowest MeHg levels. Highest MeHg levels occurred in fourhorn sculpin (Myoxocephalus quadricornis) from the epibenthic food web. Beluga hypothesized to feed in the epibenthic and Amundsen Gulf food webs had the highest Hg levels matching with high Hg levels in associated food webs, and estuarine-shelf belugas had the lowest Hg levels (2.6 ug/g dw), corresponding with the low food web Hg levels, supporting the variation in dietary Hg uptake. The trophic level transfer of Hg was similar among the food webs, highlighting the importance of Hg sources at the bottom of the food web as well as food web length (Figure 3).

Beluga feeding variations by size and habitat use:

Because the Beaufort Sea belugas segregated by length, sex and reproductive status corresponding to habitat use, it was tested whether these biological indices corresponded with feeding differences and thus Hg uptake. With the use of fatty acid signature analysis and stable isotopes it was found that the Beaufort Sea beluga diet was defined by habitat use and length. Fatty acids provided information about the effects of behavioural influences on dietary Hg, whereas stable isotopes implied tissue Hg metabolic rates. Results showed the factors driving beluga diet variability led to differences in dietary Hg uptake. For the first time, it was demonstrated that food web Hg biomagnification processes drive muscle Hg levels rather than Hg bioaccumulation over time. In addition, Hg concentrations in muscle describing diet sources were best described by liver $\delta^{15}N$, rather than muscle $\delta^{15}N$.

Beluga diet and Mercury uptake:

Results from prey and beluga fatty acid analysis indicated that overall marine prey, such as Arctic cod and pacific herring, were the most important prey items for the Beaufort Sea beluga, whereas bottom-feeding fish did not appear as significant to their diet. A marine gradient was observed in beluga fatty acids, whereby the largest beluga had a stronger marine diet signal relative to smaller whales. This suggested that larger belugas fed predominantly on Arctic cod collected from the offshore region because they had the strongest marine signal among all prey items investigated. The smallest beluga was a yearling and had the lowest level of marine fatty acids and appeared to have the largest source of near shore prey diet relative to the larger belugas. These trends suggested the immature whales have a more diverse diet, relative to larger whales. The proposed variation in beluga diet was supported by the differences in Hg concentrations and $\delta^{15}N$ values in both prey and beluga, whereby the offshore habitat use by the largest beluga associated with the highest Hg levels in offshore Arctic cod. Therefore, larger belugas using the offshore habitat are exposed to higher dietary Hg levels than smaller sized adult belugas.

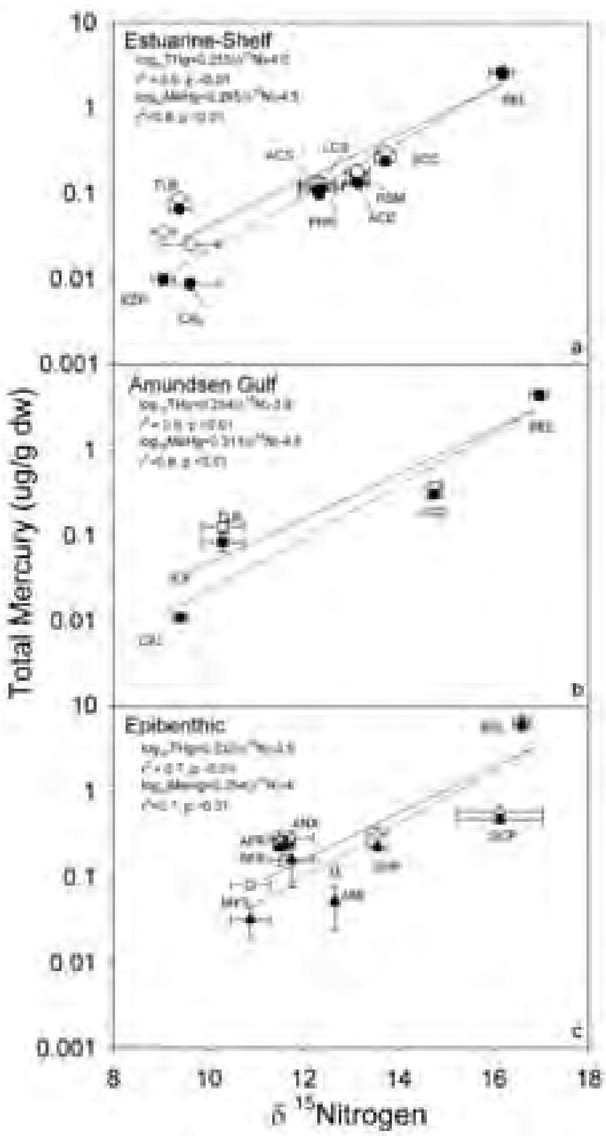

Figure 3. *Biomagnification of MeHg and THg in three food webs: a) Estuarine-shelf; b) Amundsen Gulf and; c) Epibenthic. Mean ±SE of log transformed MeHg (dashed line) and THg (solid line) (ug/g dw) versus δ15N depicting potential trophic relationships of species (Loseto et al. 2007).*

Beluga tooth isotope micro-chemistry:

Over the last 60 years, annual average $\delta^{15}N$ values in beluga tooth dentine have shown no consistent trends or associations with the recent Hg increases in tissues. Thus, there is no evidence of changes in overall (integrated values within each year) trophic level of prey selection. $\delta^{13}C$ values, which can be used to infer possible changes in feeding location, have displayed significant, steady declines since the 1970s, which were previously reported in Bering Sea bowhead whale baleen over this period. The most likely explanation for the beluga results is the Suess effect, i.e., dissolution of anthropogenic CO_2 in the ocean, and not changes in feeding location. However, a weak but significant negative association was found between annual average dentine $\delta^{13}C$ and the Arctic Oscillation Index since 1938 which bears further examination. Stronger AO index values were associated with warmer Arctic temperatures, and the negative association with beluga $\delta^{13}C$ might be evidence of greater eastwards penetration of beluga during high AO years, which would bring them closer to the Mackenzie River influence.

Table 1. *Hg flux estimates to Beaufort Sea and the Arctic Ocean (Leitch et al. 2007).*

SOURCE	TOTAL HG FLUX (TON/YR)		REFERENCE
	BEAUFORT SEA	ENTIRE HIGH ARCTIC OCEAN	
Mackenzie River	2.2± 0.9	2.2 ± 0.9	Leitch et al., 2007
Lena River		4.0[a]	Coquery et al., 1995
Ob River		1.3[a]	Coquery et al., 1995
Yenisei River		0.7[a]	Coquery et al., 1995
Atmosphere	<< (1.4 - 4.7)[b]	<< (17 - 325[c])[b]	Lu et al., 2002; Ariya et al., 2004
Coastal erosion	0.6	No data	Leitch, 2006
Oceanic transport	No data	No data	

[a] Calculated based on one sampling event only in late summer

[b] Assuming all the Hg(II) from MDEs ended up in the ocean. See text for details

[c] Including the terrestrial and aquatic systems above 60°N.

Outreach:

In addition to the community monitoring program, community visits, and partnership with the Hunters and Trappers Organization, the project was actively involved in the Fisheries Joint Management Committee (FJMC) Student Mentoring Program. The program is designed to encourage young Inuvialuit youth to become future scientific leaders and researchers. As a result, Inuvialuit high school and university students get a realistic introduction to the world of science and resource co-management. In 2004, 2005 and 2006, L. Loseto was matched up with several mentoring students and worked with them in the field at beluga tagging camps and in the lab analyzing Hg and fatty acids in fish. They also joined L. Loseto in community consultation meetings. In partnership with Devon Corporation, L. Loseto arranged to have K. Hansen-Craik sample water and zooplankton on the *CCGS Sir Wilfred Laurier* with A. MacHutchon. At the 2005 ArcticNet Annual General Meeting, K. Hansen-Craik gave a talk and presented a poster on her work. In 2006 she and L. Loseto co-authored a book chapter describing their experiences and research results (Loseto et al. 2006). K. Hansen-Craik has since gone on do undergraduate studies at Grant MacEwan in Edmonton. R. Binder and K. Lapenskie are examples of two other students who have successfully completed their mentorship programs, and both are now currently enrolled in undergraduate University programs.

4.3.7 Discussion and Conclusions

Sources of mercury to the Beaufort Sea marine ecosystem:

Mercury sources to the Beaufort Sea marine ecosystem include atmospheric deposition, riverine discharge, coastal erosional transport and oceanic transport. Table 1 represents the first effort toward a partial mass balance model for Hg in Beaufort Sea and the Arctic Ocean (Leitch et al. 2007). Based on the limited data available, the Mackenzie River is ranked the largest Hg source to the Beaufort Sea.

Major data gaps exist on the oceanic flux of Hg to the Beaufort Sea, and there is a large uncertainty on the atmospheric depositional flux of Hg, particularly as the lake sediment Hg flux record is now of questionable validity. Measurement of the atmospheric flux was pursued by the IPY-CFL project with the aid of the portable Hg speciation laboratory PILMS onboard the *CCGS Amundsen*. To estimate the oceanic flux of Hg, the *CCGS Amundsen* cruise path was extended to near the Bering Strait during Phase II of ArcticNet.

Uptake of mercury along the food web:

The finding that the highest Hg concentrations were associated with organisms from the Amundsen Gulf, Franklin Bay and eastern Beaufort Sea instead of from the Mackenzie River outflow suggests that Hg from the Mackenzie River may only become available for biological uptake in offshore environments downstream from the outflow plume. These findings, along with similar Hg trophic level transfer slopes among food webs, suggested that future research should focus on Hg speciation, and on MeHg uptake processes at the bottom of the food web and food web structure. By incorporating information on habitat use and feeding variation, beluga Hg levels corresponded to prey Hg levels (Loseto et al. 2006). Beluga muscle Hg levels reflect food web Hg biomagnification processes rather than bioaccumulation over time which is best described in liver Hg levels. Stable isotopes and fatty acids were found to be strong predictors of beluga Hg concentrations.

The analysis of prey and beluga using fatty acids revealed that fatty acids effectively partitioned prey items into groups associated with their feeding ecology and were able to link the size-dimorphic beluga with prey species. Overall beluga appeared to feed predominantly on marine fish; however, larger sized beluga appeared to prefer offshore Arctic cod that associated with their habitat use, whereas the medium and smaller sized beluga incorporated shelf Arctic cod and brackish prey species. The proposed variation in beluga diet was supported by the differences in Hg concentrations and $\delta^{15}N$ values in both prey and beluga. Beluga diet analysis provided new information about Arctic cod occurrence and ecology. Arctic marine food webs are considered to lack complexity, and may therefore be unstable because an alteration in either prey or predator populations would easily disrupt food web dynamics. Segregation of both beluga and Arctic cod into different feeding groups and habitat use may help to maintain stability in the simple Arctic food web. Annual stable isotope records retrieved from beluga tooth growth layers show that the average trophic position of the population has not changed over the past 60 years, meaning that the recent tissue Hg increases are entirely due to change in environmental pathways, and not trophic changes in food-web structure.

Linking abiotic and biotic Hg processes:

Beluga diet and habitat use results revealed that dietary Hg levels varied with habitat, whereby the shelf was a smaller source than the offshore food web. Therefore, beluga habitat use and associated food web complexity were found to be important factors driving beluga Hg levels. The variation of Hg in regional habitats may in part be related to Arctic cod in deep ocean regions being exposed to high Hg levels through detritus food web links (seen in epibenthic food web). However, given the similar $\delta^{13}C$ among the Arctic cod from shelf and offshore this scenario appears unlikely, because if offshore Arctic cod were receiving more detrital sources the $\delta^{13}C$ should be higher. Thus, it is more likely that Hg leaving the Mackenzie plume only becomes bioavailable for uptake in offshore habitats. Further analyses on Arctic cod feeding behaviour and Hg (particularly MeHg) speciation and bioavailability are required to validate this claim.

4.3.8 References

(ArcticNet generated references in italics)

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MÉTRIQUES

4.4 Marine Productivity and Sustainable Exploitation of Emerging Fisheries (Project 1.4)

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4.4.1 Abstract

The present report summarizes the work accomplished from 2004 to September 2007 in the pursuit of a long-term scientific objective to relate marine productivity and ecosystem services to changes in temperature, sea-ice cover and ocean circulation. The activities included the deployment and maintenance of three marine observatories, extensive coverage of the Canadian Arctic with multi-disciplinary biological surveys and orbiting sensors, and the development of ecosystem models. The results showed considerable, but coherent spatial and temporal variability in all indicators of productivity, which may be linked to sea-ice dynamics, ocean physics and the variable inflow/outlfow of Atlantic, Pacific and river waters. The biological consequences of changes in the physical environment cannot be demonstrated with only two years of data, but the observations and preliminary model runs provided unique insights into the impact of future warming on carbon fluxes and the productivity of key organisms in the food web.

4.4.2 Key Messages

- The yield of microalgae at the base of the marine food chain is highly variable in space and time, but generally poor. Particularly intense production of large, palatable species occurs at regional hot spots.
- Upper trophic levels congregate at hot spots, implying that food web productivity is linked to the physical phenomena that promote microalgal productivity and is susceptible to climate-driven alterations of the environment.
- Winter temperature at the ice-water interface dictates the hatching season of a pivotal species of current food webs, the Arctic cod, by limiting the early survival of the larvae.
- Remote sensing and records of vertical particle flux at autonomous marine observatories are promising tools for the detection of climate-driven changes in ecosystem productivity and inputs of terrestrial carbon to the Arctic Ocean.

4.4.3 Objectives

The long-term, overarching objective of Project 1.4 was to assess how changes in sea-ice cover, water temperatures and ocean circulation affect microalgal production, fisheries resources and marine mammal frequentation of the coastal Canadian High Arctic. Specific objectives were to relate physical parameters to:

- Key indices of ecosystem maturity at the end of the biological production season (September/October), including nutrient drawdown, microbial stocks and species composition, copepod population structure and larval fish growth;
- Microalgal dynamics as captured by orbiting remote sensors and vertical carbon fluxes;
- The availability of fish and marine mammal resources using echo-sounding, experimental trawling and passive acoustics.

4.4.4 Introduction

All the living, harvestable resources of the Arctic Ocean ultimately depend on the production of microalgae (phytoplankton and ice algae). This production requires light and is constrained by the plant nutrients supplied from deep waters, rivers and ocean currents. By blocking light and the wind-driven replenishment of nutrients from deep waters, sea ice presently limits photosynthesis over much of the Arctic and, consequently, the yield of renewable resources. Recent studies of secular polynyas imply that, as the ice cover thins, shrinks and melts earlier in the year, the greater penetration of light and intensified wind drag will bolster marine productivity in the short term.

The increased productivity and warmer waters will initially benefit some autochthonous species, but accelerate their displacement by temperate assemblages. For example, the new conditions could potentially favour the development of unpalatable or harmful algae that commonly disrupt food webs and human health at lower latitudes. Higher up the food chain, the boreal capelin and the prized Atlantic cod (*Gadus morhua*) could spread North (as seen in the Barents Sea), displacing the much smaller Arctic cod (*Boreogadus saida*). Arctic cod is the central element of the relatively simple, current food chain that leads from microalgae to the polar bear. This small and extremely abundant fish funnels an estimated 93% of the energy flow between plankton and pelagic vertebrates such as seabirds, marine mammals and man (Welch et al. 1992).

Changes in the location, species and biomass of preys and predators (birds, fish and marine mammals) due to warming, the loss of sea ice and shifting ocean currents will impact existing fisheries and should favour the development of new ones. For example, the recent warming trend benefited the salmon fisheries of Alaska and Pacific salmon have been seen further East in the Arctic basin than ever. The distribution of species such as the northern shrimp, which supports a lucrative fishery in southern Greenland, could shift. As global fisheries continue to decline, the value of new Arctic resources could soar, providing new opportunities to Northerners. However, strong policies will be required to prevent the southern corporative industry from taking control of these resources and to avoid importing North the poor management practices that led to the commercial extinction of several southern stocks.

Figure 1. *Deployment of the Rosette off the side of the CCGS Amundsen, showing the 24 sampling bottles and the site of sensors underneath. Photo: Martin Fortier.*

The marine Arctic ecosystem performs other crucial services beyond life support. For instance, photosynthesis fixes the greenhouse gas CO_2 into plant biomass, of which a portion is assimilated by herbivores and another sinks to the bottom directly or as the by-products of consumers (e.g. feces). Because this "biological pump" effectively removes carbon and decreases the partial pressure of CO_2 in surface waters, it allows more CO_2 to enter the ocean and mitigates global warming. On the shelves, additional vertical fluxes of carbon are mediated by the deposition of organic and inorganic (e.g. silt, sand grains) particles supplied by rivers and coastal erosion. By altering these fluxes and the biological pump, either physically or via biological activity, changes in sea ice and temperature will feedback on climate by altering the capacity of the Arctic Ocean to stow carbon away from the atmosphere.

4.4.5 Activities

Activities during the first phase of ArcticNet fell into three broad categories: (1) the acquisition of new knowledge on the marine ecosystem, (2) the development of applied techniques and methods that procure this knowledge, (3) the construction of ecosystem models. The networking needed to achieve the scientific objectives, support and integrate with other ArcticNet teams and disseminate knowledge is discussed in the last section of this report.

Study area and time frame: The main thrusts of the sampling effort took place onboard the icebreaker *CCGS Amundsen* in 2004 (pilot study), and in 2005 and 2006 with the comprehensive sampling of the North Water, the Northwest Passage and the southeast Beaufort Sea (see general map).

Activities: Two types of activities were performed during or in connection with the 2005 and 2006 ArcticNet successful expeditions: (1) biological oceanographic sampling of the water column proceeded and at a large number of oceanographic stations, and (2) marine observatories were established and monitored locally with autonomous instruments and remotely with orbiting sensors.

Figure 2. *Net deployment off the foredeck of the CCGS Amundsen. Photo: Marie-Emmanuelle Rail.*

Oceanographic sampling

The water column in the Canadian Arctic is highly layered, providing a host of habitats with different conditions of turbulence, temperature, light and nutrients for organisms. These layers must be sampled at various scales in order to comprehend how the ecosystem functions and interpret remote sensing images correctly. To this end, vertically-resolved information was acquired during continuous, underway acoustic surveys and with discrete sampling for optical properties and particles, nutrients, dissolved inorganic nitrogen and exopolymeric substances, microbial stocks, isoprenoid markers of ice algae, zooplankton and fish at key stations along the track of the *CCGS Amundsen*.

Water samples for the analysis of nutrients, dissolved substances and microbial stocks were obtained with a Rosette device equipped with 24 sampling bottles and sensors for temperature, salinity, light, oxygen and fluorescence (Figure 1). Nutrients were determined fresh using fluorometric and colorimetric methods. Primary production (i.e. photosynthesis) and nutrient uptake by microalgae were estimated by incubating live samples under simulated in situ conditions. Samples for microbial stocks were collected on filters or preserved with chemical agents. These samples were submitted to a host of analyses, including but not limited to pigment determinations (HPLC), chemical composition and taxonomy (microscopy, flow cytometry, DNA).

The abundance of zooplankton and fish (larvae and juveniles) was assessed using a combination of direct sampling with nets and active acoustics with the ship-mounted, multifrequency echosounder SIMRAD EK60. Discrete samples were collected with a variety of vertically and horizontally towed devices (e.g. Figure 2), including a Hydrobios, a Bioness, a Tucker and an experimental mesopelagic trawl. The catch was sorted and preserved for subsequent morphometric and taxonomic analysis in the laboratory. Juvenile and adult gadoids (e.g., Arctic cod) from the Beaufort Sea were identified to the species level and their age (otholimetry), size, condition, sex, maturity and gut content were determined.

Marine observatories: moorings and remote sensing

The backbone of each marine observatory consisted of bottom-tethered lines that held a comprehensive suite of autonomous recording instruments positioned in key water layers (Figure 3). These moorings must be deployed with a large ship and, ideally, serviced every year to download data, collect samples and replace batteries. The autonomous instruments gather physical data (e.g. currents & temperature), monthly or bi-weekly records of settling particles and, on a subset of moorings, chlorophyll fluorescence and passive acoustic data on marine mammals. In 2004, the CCGS Laurier and Amundsen serviced and deployed four moorings (CA-04, 05, 07 & 18) in the Beaufort Observatory. In 2005, these moorings were serviced and the *CCGS Amundsen* launched four additional ones (BA-01, BA-02, BA-03 and BA-04) in northern Baffin Bay to establish the North Water Observatory. The 2006 expedition proved challenging as BA-04 could not be retrieved, the upper portion of BA-03 was severed and carried to Iqaluit and BA-01 was partly retrieved; hence the lack of data on settling particles and marine mammal frequentations at these sites for 2005-2006. Fortunately, there were enough spare instruments on board to rebuild these moorings and the long-term program was not compromised.

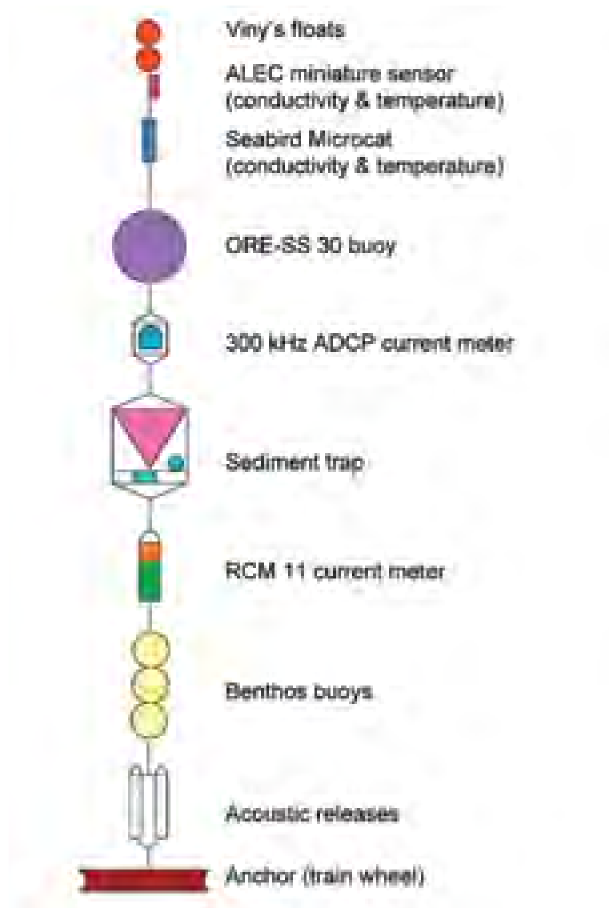

Figure 3. *Schematics of a shallow mooring line, showing the sequence of various components on the vertical.*

The Beaufort moorings were successfully serviced and re-deployed. In the context of IPY, and with new funds awarded by the Canadian Foundation for Innovation, three moorings were added to the Beaufort Observatory in 2007. Close collaborations with the Russia/US program NABOS led to the establishment of a third observatory in the Laptev Sea. The ArcticNet contribution started with a full "Canadian Mooring" and two acoustic current meters on Russian moorings deployed North of the New Siberian Islands during the September 2004 NABOS expedition. Biological sampling was also conducted at this time and during the 2005 expedition that serviced the moorings. This

Figure 4. *Retrieval of a sediment trap (vertical carbon fluxes) attached to a mooring cable. The sequential sampling cups are visible at the bottom. Photo: Keith Lévesque.*

international collaboration was bolstered in 2007 with the deployment of two additional Canadian moorings in the Laptev Sea.

Settling particles, which were collected sequentially in the rotating cups of particle interceptor traps attached to moorings, provided crucial information on biological activity in the upper layers (Figure 4). One can reconstruct some aspects of the history and timeline of biological productivity near the surface and identify the key organisms involved. Because each sample in these traps covered a period of 2-4 weeks at a fixed location, it was useful to estimate vertical fluxes at shorter time scales or other sites to elucidate driving processes and spatial variability. Accordingly, vertical particle fluxes using the Thorium approach and free-drifting traps deployed for a day at most were assessed by collaborators with coupled measurements of the microbial degradation of particles along their downward transit.

The remote sensing component of observatories aimed at monitoring microalgal production (SeaWiFS, AQUA-MODIS and MERIS sensors) and sea-surface temperatures (AVHRR) at various spatial and temporal scales as well as providing context for the moorings and oceanographic surveys.

Modelling

Direct observations of the marine Arctic fauna will always be available only for a small fraction of the vast Arctic Ocean. These observations provide crucial information on ecosystem processes, but they have limited statistical value when trying to extrapolate the evolution of the system into the future. Numerical modelling is the golden tool to expand the observational understanding of the response of the ecosystem both spatially and into the future. Thanks to external funding from the Quebec Government (FQRNT) and the Canada Foundation for Innovation, and in close collaboration with Project 1.1, Project 1.4 has developed new expertise in coupled physical-biological models of Arctic marine ecosystems. One model addressed the coupling between physics, primary production and zooplankton (NPFZ model) and the other addressed the recruitment of Arctic Cod in relation with environmental parameters and food availability. Each of these models processed the data generated by field activities and now represent a central contribution to ArcticNet IRISes.

To support the modelling, a large variety of sampling designs, field work techniques and analytical procedures was used throughout this project. The detail field and experimental protocols used are described in documents cited in the «References» section of this report. The project team successfully designed and developed numerous sampling techniques, including as follows:

Remote sensing

Orbiting sensors of ocean color detect the radiation emanating from the surface and the algorithms used to decode this data must correctly interpret the signal when it reaches space. This task is straightforward for relatively clear oceanic waters (Bélanger 2001), but data from CASES indicated that current algorithms may be ill adapted to the southeast Beaufort Sea and the Mackenzie Shelf, where optical properties are often affected by freshwater runoff. A validation exercise was initiated by comparing in situ measurements of particulate and dissolved substances with above-water radiometry and profiles of inherent and apparent optical properties.

Passive acoustic monitoring

The continuous observation of marine mammals over large areas is required to detect and understand the effects of climate change on their habitat use and annual migrations. This task posed a colossal technical challenge that could not have been met a few years ago. Current progress in underwater acoustics, signal processing, computers and instrumentation made it possible to track the signature vocalisations of marine mammal species, which propagate over tenths to hundreds of km in ocean basins. One of the main challenges in the interpretation of acoustic data is to deconvolute the different biological signals from ambient noise. The remoteness and

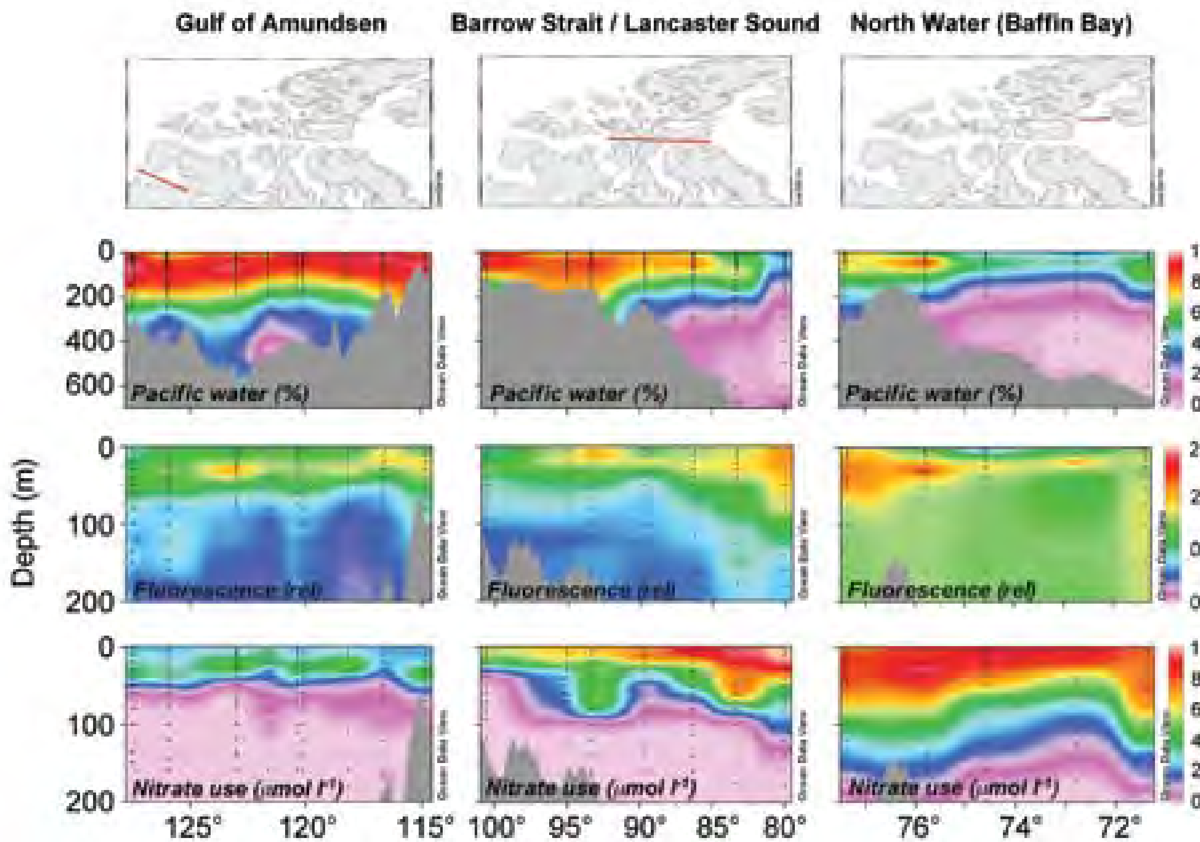

Figure 5. *Spatial variations of the percentage of Pacific water (top row), in situ chlorophyll fluorescence (middle row) and cumulative, seasonal nitrate use by micro-algae (bottom row) along vertical oceanographic sections across the Gulf of Amundsen, Barrow Strait/ Lancaster Sound, and northern Baffin Bay (North Water). Note the different vertical scale in the top row and the logarithmic scale for fluorescence. Data from J.-É Tremblay and J. Martin.*

immensity of the ArcticNet study area seemed ideal to test and implement innovative, passive acoustic monitoring technologies. The new AURAL autonomous hydrophones were installed on some of the moorings deployed in observatories. These programmable instruments, which are able to record underwater sound over a year, were successfully tested at the Mackenzie shelf break in autumn 2004, when ice was closing in and whales were migrating out. Second-generation instruments (AURAL M2) were attached to other moorings in 2005 and provided the first annual cycle of acoustic data in the Arctic.

Experimental trawling

The *CCGS Amundsen* is a very efficient scientific research vessel but has no fish trawling capacity. On commercial trawlers, nets are deployed directly from behind the ship; this is not feasible on the *CCGS Amundsen* whose aft portion is occupied by the much needed heli-deck. Since 2004, considerable efforts have been devoted to develop a mesopelagic trawl that can be deployed from the foredeck of the *CCGS Amundsen*. Extensive trials were first conducted on a DFO research trawler to improve the design and efficiency of the trawl to the point that it can catch large zooplankton and forage fish such as capelin. Tests with the improved trawl were also performed with the *CCGS Amundsen* to the extent that it now has the capability of sampling concentrations of forage fish in the Arctic. With DFO, the possibility of chartering a scientific or commercial trawler was explored to assess the potential of commercial fishery development in some areas of the Canadian Arctic. The feasibility of this endeavour for Phase II will be reported to Inuit partners.

4.4.6 Results

The processing of discrete biological samples and terabytes of acoustics and remote sensing data was a time-consuming task, which can take up to years in many cases. For this reason, the overview of deliverables presented in this section draws primarily from the final data products of the comprehensive 2005 expedition and, when possible, integrates results from 2006.

Biological oceanographic context, seasonal productivity and microalgal hot spots:

The Canadian Arctic is at the confluence of Pacific, Atlantic and river waters. Because these waters have distinct origins and characteristics, changes in their relative penetration into the Arctic have far-reaching implications for the dispersal of heat (warming and ice melt), nutrients and microbial stocks. A first step in understanding the interaction between biological productivity and the physical environment is to monitor Pacific and Atlantic water incursions. This task was achieved by comparing the ratios of different nutrients at the sampling sites with the signatures of end-members in the central Beaufort Sea and the eastern North Atlantic, using the quantitative approach of Tremblay et al. (2002a) modified after Jones et al. (2003). Results clearly showed the deep layer of Atlantic water (purple-blue) in the Gulf of Amundsen and Baffin Bay (Figure 5, top row). This deep water enters via two remote gateways, one is Davis Strait (northern Labrador Sea) and the other is Fram Strait (Greenland Sea). Because of its relatively low density, the Pacific Water that enters through Bering Strait flows on top of the Atlantic Layer in the Beaufort Sea. A faint river signal can be seen at the very surface in the western Amundsen Gulf. Deep Atlantic waters do not penetrate the shallow Northwest Passage and Barrow Strait from the west. However, the surface Atlantic water supplied through Davis Strait is clearly present in Baffin Bay and eastern Lancaster Sound, where it collides with the wedge of Pacific water. The "bubble" seen near the surface in western Baffin Bay originates from a different branch of Pacific Water, one that comes from the north through Nares Strait.

Chlorophyll fluorescence is a useful index of microalgal biomass in the water column (Figure 5, middle row). At any given location, the microalgae are most concentrated in the upper ocean where there is enough light to drive photosynthesis. The maximum fluorescence, however, is generally observed away from the surface in layers that can be as deep as 60 meters. The prevalence of these subsurface layers suggests that microalgae are potentially nitrogen-limited at the surface and this has serious implications for food web dynamics and the ability to detect microalgal biomass from space. The maximum biomass attained on the vertical was highly variable across regions. At the core of what is hereafter called “hot spots”, maximum fluorescence was 1 to 2 orders of magnitude higher than background values in adjacent waters. The relative difference in biomass per hectare between the tropical rain forest and the tundra is a reasonable terrestrial analogy. From west to east, these hot spots were located in the central Gulf of Amundsen, the steep continental rise at the entrance of Dolphin and Union Strait, off Resolute at the head of the sill, at the Pacific/Atlantic front near the entrance of Lancaster Sound and in the western and eastern North Water. Of these, the hot spots located in the Atlantic sector of the Canadian Arctic were the most intense.

The cumulative, new production of microalgae during the growth season is a powerful indicator of the potential productivity of higher trophic levels. In the Arctic Ocean, the net synthesis of organic carbon by microalgae is proportional to the consumption of labile, allochthonous nitrogen, which consists primarily of nitrate away from rivers (Tremblay et al. 2006a). The nitrate consumed by microalgae during the growth season is replenished by the upwelling of deep waters and the mixing caused by wind shear, convection and brine rejection during late fall and winter, tides or internal waves. Results from the NOW and CASES projects revealed that this renewal is extensive in Baffin Bay and modest in the Beaufort Sea due to contrasted regimes of stratification and atmospheric forcing (Tremblay et al. 2002a; 2008). These programs also provided the necessary baseline relationships between salinity and nitrate during late winter. Because nutrients are mixed, diluted or concentrated conservatively with salt in the absence of biological activity, salinity profiles (Project 1.1) at the time of ArcticNet expeditions can be used to infer nitrate inventories prior to the growing season. After correcting for the fraction of Pacific water at a given site, the new production of plant biomass is estimated by subtracting observed concentrations from inferred, initial ones. The intensity and vertical extent of the nitrate deficit generally increased towards the east (Figure 5, bottom row), with regional peaks located at or near fluorescence hot spots. The largest nitrate deficit was observed in August 2005 in the North Water and reached as deep as 160 m. This deficit was equivalent to a new carbon production of 83 g C m^{-2} (assuming a C:N production ratio of 7.0). A scaling exercise showed that the overall yield of microalgae along a single, 1-km wide strip of ocean from Ellesmere Island to Greenland was equivalent to the approximate mass of 1000 large bowhead whales. By contrast, the apparent new production in the North Water had dropped to 43 ± 14 g C m^{-2} in 2006. Corresponding averages for the Gulf of Amundsen were 18 ± 3 and 15 ± 4 g C m^2 for 2005 and 2006, respectively.

The taxonomic composition, chlorophyll biomass and short-term production rates (i.e. amount of carbon fixed photosynthetically on a given day) of microalgae were assessed at a subset of stations (Figure 6). In 2005, production rates and chlorophyll a were generally much higher in the North Water and eastern Lancaster Sound than in the Gulf of Amundsen and the Beaufort Sea. Small cells (<5 µm) systematically dominated the assemblage outside of hot spots, where large microalgae (>5 µm) were especially active. In addition, picoeukaryotes dominated over picocyanobacteria in all regions, but the latter were six times more abundant in the Beaufort Sea than in the North Water (not shown). The nano-planktonic microalgal community was always dominated by flagellates, except at hot spots where centric diatoms of the genus *Chaetoceros* took over. Dinoflagellates were in very low abundance at all sites sampled.

Remote sensing:

In situ measurements correlated well with satellite observations for temperature, but not for chlorophyll in the coastal Beaufort Sea, confirming the suspicions about the complexity of optical properties in that region. The results of the validation exercise

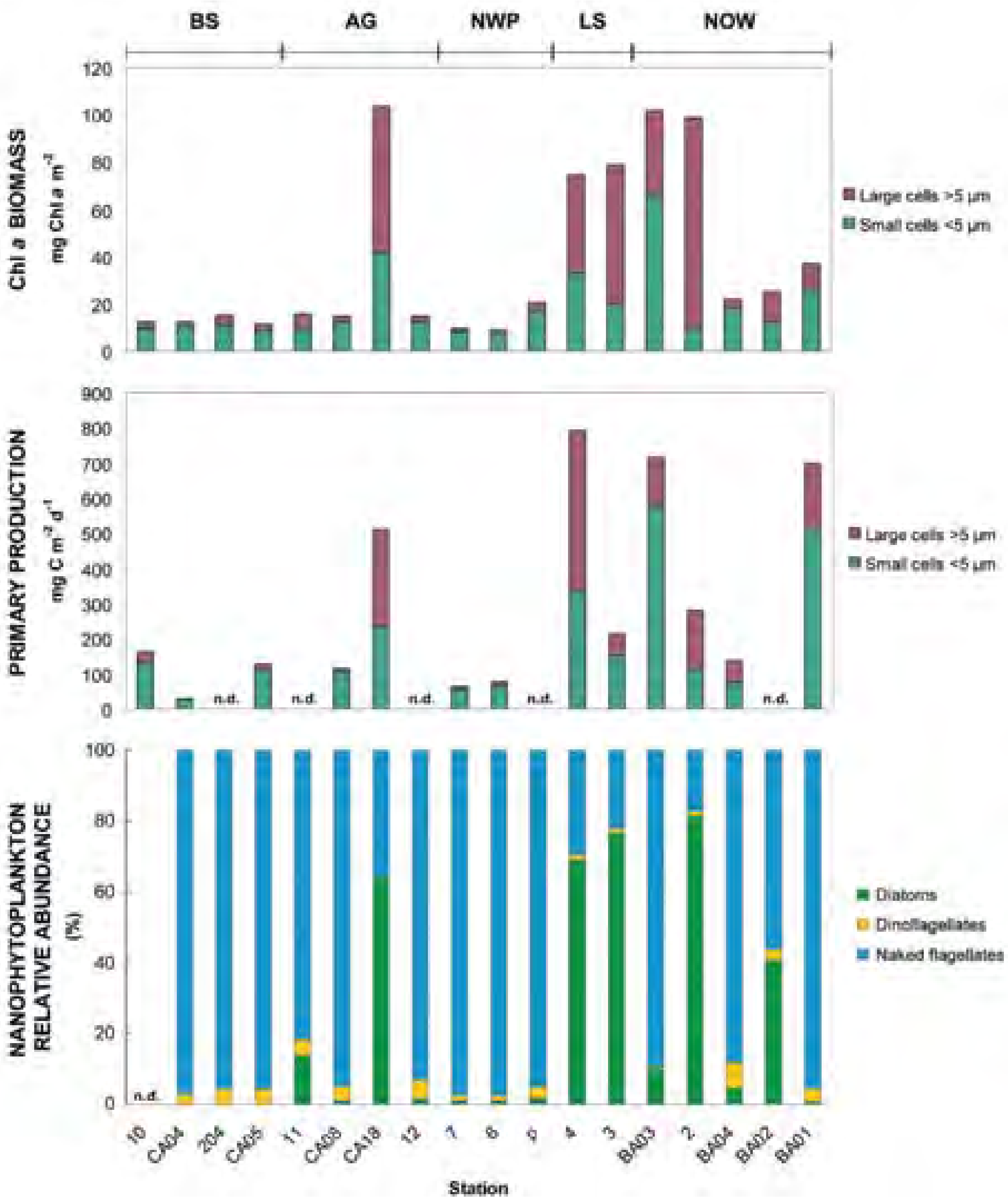

Figure 6. *Spatial variations of size-fractionated micro-algal biomass (upper panel), production (middle panel) and taxonomic composition (lower panel; subsurface layer of maximum fluorescence) across a transect intercepting the Beaufort Sea (BS), the central Gulf of Amundsen (AG), the Northwest Passage (NWP), Lancaster Sound (LS) and the North Water (NOW). Data from M. Gosselin, M. Poulin and G. Tremblay.a*

confirmed that neither the OC4v4 or the OC3M algorithm currently used for processing ocean colour data were appropriate for the assessment of microalgal biomass in the Gulf of Amundsen. Algorithms developed specifically for the Arctic (OC4P and OC4L) did not offer better performances. The nature of this problem is illustrated in Figure 7, where ocean colour in the southern Beaufort Sea showed the strong influence of the Mackenzie River plume near the shore. The isolated green swirl off the shelf and thin filaments in the central Gulf of Amundsen indicated microalgal blooms, but it was difficult to deconvolute the different spectral signatures in the immediate vicinity of the shelf break. In the relatively clear water of the eastern Canadian Arctic, elaborate mesoscale structures in microalgal biomass were observed at the junction of Lancaster Sound and Baffin Bay and a bloom took place in the northern and central North Water. Sea-surface maps of temperature are not presented here, but are accessible on the web site of the St. Lawrence Observatory (www.osl.gc.ca).

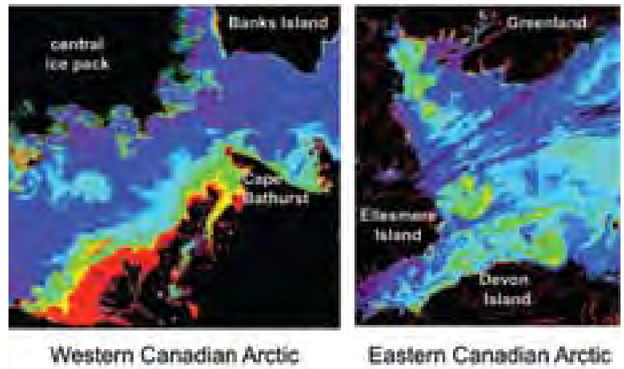

Figure 7. *MERIS images of suspended matter for a) the Beaufort Sea (5 sept 2006) and b) Baffin Bay (9 July 2006) showing the complex spatial structures observed in both regions. The colour scale goes from purple for background concentrations of suspended matter to red for the highest loads. Images provided from P. Larouche.*

Vertical carbon fluxes: present and future sequestration of atmospheric CO_2:

Vertical flux data obtained at the observatories indicated marked differences in the timing and magnitude of organic carbon fluxes for 2005-2006 (Figure 8). The timing of the summer rise in sedimentation provided a good indication of when the microalgal bloom is available for grazers in the different regions. This rise occurred first in the eastern North Water, where maximum fluxes were also the highest. Cumulative annual fluxes for 2005-2006 were estimated at 1.6, 2.4, 5.9 and 4.2 g C m^{-2} yr^{-1} for the Mackenzie shelf break, the Gulf of Amundsen, the eastern North Water, and the Laptev Sea, respectively. Note the relatively high annual fluxes in regions that are strongly influenced by Atlantic water.

Acoustics:

Echograms of the water column generally revealed denser biomasses in the eastern Canadian Arctic than in the archipelago and the Beaufort Sea (Figure 9). A particularly dense layer was found along the north-eastern coast of Baffin Island at depths between 200 and 500 m (Figure 9, layer 1). This layer was more concentrated at shoaling points along the continental shelf and in fjords perpendicular to the shelf break. Unfortunately, the relative contribution of small fish and zooplankton to the signal could not be resolved since direct fishing of the acoustic targets was not possible. Another dense layer with a fish-like acoustic signature was found between the surface and about 70 m, which varied in extent between years and occasionally showed well-defined sub-layers (Figure 9, layer 2). The layer was generally denser at the mouth of Lancaster Sound, in the North Water and along the eastern coast of Baffin Island. In the Gulf of Amundsen, the lower half of the water column harboured substantial densities of Arctic cod (Figure 9, layer 3), which exhibited an exceptionally dense over-wintering aggregation at the mouth of Franklin Bay in winter 2004 (Figure 9, bottom; Benoit et al. 2008). Densities increased towards the head of the Gulf. The shallow Dolphin and Union Strait leading to Coronation Gulf presented particularly high densities every year (Figure 9, layer 4). In the Beaufort Sea, a 100-m thick fish layer was occasionally observed in the upper

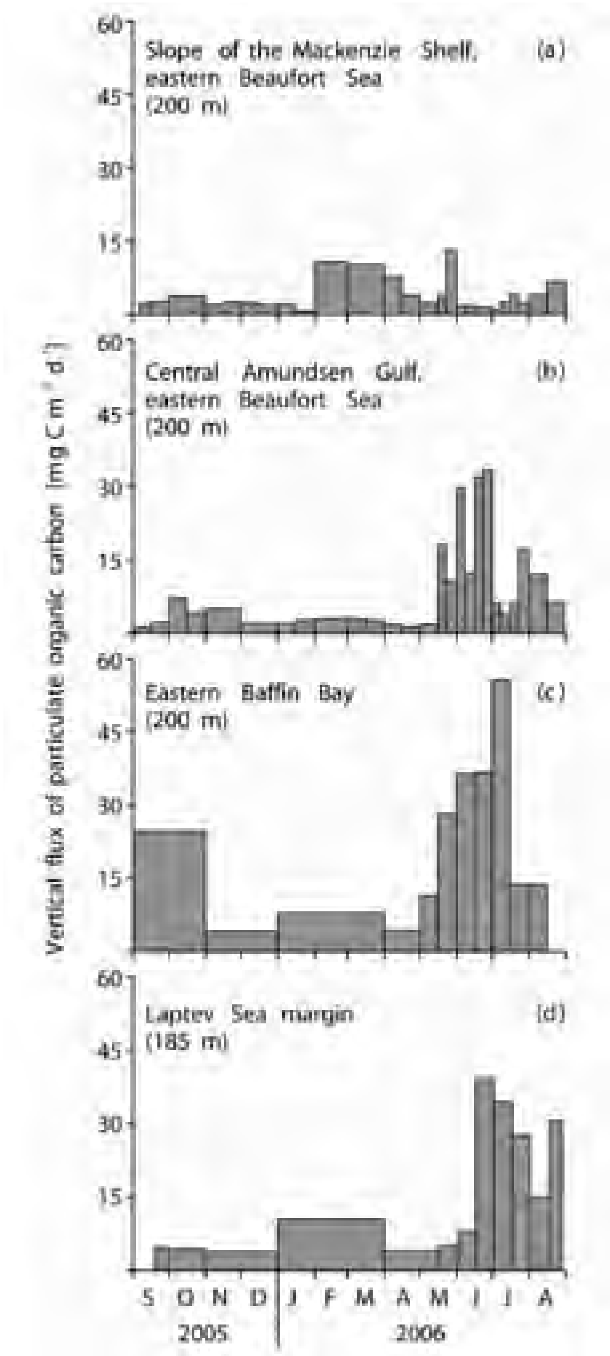

Figure 8. *Time series of particulate organic carbon (POC) fluxes at around 200 m in different regions of the Canadian and Siberian Arctic Ocean from September 2005 to August 2006. Data from A. Forest and L. Fortier.*

water column off the Mackenzie shelf (Figure 9, layer 5). Fish were more scattered on the shelf, where no significant aggregation was detected. Although intensive ice breaking often interfered with echosounding in the Northwest Passage, the discontinuous data available indicated the lowest densities of organisms in the Canadian Arctic. Preliminary analyses of the passive acoustic data indicated that vocalisations from several species are present throughout the year, with peak densities at particular seasons depending on the species (Figure 10). Ocean noise also had strong seasonal variations due to surface waves and ice rafting.

The Arctic cod (*Boreogadus saida*), a key species in the Arctic marine ecosystem:

Arctic cod spawn at depth on ice-covered Arctic shelves in late fall and early winter and the large buoyant eggs rise slowly to the ice-water interface. At the sub-zero temperatures prevailing under the ice, egg development is slow and the incubation can last for 60 to 90 days. Based on field and laboratory studies, the larvae measure from 5 to 7 mm at hatch. Metamorphosis into pelagic juveniles occurs at 27 to 35 mm. Starting in late summer, Arctic cod fry are increasingly preyed upon by their adult congeners and by Arctic seabirds. The larger the size they attain at the end of the short Arctic summer, the less vulnerable Arctic cod pelagic juveniles will be to avian predation and cannibalism. Accordingly, Fortier et al. (2006) proposed that the spawning and hatching strategy of the species aims at maximizing pre-winter size.

Bouchard and Fortier (2008) reviewed the literature and found two distinct hatching patterns across Arctic Seas. First, a short spring hatching season (May to June/July) centered on the ice break-up and the onset of biological production in the Barents Sea, Northern Baffin Bay and the Greenland Sea (Baranenkova et al. 1966; Sekerak 1982; Fortier et al. 2006). Second, a protracted winter/spring/summer hatching season (January to July/August) in the Kara and Laptev Seas where

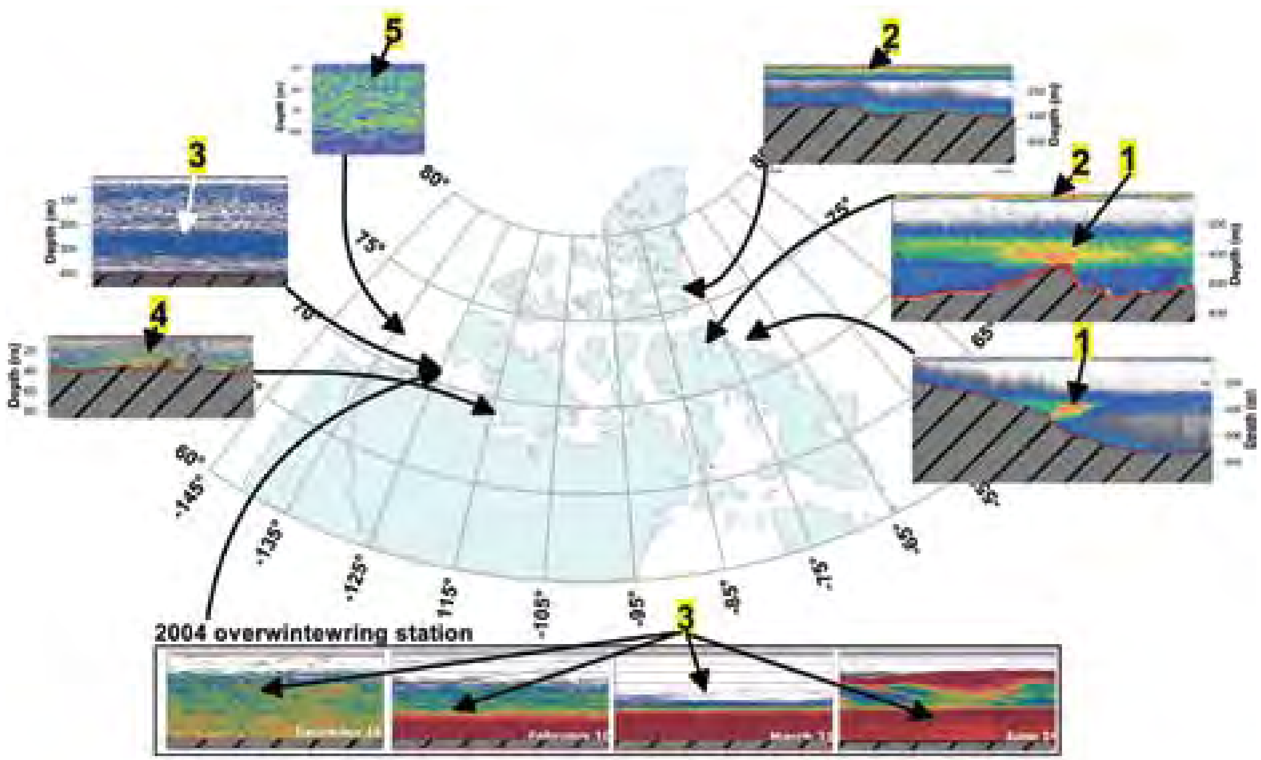

Figure 9. *Examples of the dense layers of fish and zooplankton detected in the western and eastern Canadian Arctic by the multi-frequency acoustic system of the CCGS Amundsen during 2004 and 2005. Data from D. Benoît, Y. Simard and J. Gagné.*

most larvae emerge under the sea ice in late winter (Baranenkova et al. 1966; Bouchard and Fortier, 2008). Bouchard and Fortier (2008) hypothesized that winter temperature at the ice-water interface, which depends on salinity, dictates the hatching season of Arctic cod by limiting the early survival of the larvae. Water temperature at the interface will vary with salinity from ca. -1.8°C (S = 33) to 0°C (S = 0). In coastal seas influenced by large rivers, brackish conditions in the under-ice river plume in winter would provide the larvae with temperatures only slightly below 0°C, allowing successful first-feeding and survival. In regions with little freshwater input, the extreme low temperature prevailing in the surface layer (-1.8°C) would prevent locomotion, prey capture and survival as shown under experimental conditions for first-feeding Atlantic cod larvae (Valerio et al. 1992). In these regions, hatching must be delayed until the ice break-up and the warming of the surface layer in spring. To test this hypothesis, the Hatchdate Frequency Distribution (HFD) of Arctic cod was determined during ArcticNet. In 2005, for example, the larvae hatched in winter or winter/spring in Hudson Bay and the Beaufort Sea, and in spring and summer in Baffin Bay and Lancaster Sound (Figure 11).

Coupled physical-biological models of the Arctic marine ecosystem:

Physical models of the circulation in the Canadian Archipelago were developed and its ancillary seas that are driven by climatology and larger-scale models. Then different biological modules that simulate ice algae and phytoplankton production and larval fish growth were also developed. For example, and Individual-Based Model (IBM model) of larval and juvenile growth forced

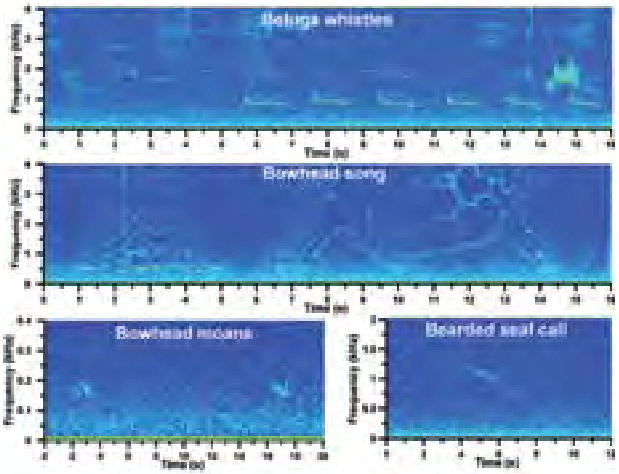

Figure 10. *Typical sonograms of the vocalizations of different marine mammals recorded with an autonomous AURAL hydrophone on ArcticNet moorings. Data from Y. Simard.*

by temperature, food availability, and predation was developed to simulate the early growth of Arctic cod. The model successfully reproduced observed differences in growth between the Beaufort Sea, the North Water in Baffin Bay and the Northeast Water in the Greenland Sea (Figure 12). This IBM model was coupled to the circulation model for the Archipelago with the aim of forecasting the response of the species to the future climate and ice regimes anticipated by IPCC scenarios.

4.4.7 Discussion and Conclusions

The impact of changes in temperature and ice cover cannot be demonstrated with only two years of comprehensive data. The objectives were framed for a longer window of observation extended to Phase II of ArcticNet. Nevertheless, clear spatial structures and temporal differences were observed in the various biological indices of food web productivity. These patterns were coherent across the suite of ecosystem indicators considered, providing crucial insights on the present and future state of the Canadian High Arctic.

Project 1.4 performed the first synoptic investigations of the marine biota across the Pacific and Atlantic sides of the High

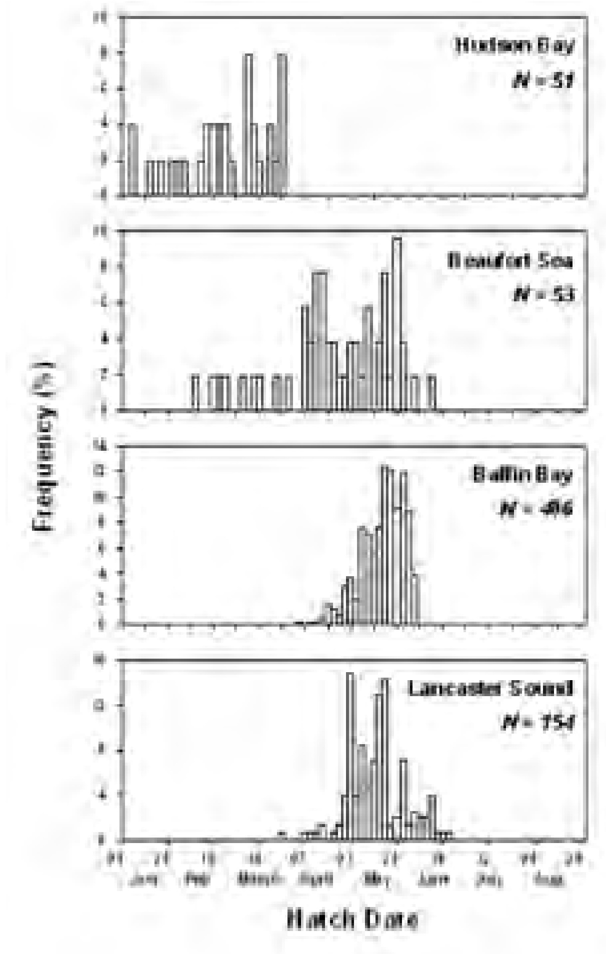

Figure 11. *Hatch date frequency distributions (HFDs) of Arctic cod larvae and juveniles collected from 05 August to 16 October 2005 in different regions of the Canadian Arctic and sub-arctic. Fish were grouped in 3-day sub-cohorts represented by a single bar. HFDs are corrected for mortality and dispersion. Data from C. Bouchard and L. Fortier.*

Canadian Arctic. A preliminary comparison with other years (data not shown here) indicated that the longitudinal position of the Atlantic/Pacific front in Lancaster Sound is variable, which may have a profound influence on the productivity of this hot spot. The Pacific water content of the North Water was lower in 2005 than in 1998 (NOW program; Tremblay et al. 2002a), suggesting some degree of "atlantification" in northern Baffin Bay. Since a similar trend was observed in the central Arctic and the Greenland Sea (McLaughlin et al. 2004; Falck et al. 2005) the early signs of a large-scale response to climate forcing may have been observed. The cumulative seasonal drawdown of nitrate in the North Water and the Gulf of Amundsen was relatively high in 2005, which could be related to the record low in ice extent for that year (www.nsidc.org). However, the different data sets were not collected at exactly the same time every year and the influence of seasonality on the results cannot be discarded yet.

The highest seasonal estimates of new production were associated to polynyas with low to moderate amounts of Pacific water, suggesting that the presence of Atlantic water in the Canadian Arctic has a positive effect on ecosystem productivity. This effect was presumably linked to the relatively high salt content and weak stratification of the Atlantic water (data from Project 1.1), which makes it more susceptible to mixing by winds, convection and brine rejection. This notion is supported by the deep extent of the nitrate depletion in the North Water. Since the subsurface chlorophyll maximum (SCM) is generally confined to the upper 60 m, where there is enough light for photosynthesis, the deep nitrate deficit was likely caused by vertical mixing and upward diffusion during the growth season (see Tremblay et al. 2002b).

Taxonomic analysis and size-fractionation procedures indicated that hot spots where dominated by large diatoms (Figure 6), which are regarded as the palatable macro-algae that support short and efficient food chains. This contrasted with the wide-spread dominance of small-sized flagellates and cyanobacteria in surface waters. These organisms generally do not promote efficient transfers of carbon to top predators due to their small size (i.e. more feeding steps and energy losses are required to reach the largest organisms) and, possibly, lesser palatability. Interestingly, other results (not shown here) showed that picoeukaryote abundance increased with water temperature whereas the abundance nanophytoplankton decreased with

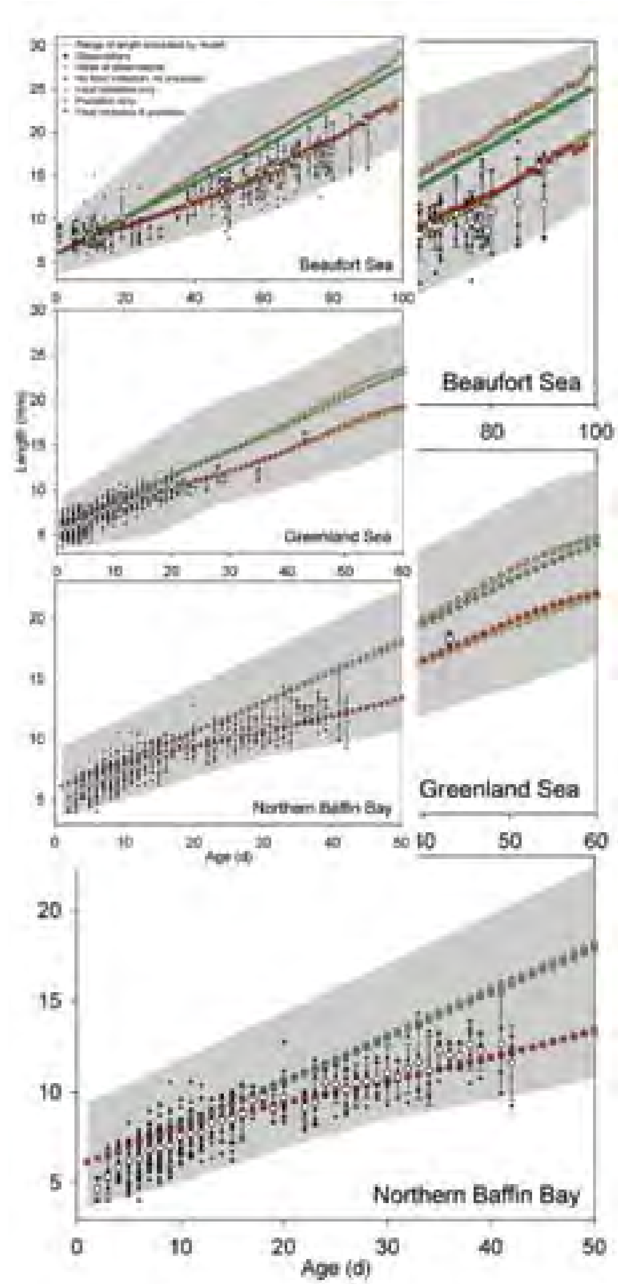

Figure 12. *Numerical simulations of the early growth of Arctic cod* (Boreogadus saida) *in different regions of the Canadian Arctic Ocean. A complex eco-physiological model in which growth is forced by temperature and a combination of food availability and/or predation is used to reproduce the actual growth (size at age) of fish collected at sea. Data from S. Thanassekos and L. Fortier.*

the vertical stability of the water column in late summer. Furthermore, brackish waters seemed to favour picocyanobacteria that, as noted previously by Waleron et al. (2007), are advected in the plume of the Mackenzie River. These results suggested that increases in river discharge and temperature will influence the distribution and abundance of macro-algae and affect the attractiveness of a given region for consumers. It is noteworthy that the abundance of dinoflagellates, the group of micro-algae that harbours the highest number of potentially harmful species, is presently negligible.

The association between regional maxima of seasonal nitrate drawdown and microalgal biomass and production in late summer suggested that hot spots are not transient phenomena but persist throughout the ice-free season (Figures 5, 6 and 7). The coincidence is even surprising because nutrient-depleted waters should eventually become inhospitable for large microalgae. This is probably what happened in the eastern North Water where fluorescence was relatively low compared to the large nitrate deficit. Other hot spots exist, obviously, since the data presented here only cover a portion of the CCGS Amundsen surveys. Remote sensing data revealed the spatial extent and complex structure of the microalgal hot spots, providing context for the linkages between ecosystem productivity and large-scale physics (Figure 7). For instance, the spiral-shaped pattern of chlorophyll biomass seen off the Mackenzie shelf in 2006 implied the presence of an oceanic eddy, which may have been pumping nutrients to the surface.

The remote-sensing validation exercise implied that the description of microalgal biomass and production based on previous remotely-sensed data for the Gulf of Amundsen (Arrigo and Van Dijken 2004) are biased towards higher values. When divided by the mean normalized bias value for the OC4L algorithm (3.64), the maximum daily primary production estimated from SeaWiFS was the lowest of all major Arctic polynyas, consistent with the relative differences in nutrient drawdown discussed above. However, the spatial and temporal patterns described in Arrigo and Van Dijken (2004) are generally valid and show that the microalgal bloom in the Gulf of Amundsen generally occurs a month or two later than in the North Water, consistent with the early seasonal rise of vertical fluxes in the later (Figure 8). Efforts later concentrated on the development of a regional algorithm for the Beaufort Sea, which will be used to reprocess archived time series of SeaWiFS and MODIS images and provide accurate representations of hot spots in relation to large-scale physical processes. The effect of subsurface chlorophyll maxima on the ability to estimate total water-column biomass from space is under investigation.

The sediment traps deployed at strategic locations enabled us to assess the vertical and horizontal fluxes of particulate carbon (O'Brien et al. 2006). Given the logistical difficulty of monitoring the Arctic marine ecosystem over the annual cycle, these vertical fluxes were used as indices of primary production, zooplankton grazing and the timing of crucial events in the surface layer. Vertical carbon fluxes at 200 m scaled fairly well with the fluorescence hot spots and seasonal new production (Figures 5 and 8). For 2005-2006, the lowest vertical fluxes were observed on the slope of the Mackenzie shelf, coincident with background levels of chlorophyll and production (Figures 6 and 7). Annual fluxes and cumulative new production were 2.5 and 2.9 times higher, respectively, in the North Water than in the central Gulf of Amundsen. Note that vertical fluxes at 200 m were ca. 6-7 times lower than the estimated new production of carbon in the upper layer, consistent with a detailed investigation of these processes based on time series of measured microalgal production rates (and not reconstructions based on nutrient deficits) in the North Water (Tremblay et al. 2006b). This difference reflected the vertical attenuation of particle flux by the activity of grazers and decomposers that transform microalgal matter into dissolved inorganic and organic substances. It was clear that a scaling factor must be applied to reconstruct surface productivity from vertical fluxes, but more years of data are necessary to determine the correct value of this factor for the different observatories.

A conceptual model was formulated in which the ecosystem shifts from an algal to a detrital mode according to seasonal changes in the relative importance of fresh and old particulate organic carbon supplies (Forest et al. 2008). For instance, the increase in sinking flux observed during late winter 2006 at the shelf slope occurs too early to result from recent microalgal production in the water column or the ice and so must be driven by a combination of re-suspension and horizontal transport (Figure 8). Based on the model of Forest et al. (2008), the ecosystems of southeastern Beaufort Sea and the Laptev Sea could evolve towards a less productive equilibrium dominated by sediment re-suspension in response to the on-going reduction of the ice cover and the increase in river discharge. On the contrary, ecosystems less dominated by riverine inputs of terrestrial sediments (e.g. Baffin Bay) could become more productive as the ice regresses, especially in areas where increased wind mixing and upwelling will break stratification and recharge the surface layer with nutrients. During Phase II of ArcticNet, the cross-shelf fluxes of POC in response to sea-ice thermodynamics and mixing on the Mackenzie Shelf were modeled. The goal is to assess how the oceanic and atmospheric processes (e.g. storms, eddies and thermohaline convection) linked to the formation of sea-ice re-suspend the nepheloid layer (a dense layer of biogenic particles settled on the bottom) over the shallow continental shelf and transport it horizontally to the deep Arctic Ocean (Forest et al. 2006). Most of the carbon transported at depth in this way originates from the atmosphere and the fluxes measured represent the capacity of the coastal Arctic Ocean to sequester the CO_2 responsible for the Greenhouse effect and climate warming.

Multi-frequency echograms of the water column throughout the Canadian High Arctic revealed the spatial structure of fish and large-size zooplankton biomass in the Canadian Arctic to an unprecedented extent and generated new insights into the ecology of a key player, the Arctic cod (Benoit et al. 2008). This biomass represented the multi-year outcome of production at the lower trophic levels and the forage base that supports top predators such as the birds, fishes and marine mammals exploited by the local Inuit communities. Active, acoustic surveys revealed a spatial heterogeneity matching that of microalgal production in 2005 and 2006. The previously identified hot spots of microalgal biomass in the central Gulf of Amundsen, the head of Dolphin and Union Strait, the mouth of Lancaster Sound and the North Water were also the sites of enhanced aggregation of animals, suggesting bottom-up control of food web productivity by ocean physics (Figures 5 and 9). Unfortunately, the difficulty of fishing from the *CCGS Amundsen* and the tight schedule of the multidisciplinary surveys did not allow the comprehensive validation of echograms. One major gap of information that needs urgent attention from the competent authorities is the absence of adequate fishing in the different acoustic layers. This task requires a well-equipped fisheries research vessel with a trained team of experts, as well as systematic indirect ground truthing from the research ice-breaker with innovative new technologies such as the long-range viewing Didson acoustic cameras and high-resolution specialized still- and video-cameras, eventually deployed on autonomous underwater vehicle platforms (AUVs).

The hatch date frequency distribution of Arctic cod during ArcticNet generally supported the hypothesis that winter temperature at the ice-water interface, which depends on salinity, dictates the hatching season of Arctic cod by limiting the early survival of the larvae (Figure 11). Cod larvae hatched in winter or winter/spring in Hudson Bay and the Beaufort Sea where riverine inputs are substantial (e.g. Figure 7). Later hatching (spring and summer) occurred in the productive waters of Baffin Bay and Lancaster Sound, two regions where the influence of rivers was negligible. Similar insights have been gained into the potential response of key zooplankton species to climate-induced changes in sea-ice and freshwater regimes in the coastal Arctic Ocean. For example, to anticipate the impacts of an earlier ice breakup, Seuthe et al. (2007) documented grazing, respiration and fecal pellet production at the crucial transition from winter diapause to active life in early spring. Darnis et al. (2007) described zooplankton assemblages in relation to sea-ice regime and depth in coastal Beaufort Sea, predicting that, under continued warming, a reduction of ice cover on the Mackenzie Shelf will affect zooplankton distribution patterns, to the potential advantage of small neritic form as such *Pseudocalanus* spp., the main prey of larval Arctic cod.

Observations and models provide unique insights into the impact of future Arctic warming on carbon fluxes and key species of the marine ecosystem of the Arctic Ocean. In the short term (say until 2050), increased winter river flow and more frequent winter and spring polynyas could favour the reproduction of the Arctic cod by allowing early hatchers to survive the winter months and reach a large pre-winter size. In the longer term however, the reduction of the icy habitat of the highly-specialized Arctic cod could bring its ineluctable replacement as the dominant forage fish of the Arctic Ocean by boreal generalists such as the capelin (*Mallotus villosus*). The consequence may be the destabilization of the entire marine Arctic ecosystem towards a new equilibrium, as seen in the Bering Sea in recent years (Grebmeier et al. 2006). This new equilibrium will increase the overall biological productivity and the vertical carbon fluxes in coastal Arctic seas (Barber et al. 2006; Barber et al. 2008), in particular in regions where vertical mixing of the highly-stratified surface layer will bring nutrients upwards (Tremblay et al. 2008). In the future the team hopes to study, monitor and model these biological hotspots in the Canadian Arctic, with the objective of formulating strategies for their sustainable exploitation. In some regions of the Canadian Arctic, the fisheries yield could become as large as in the Norwegian and Barents Seas, providing local communities with new economic opportunities. These gains, however, might be offset by economic and cultural losses linked to the partial extinction of key elements of the present assemblage such as the ringed seal, the walrus and the Polar bear.

4.4.8 Acknowledgements

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4.4.9 References

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4.5 Changes in Dietary Pattern and Impacts on Chronic Diseases Emergence (New Diseases) (Project 1.5)

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4.5.1 Abstract

The main objective of the present study was to evaluate the impacts of a changing environment (climate, contaminants, globalization, diet, etc.) on the health of Canadian Inuit. This study began in Nunavik in fall 2004 through the “Qanuipittaa?” survey and continued in Nunavut with the “Qanuippitali” survey. These studies were part of a cohort study entitled The Inuit Health in Transition Study that was carried out among Inuit of three circumpolar countries. The cohort study focused on chronic diseases and their associated risk factors. Diet was the primary focus of this project particularly, marine lipids (omega-3 fatty acids).

4.5.2 Key messages

- The modernization of the Inuit society and particularly changes in dietary habits will possibly compromise the inherited benefit of traditional food in protecting Inuit against chronic diseases.
- Since the 1992 health survey, results show a general improvement of cardiovascular risk factors in this population.
- The population from Nunavik is relatively well protected against these diseases and related risks.
- However, this study revealed an impressive prevalence of risk factor of diabetes such as obesity and hyperinsulinemia in women.
- This study proposes to encourage maintaining and reinforcing diabetes prevention in Nunavimiut.

4.5.3 Objectives

- Investigate the impact of modernisation (mostly diet) on the emergence of chronic diseases (cardiovascular diseases and diabetes) among Canadian Inuit.
- Specify the role of marine fatty acids in cardiovascular diseases protection.
- Better characterize marine fatty acids in the Arctic and the impact of climate change on fatty acids profiles and distribution.

4.5.4 Introduction

Until recently (around 1950), the Inuit could be considered geographically isolated. Effectively, before World War II, the majority of the Inuit in Alaska, Canada, and Greenland lived mainly according to a traditional lifestyle, which was based on subsistence activities such as hunting and fishing (Duhaime 1989 and 1991; Pars et al. 2001). These activities involved vigorous physical activity and high dietary intake of marine mammals and fish. The protection of the Inuit from cardiovascular disease (CVD), diabetes and some types of cancer could be the result of a particular genetic endowment and/or their traditional living conditions.

However, in recent decades, changes in lifestyle and dietary patterns have been observed among Inuit populations. Because of the rapid social transition subsequent to the improvement of communication and transportation with southern regions, and with the settlement of Inuit populations into permanent communities, a shift away from traditional lifestyles and diet was observed in these populations (Nobmann et al. 1992; Kuhnlein and Receveur 1996; Pars et al. 2001; Blanchet et al. 2002; Bjerregaard and Curtis 2002). The traditional food system is declining rapidly, though not uniformly across the Arctic; for most circumpolar regions, dietary intake from market foods exceeds those from traditional foods. In Alaska and Canada, ischemic heart disease and diabetes are on the increase and clinical observations from Greenland support these observations (Moffat and Young 1994; Schaeffer et al. 1996; Bjerregaard et al. 1997; Schraer et al. 1997).

The gradual abandonment of traditional lifestyles and diet has also been associated with an increased prevalence of CVD risk factors such as obesity, high blood pressure and elevated blood lipids. Studies conducted during the 1960s and 1970s suggested that the Inuit appeared to have been spared the diabetes epidemic experienced by many North American Indian groups (Scott and Griffith 1957; Sagild et al. 1966; Mouratoff and Scott 1967; Mouratoff and Scott 1973; Bjerregaard and Young 1998). However, recent data from the Alaskan Native Diabetes Registry indicated that the prevalence among Eskimos is rising, although it is still lower than the rate in the U.S.A. The lower prevalence of diabetes among Inuit has been attributed to their higher consumption of traditional foods (Adler et al. 1994; Murphy et al. 1995; Cervenakova et al. 2002).

The current health status of the Inuit reflects the interaction of genetic and environmental factors (Hegele et al. 1997a). However, despite the above-mentioned unfavourable observations, mortality and morbidity rates for ischemic heart disease (IHD) are still lower in Inuit populations, compared to rates of southern populations, probably reflecting protective lifestyle factors still in operation to some degree (Blanchet et al. 2000; Dewailly et al. 2003; Cote et al. 2004) and possibly a lower genetic susceptibility (Middaugh 1990; Bjerregaard et al. 1997; Hegele et al. 1997a; Hegele et al. 1997b; Schraer et al. 1997; Dewailly et al. 2001). For instance, from 1987 to 1996, the mortality rate (per 100,000 person-years) from IHD amounted to 72.3 in Nunavik compared to 153.5 for Québec as a whole. Furthermore, for the same period, the mortality rate from myocardial infarction was 24.2 in Nunavik, compared to 92.7 for Québec. In Greenland, the mortality rate (per 100,000 person-years) from IHD was 60.0 in 1990 (Bjerregaard and Young 1998). An analysis of death certificates in Alaska during the 1980s showed that Eskimos still had a significantly reduced risk of mortality from IHD (Middaugh 1990), the relative risk being 0.5 compared to US Caucasians (Davidson et al. 1993). Similar low rates have also been reported from the Inuit in the Northwest Territories (Young et al. 1993).

In 1992, "Santé Québec" conducted a health survey among the Inuit population of Nunavik. Main conclusions of this study related to CVD and to their risk factors were: 1) CVD risk factors seemed less prevalent in the Inuit population than among other Quebecers except for obesity and smoking (estimated at 19% and 73% respectively) (Blanchet, C., J. Genest, J. Moisan, L. Sauve and E. Schiffrin. 1992. Health factor leading to cardiovascular disease. In Santé Québec and M. Jetté (eds), A health profile of the Inuit; report of the santé Québec health survey among the Inuit of Nunavik, vol. 2. Ministère de la Santé et des Services sociaux, Gouvernement du Québec, Montréal); 2) prevalence of hypertension was low in the Inuit population in general (Bjerregaard et al. 2003); 3) the lipid blood profile of the Inuit was better than Quebecers' blood profile. Because the data did not permit a definitive conclusion on the prevalence of diabetes among the Inuit, researchers suggested a closer surveillance of diabetes in individuals aged 45 years and over. In light of other results on changes in eating habits, notably the reduction of highly nutritional, traditional food intake and the rising consumption of commercial foods high in refined carbohydrates, saturated and trans-fatty acids, researchers stressed the need for better surveillance and prevention of CVD and related risk factors.

Particularly for cardiovascular and diabetes conditions, the 2004 health survey pursued the following objectives: 1) to determine the prevalence of CVD and diabetes as well as their risk factors; and 2) to estimate the evolution of these health outcomes since 1992. This report presented the main results obtained during the survey.

4.5.5 Activities

Nunavik Health Survey

Study sites and time frame: The collection of the data analyzed for this study was conducted over a period of 5 weeks at the end of the summer of 2004. The target population comprised all permanent residents of Nunavik and the participants constitute a stratified probability sample of the Nunavik population. The 14 villages were visited on board the *CCGS Amundsen* and the cruise started in Kuujjuaraapik and ended in Kuujjuaq. During this health survey, 924 subjects aged between 18 to 74 years old answered a clinical questionnaire providing information on their personal and family medical history (CVD, cancer and associated risk factors).

Activities: Medical records were verified at baseline by a trained nurse to confirm the participants' medical history regarding the specific topics addressed by the study. For each subject enrolled in the cohort, extensive questionnaires were administered to document life-style, diet, exposure to environmental contaminants, etc. A series of medical testing were carried-out, including osteo-densitometry (for osteoporosis risk), ultrasound measurements of carotid thickness, general physiological and anthropometric measurements (height, weight, and hip circumference), blood pressure, etc. Blood samplings (for lipid profile, insulin and glycaemia analyses), hair and toe nail samples were collected for biochemical testing (general medical biochemistry) and contaminants measurements.

All biological samples have been analyzed. Data from analyses and questionnaires were compiled into a database and statistical analyses were completed. Most of thematic chapters and technical reports (i.e. Dewailly et al. 2006) have been written and final results were presented to the Nunavik population in late 2006. A DVD presenting key findings was distributed in all Nunavik households. In December 2006 some results were also presented at the ArcticNet's ASM and NCP's meetings. The final presentation of the "Qanuipittaa?" survey was presented to the Nunavik board of Health in fall 2007.

Follow-up time will be counted from the date of recruitment to seven years later or the date of death or loss to follow-up. Every seven years, the information on potential risk factors, the identification of newly diagnosed cases of CVD, cancer, diabetes and other illness will be updated. In 2008, medical files of participants were examined and hospitalization, cancer and death registries were consulted. In addition, a consultation (community and individual) to seek authorization for genetic testing (susceptibility polymorphisms) in collaboration with Robert Hegele was prepared.

Methods: All interviews, clinical tests and anthropometric measurements were conducted according to standardized protocols.

Anthropological measurements (weight/height/hip) and blood pressure

Height was measured using a rigid square measuring tape with the participant standing barefoot on a hard surface up against a wall. Weight was measured on a beam scale. Waist size was measured after exhalation with the tape horizontal to where the abdomen curves in. If a subject's waist was not sufficiently defined, he or she was measured at roughly the location of the last floating rib. Hip circumference was measured by placing the measuring tape horizontal to the hips at the pubic symphysis and the most prominent part of the buttocks. The measures were recorded to the nearest centimetre. Mean of the four measurements was used for statistical analyses. Anthropological measurements were transformed into Body Mass Indices (BMI: kg/m2) and into standardized body mass indices (BMIstd: kg/m2). A BMIstd value is based on BMI corrected by the Cormic Index and was used in the analysis because it better corresponded with the corpulence of the Inuit population (Charbonneau-Roberts et al. 2005). However, BMI value was used for comparison with the 1992 health survey. International cut-offs to evaluate obesity in the population (BMI≥30) were used (Kuczmarski and Flegal 2000). Abdominal obesity was defined by the waist to hip ratio (W/H ≥1.00 in men and ≥0.85 in women).

Blood pressure was taken according to the "Canadian Coalition for High Blood Pressure technique" using mercury sphygmomanometers, 15-inch stethoscopes, and cuffs sized to the subjects' arms. Prior to having their blood pressure taken, subjects must have rested for five minutes and not eaten or smoked for at least 30 minutes. Each subject had three blood pressure readings. The mean blood pressure was calculated using the two last measurements.

Biological parameters

Nearly 60 ml of blood was taken from each participant after centrifugation; all tubes were labelled and stored in -80°C freezers on board. They were then sent to the Centre Hospitalier de l'Université Laval (CHUL), where they were analyzed for total cholesterol, HDL cholesterol, LDL cholesterol, triacylglycerols (triglycerides), glucose and insulin. Other parameters, such as inflammation and oxidation were not reported in the present document since they were part of a companion research program (Cohort study). Omega-3 blood concentrations will be reported in another report.

Biochemical analyses were performed using a Hitachi 917 autoanalyzer and reagents from Roche Diagnostics. Plasma analysis assessed fasting glucose levels [reference value (RV): 3.6–5.8 mmol/L], cholesterol, triglycerides. HDL cholesterol was measured directly by selectively inhibiting reaction with other lipoproteins. LDL cholesterol was calculated using the Friedwald formula. Target values for individuals at high risk of cardiovascular disease are ≥ 6.2 mmol/L for total cholesterol, ≥ 5.0 for cholesterol/HDL ratio, ≤ 0.9 mmol/L HDL cholesterol, > 3.4 mmol/L for LDL cholesterol, and triglyceride values of ≥ 2.3 mmol/L.

Plasma insulin levels were measured using the Elecsys-2010 system from Roche. Reference values are 0–150 pmol/L for insulin.

Atherosclerosis

Atherosclerosis was measured by carotid ultrasound examination on a sub-group of subjects aged 40 years and over (n=282). Carotid Intima-Media Thickness (IMT) is the best assessment of sub-clinical atherosclerosis and was measured by a portable

Table 1

	OVERALL		WOMEN		MEN	
	MEAN	SD	MEAN	SD	MEAN	SD
BMI						
15-24.9	0.65	0.02	0.62	0.02	0.68	0.04
25-29.9	0.74	0.03	0.69	0.04	0.78	0.04
30-49	0.71	0.02	0.64	0.02	0.79	0.03
Age group						
40-44 years	0.56	0.01	0.53	0.01	0.59	0.02
45-54 years	0.63	0.02	0.59	0.01	0.67	0.03
55-74 years	0.88	0.02	0.81	0.03	0.93	0.03
Fasting glucose						
Normal (< 6.1)	0.70	0.01	0.63	0.02	0.74	0.02
At risk (6.1-6.9)	0.63	0.05	0.51	0.04	0.73	0.07
Diabetes mellitus (≥ 7.0[a])	0.83	0.05	0.77	0.05	0.95	0.10

[a] *Fasting glucose ≥ 7 plus people taking medication for diabetes.*

Table 1. *Mean maximum carotid artery intimal medial thickness (mm) by gender according to various determinants (%), population aged 40 to 74 years, Nunavik, 2004. Source: Nunavik Inuit Health Survey 2004.*

non-invasive ultrasound technique on twelve segments: 2 each of internal, external and common carotids, left and right sides. Carotid IMT was performed only for individuals age 40 to 74 using a GE Logiq Book. Images were stored on disks and interpreted at McMaster University.

Statistical analysis: The analyses reported here are descriptive according to the categories of the various variables such as socio-demographics, lifestyle habits and anthropometric variables. Arithmetic means were calculated for normally distributed variables and geometric means were considered for variables with a log-normal distribution. Variance analysis allowed comparison of means or geometric means and the Khi2 test was used to compare proportions. All data were weighted to make estimations generate from the survey data to representative of the covered population and not just the sample itself. All comparisons with 1992 survey were adjusted for age using the 2001 Canadian Census age distribution for Nunavik as the standard population.

The data used in this study came from a sample and was thus subject to a certain degree of error. The coefficient of variation (CV) was used to quantify the accuracy of estimates and the Statistics Canada scale was used to qualify the accuracy of estimates. The presence of an "E" footnote next to an estimate indicates a marginal estimate (CV between 16.6% and 33.3%). Estimates with unreliable levels of accuracy (CV > 33.3%) were not presented and have been replaced by the letter "F".

A very low response rate of 10% was observed for the Oral Glucose Tolerance Test (OGTT). This response rate did not permit the application of sampling weights since an insufficient proportion of the population was represented. Results of the test cannot therefore be inferred to the Nunavik population and should be used for information only.

Nunavut Health Survey

Nunavumiut have expressed a need for "Timikut Qaujsaqsia-tauniq" that is to have their health looked after and cared for.

Table 2

	OVERALL					
	18-24 YEARS		25-44 YEARS		45-74 YEARS	
Total cholesterol (mmol/L)	4.32[a]	(0.06)	5.03	(0.04)	5.46	(0.06)
	4.24[b]	[4.13-4.36]	4.94	[4.85-5.02]	5.36	[5.24-5.49]
Cholesterol/HDL	2.91	(0.05)	3.31	(0.05)	3.34	(0.08)
Ratio	2.83	[2.74-2.92]	3.16	[3.08-3.24]	3.15	[3.02-3.28]
HDL (mmol/L)	1.54	(0.02)	1.63	(0.02)	1.80	(0.04)
	1.50	[1.46-1.55]	1.56	[1.53-1.60]	1.70	[1.64-1.77]
LDL (mmol/L)	2.30	(0.05)	2.83	(0.04)	3.05	(0.06)
	2.21	[2.12-2.30]	2.70	[2.63-2.78]	2.91	[2.80-3.03]
Triglycerides (mmol/L)	1.04	(0.04)	1.25	(0.03)	1.33	(0.06)
	F	-	1.09E	[1.05-1.15]	1.15E	[1.07-1.23]
	MEN					
	18-24 YEARS		25-44 YEARS		45-74 YEARS	
Total cholesterol (mmol/L)	4.19	(0.08)	4.89	(0.06)	5.40	(0.10)
	4.13	[3.97-4.28]	4.80	[4.68-4.92]	5.30	[5.11-5.49]
Cholesterol/HDL	3.05	(0.08)	3.56	(0.07)	3.68	(0.13)
Ratio	2.96	[2.82-3.10]	3.41	[3.28-3.54]	3.44	[3.22-3.67]
HDL (mmol/L)	1.43	(0.03)	1.45	(0.02)	1.62	(0.05)
	1.40	[1.34-1.45]	1.41	[1.37-1.46]	1.54	[1.45-1.64]
LDL (mmol/L)	2.30	(0.07)	2.86	(0.05)	3.16	(0.09)
	2.21	[2.08-2.34]	2.73	[2.62-2.83]	2.99	[2.82-3.17]
Triglycerides (mmol/L)	1.01	(0.05)	1.27	(0.05)	1.36	(0.08)
	F	-	1.11E	[1.05-1.19]	1.16E	[1.06-1.28]
	WOMEN					
	18-24 YEARS		25-44 YEARS		45-74 YEARS	
Total cholesterol (mmol/L)	4.45	(0.09)	5.17	(0.06)	5.51	(0.07)
	4.37	[4.22-4.53]	5.09	[4.98-5.20]	5.43	[5.29-5.58]
Cholesterol/HDL	2.77	(0.06)	3.04	(0.05)	2.99	(0.08)
Ratio	2.70	[2.59-2.81]	2.92	[2.82-3.01]	2.87	[2.74-3.00]
HDL (mmol/L)	1.66	(0.03)	1.81	(0.03)	1.97	(0.05)
	1.62	[1.56-1.69]	1.75	[1.69-1.80]	1.89	[1.81-1.99]
LDL (mmol/L)	2.31	(0.07)	2.80	(0.05)	2.95	(0.06)
	2.21	[2.10-2.33]	2.67	[2.58-2.77]	2.83	[2.71-2.96]
Triglycerides (mmol/L)	1.06	(0.05)	1.23	(0.04)	1.29	(0.06)
	F		F		1.13E	[1.05-1.22]

Table 2. *Blood lipid concentration according to age and by gender, population aged 18 to 74 years, Nunavik, 2004. Source: Nunavik Inuit Health Survey 2004.*

[a] *First line always refers to arithmetic means (SD).*
[b] *Second line always refers to geometric meang [95% CI].*

E Interpret with caution.
F Unreliable estimate.

Also, upon learning of the Nunavik Health Survey named “Qanuippitaa” (how are we), Nunavumiut partners responded, “Qanuippitali” (what about us, how are we?). The Inuit health survey involves:

- adult health survey (> 18 years of age);
- child health survey (< 5 years of age);
- household survey

Study sites and time frame: Inuit have also expressed a desire to not just engage in a one-time project but to develop a project that leaves a legacy for the future. The cross-sectional health survey will form baseline information for possible future comparisons. It also represents an opportunity to link with the International Inuit Cohort, a follow-up evaluation to prospectively evaluate factors leading to progression of disease in collaboration with Greenland, Nunavik and Alaska. Information from the survey will be useful in developing future health policy and public health interventions. The health survey was conducted in Kivalliq and Baffin coastal communities in 2007 with the *CCGS Amundsen* which traveled 10,000 km, visited 18 coastal communities in which 1,200 adults participated in the adult survey.

Activities: Memorandum of Agreements with representatives of land claims organizations, health officials, and hamlets described the working agreements that enabled the survey work to be developed in a collaborative spirit and for long-term co-ownership of the data. The partnerships ensured that work was conducted in a manner and process that benefited northerners. Confidential personal results were communicated back to individuals. Only summary reports were provided back to communities, regions, government bodies and other Inuit organizations and agencies.

The first activities for the “Nunavut cohort study” included planning meetings: 1) Cambridge Bay in May 2005 with Nunavut Association of Municipalities (NAM); 2) Iqaluit meeting in February 2005 with a wide range of groups and Nunavut Government’s CHRs, public health promotion officers, nurses and MDs; 3) teleconference and September meeting with NAM and Chief Medical Officer of Health. The research license application to NRI and the incorporation of an environmental component to the Inuit Health Survey (to NCP) were also accomplished.

The planned meetings were afterward carried out: Community consultations – Iqaluit, October 2006 – meeting with N.A.M. and government – Cambridge Bay, May 2006 – meeting with N.A.M. and IPY planning meeting – Iqaluit, February 2006 –with government and Inuit Organizations.

Additional consultations took place in 2007 (Inuvik) and in early 2008 with Nunatsiavut’s steering committee, and regionally in Kitikmeot with follow-up meetings for Inuvialuit. Internationally, field work was conducted in Greenland in spring and fall 2006 (Nuuk) and in the North West Coast (September 2006). 1500 participants were enrolled. Another collect of data was organized in January 2007 (ending on January 22).

Modification of the project in 2007-2008

Considering 1) the necessity to better integrate health, human and biological sciences within ArcticNet, 2) considering satisfactory funding from IPY to cover the Nunavut part of the cohort study, and 3) considering the new funding on lipids studies in the Arctic form IPY (URQSUK program), it was decided in 2007-2008 to start a slight reorientation of the project. In 2007, it was proposed to focus the project on marine fatty acids and health, particularly to characterize fatty acids concentrations and profiles at all levels of the Arctic marine food web from algae to humans and assess changes in long chain polyunsaturated fatty acids (LCPUFA) profiles according to East-West and South-North gradients. Specifically, the objectives were to: 1) identify new LCPUFA in Arctic marine biota and their potential use for health prevention or cure; 2) investigate omega-3 fatty acids; and 3) determinethe fatty acids of marine origin and health conditions (CVD and diabetes) in the International Inuit Cohort.

4.5.6 Results

Cardiovascular Diseases

Prevalence of self-reported CVD and risk factors

In this study, cardiovascular disease (CVD) was evaluated using two complementary methods: 1) a clinical questionnaire on self-reported CVD problems (reported to be diagnosed by a physician or a nurse); 2) during the clinical session by carotid ultrasonography to measure atherosclerosis, blood pressure, blood lipids and diabetes markers.

Figure 1 presents frequencies of self-reported CVD. The main self-reported CVD was high blood pressure. Close to 17% of participants declared suffering from hypertension. Cerebrovascular disease appeared in the second position with a frequency of 4.1%, and other self-reported CVD were recorded with a frequency of 6.7%. For coronary heart disease (CHD) such as myocardial infarction, the self-reported frequency was low and was reported to be 2.3%. There was no difference in these various frequencies according to gender. Because of a low number of declared events, no conclusions could be drawn between parental history and self-reported CVD except for self-reported high blood pressure which was positively associated with heredity. In the clinical questionnaire, 7.9% of participants reported having high cholesterol.

Given the frequencies presented above, conventional comparisons could not be performed since the questions in the two

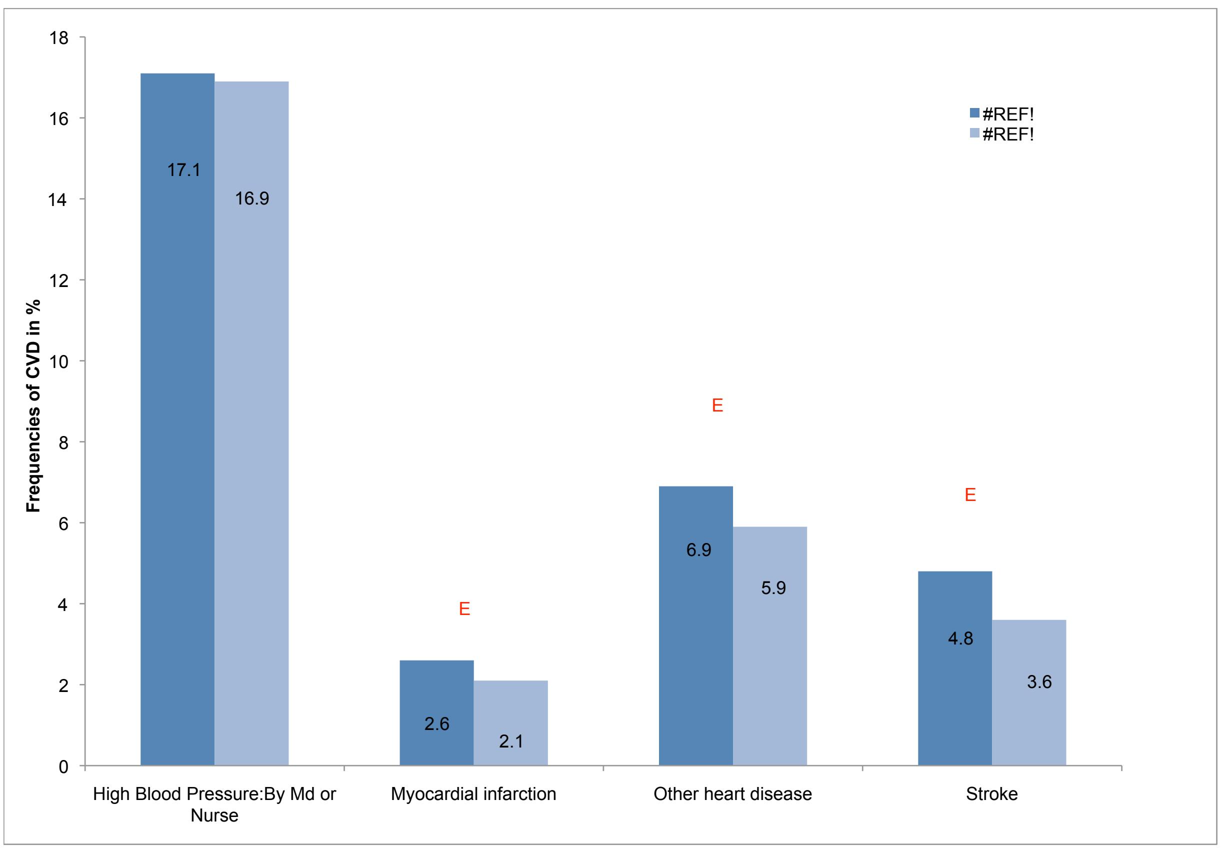


Figure 1. Frequencies of self-reported CDV diagnosed by a physician or a nurse stratified by sex (%), population aged 18 to 74 years, Nunavik 2004. Source: Nunavik Inuit Health Survey 2004.

surveys were not similar. However, self-reported prevalence of some CVD problems seemed to have increased since 1992. As an example, in 1992, only 5.2% of participants reported hypertension problems during the two weeks preceding the interview compared to 17% in 2004.

Atherosclerosis

For atherosclerosis, among men, the geometric mean maximum carotid artery intima media thickness (mmIMT) was 0.71 (arithmetic 0.75) mm (CI at 95%: [0.7-0.8]) and among women, the geometric mmIMT was 0.62 (arithmetic 0.65) mm (CI at 95%: [0.6-0.7]). Adjusted for age distribution, the mmIMT was significantly lower in women (p<0.0001). Moreover, mmIMT increased significantly with age in the entire group (p<0.0001) as well as in each gender (p<0.0001). In the analysis, main determinants of atherosclerosis were age, sex, hypertension, BMI, diabetes (Table 1). But, IMT was not associated with total cholesterol, LDL or HDL cholesterol. For smoking habits, results showed an inverse relationship (p<0.001) related to the fact that in this sample smokers are mainly young people and non smokers were older individuals. Since atherosclerosis was not measured in 1992, comparisons could not be done.

Blood pressure

High Blood Pressure (HBP) was evaluated during the clinical session. The study revealed that HBP occurred in 14.5 % of the population. The prevalence of HBP increased linearly with BMI, (p<0.0001) and age (p<0.0001). The prevalence of HBP was higher among people with abdominal obesity (18.7%) compared to others (11.6%), but HBP results were not related to gender (p=0.42). HBP data from 1992 were not comparable with 2004 since the estimation of HBP in 1992 came from the household questionnaires. However it was important to note that the frequency of HBP seemed to increase from 6.0% to 14.7% if compared to 1992 results.

Blood lipids

The prevalence of high cholesterol (≥ 6.2 mmol/L) among adults was 12.1%. This prevalence was not associated with gender (p=0.39), obesity (p=0.67). However, as presented in Table 2, total cholesterol level was positively associated with age (p<0.001). Similar positive associations were observed for other blood lipid concentrations, such as total cholesterol/HDL ratio (p<0.001), HDL (p<0.001), LDL (p<0.001) and triglycerides (p<0.001).

The prevalence of high total cholesterol/HDL ratio (≥5.0) was significantly different between genders (9.6% in men and 3.2% in women p<0.001) and higher in obese people (16.1% in obese vs. 4.4% in non-obese; p<0.001). Prevalence of low HDL (≤0.9 mmol/L) varied between genders (7.6% in men and only 2.0% in women; p<0.001) and by weight (9.8% in obese vs. 2.3% in non obese people; p<0.001) but not with age (p=0.49). The prevalence of high LDL (>3.4 mmol/L) was significantly (p<0.01) different between genders (25.3% in men and 18.7% in women), and higher in obese people (37.1% in obese vs. 18.8% in non-obese people; p<0.001) and was associated with age (p<0.001). The prevalence of a high level of triglycerides (>2.3 mmol/L) was higher in obese people (14.0% in obese vs. 3.1% in non-obese people; p<0.001) but was not different between genders (7.0% in men and 7.9% in women; p=0.61), and not different according to the standardized BMI (Table 2).

A comparison of the 1992 and 2004 blood lipids results revealed various changes for the lipid fractions of interest, with no consistent pattern (Table 3). Comparisons of prevalence of blood lipid abnormalities between these two health surveys were based on age-standardized proportions. There was a general trend indicating an improvement of CVD biological parameters. Total average cholesterol concentrations did not change significantly in the population as a whole (p=0.23) nor in either gender. A similar observation was made for the prevalence of high total cholesterol (men_{1992}: 13.5% vs men_{2004}:

11.3% p=0.38; $women_{1992}$: 14.6% vs. $women_{2004}$: 11.6% p=0.21; see Figure A1, Appendix). The ratio total cholesterol/HDL changed significantly (p<0.001) in the total population and in both sexes (male p<0.01 and female p<0.001). A decrease in the prevalence of a high total cholesterol/HDL ratio was observed (men_{1992}:17.8% vs. men_{2004}: 9.6% p<0.01; $women_{1992}$: 9.2% vs. $women_{2004}$: 3.1% (p<0.001); see Figure A2, Appendix). HDL and LDL concentration also significantly changed (p<0.0001). The prevalence of low HDL decreased (men_{1992}:16.7% vs men_{2004}: 7.4%, p<0.001; $women_{1992}$:5.8% vs. $women_{2004}$: 1.9% p<0.01; Figure A3, Appendix). A similar decrease was also observed for the prevalence of high LDL (men_{1992}: 33.9% vs. men_{2004}: 24.0%, p<0.01; $women_{1992}$: 27.5% vs $women_{2004}$: 17.8% p<0.01), Figure A4, Appendix). However, triglycerides did not change in the population as a whole (p=0.07) nor in either sex (male: p=0.08 and female: p=0.08), nor did the prevalence of high triglycerides (men_{1992}:14.9% vs slight decrease in men_{2004}: 10.0% p=0.08; $women_{1992}$: 8.2% vs. slight increase in $women_{2004}$: 11.8%, p=0.07; Figure A5, Appendix). In general, lipid profiles had improved among Nunavimiut except for triglycerides.

Diabetes

Prevalence

In this study, diabetes was evaluated in the following ways: 1) self-reported diabetes was measured during the clinical questionnaire by asking the participants if a physician or a nurse ever told them that they were diabetic; 2) by blood analysis (blood collection during the clinical session). Participants were advised to fast for at least eight hours prior to blood sampling. Glycaemia and insulinemia were evaluated, and an "Oral Glucose Tolerance Test" (OGTT) was also performed on a non representative sub-sample of solely non-diabetic, non-pregnant participants under fasting conditions (n=166). Diabetes diagnosis was defined according to the Canadian Diabetes Association's cut off levels.

In the population as a whole, 5.5% of participants reported knowing they suffer from diabetes. Through blood sampling, results showed that only 2.4% of the population was diabetic. To this prevalence of newly screened diabetics, people who declared they took medication for diabetes were added (but had normal blood glucose due to treatment), which increased the prevalence to 4.8%. Given the detection of a significant agreement between the evaluation of diabetes by questionnaire and the results based on blood glucose measurements (plus participants taking medication) (kappa=0.73 (CI 95%: [0.63-0.82]), it was decided to use the second, more objective measure to estimate the prevalence of diabetes.

No cases of gestational diabetes among 27 pregnant women were suspected. Adjusted for age, the prevalence of diabetes was significantly higher in women (p<0.0001). It was detected that 3.4% of participants had impaired fasting glucose (glycaemia level between 6.1-6.9 mmol/L), and hyperinsulinemia under fasting conditions was detected in 12.7% of participants. The prevalence of hyperinsulinemia was higher in women (15.2%) than in men (10.2%). This proportion was significantly different (p=0.03). OGTT was performed on 166 participants. Among them, 12.0% were diagnosed with diabetes or showed pre-diabetes (≥7.8 mmol/L). These results are presented in Table 4.

Evolution 1992-2004

Since 1992, glycaemia and insulinemia have significantly improved in the population (p<0.001 adjusted for gender and age distribution). For glycaemia, levels significantly decreased in both genders (males: $mean_{1992}$: 5.3, CI 95% [5.1-5.4] vs. $mean_{2004}$: 4.6; CI 95% [4.5-4.7]); females: $mean_{1992}$: 5.2, CI 95% [5.0-5.3] vs. $mean_{2004}$: 4.6, CI 95% [4.5-4.6]). However, the situation varied according to different diabetes categories as seen in Figure 2. Indeed, in men, the proportion of those with a normal value for glycaemia had increased since 1992, with the proportion of those with impaired glucose tolerance decreasing (6.1-6.9 mmol/L) and the decreasing trend observed for men with values compatible with diabetes was not significant. However, among women none of the proportions changed significantly between 1992 and 2004.

Table 3

VARIABLES		1992		2004	
		MEAN	CI 95%	MEAN	CI 95%
Total Cholesterol (mmol/L)	Men	5.07	4.93-5.21	4.85	4.77-4.94
	Women	5.11	5.01-5.22	5.09	5.01-5.17
Cholesterol/HDL	Men	3.93	3.75-4.10	3.47	3.36-3.57
	Women	3.41	3.29-3.52	2.96	2.89-3.04
HDL (mmol/L)	Men	1.39	1.34-1.44	1.49	1.45-1.53
	Women	1.61	1.56-1.66	1.82	1.77-1.86
LDL (mmol/L)	Men	3.09	2.97-3.21	2.80	2.72-2.88
	Women	2.99	2.90-3.09	2.72	2.65-2.79
Triglycerides (mmol/L)	Men	1.29	1.17-1.41	1.23	1.16-1.30
	Women	1.14	1.06-1.21	1.21	1.15-1.26

Table 3. *Blood lipid concentrations measured, population aged 18 to 74 years, Nunavik, 1992 and 2004. Sources: Nunavik Inuit Health Survey 2004 and Santé Québec Survey 1992.*

Plasma insulin concentrations in 1992 and 2004 were respectively 55.9 and 62.6 pmol/L in men, proven to be a non-significant increase (Figure 3). In women, insulin concentration increased from 60.2 to 69.1 pmol/L, and this difference was statistically significant. Moreover, since 1992, the prevalence of hyperinsulinemia tended to decrease in the entire population (15.5% vs. 12.7%) but, the difference was not statistically significant (p=0.17). This difference was attributable to the male population (16.5% vs. 10.2% p=0.03) and was not seen among females (14.4% vs. 15.2% p=0.76).

Diabetes risk factors

Prevalence

No association was observed between diabetes and pulse (p=0.90), ethnic origin (p=0.61), total personal income (p=0.32) or geographical sector (p=0.34). However, diabetes was associated with schooling (highest prevalence among people with the lowest schooling level), gender (highest in women) and positive family history of diabetes (p<0.01). For insulinemia, an increase of this parameter was observed according to both BMI and age (p<0.001).

The great majority of diabetics in this study were obese (65%) and an additional 23% of diabetics were overweight. In the Inuit population, the prevalence of obesity defined by the BMI is 19.4% and abdominal obesity is 38.9%. This risk factor essentially affects women, as 70.8% of them showed an abdominal obesity compared to 9.9% among men. Whilst fat mass is higher in women (22.3 kg vs. 16.6 kg), fat-free mass (kg) is higher in men. Moreover, it was observed that BMI increased with age (p<0.001) in both genders. As for diabetes, BMI was inversely associated with schooling and income (p<0.0001) but not with geographical sector.

Evolution of diabetes risk factors

Abdominal obesity has changed in the population since 1992 (p<0.0001) with an increase of 29% to 39%. This is mainly due to the proportion of women with Abdominal obesity, which increased significantly by 17%, between 1992 and 2004 (p<0.0001). In men, the proportion of obesity did not change (p=0.54) (Table 5). Similarly, population distribution throughout the BMI strata has also significantly changed (p<0.0001). This situation, presented in Figure 4, seems to correspond to a shift of the overweight population to the status of obesity.

4.5.7 Discussions and Conclusion

CVD and risk factors

Cardiovascular results obtained during this health survey are in some way contradictory with observed improvements in some risk factors (lipid profiles) and deteriorations in other factors (high blood pressure in general and hyper-triglyceridemia in women). Indeed, an increase of CVD prevalence triggered by an increase in the prevalence of some risk factors

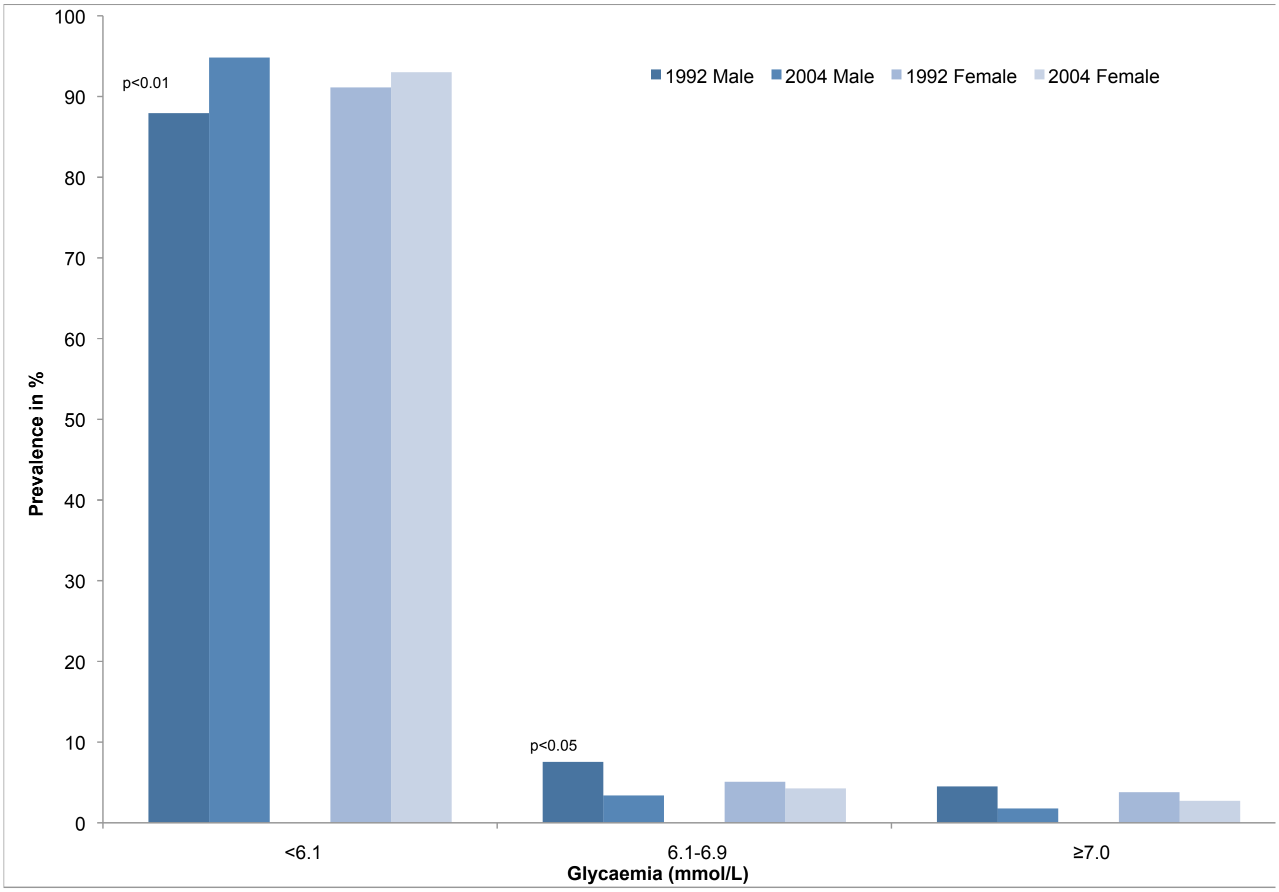


Figure 2. *Comparison of abnormal glycaemia results stratified by gender, population aged 18 to 74 years, Nunavik, 1992 and 2004. Sources: Nunavik Inuit Health Survey 2004 and Santé Québec Survey 1992.*

seemed to be verified, at least in the case of hypertension with an increase of 8% since 1992 (from 6.0% to 14.5%).

It was difficult to compare self-reported conditions with those of surveys from other regions or countries. In general, self-reported CVD frequencies obtained here seemed similar to those obtained in other Canadian Aboriginal populations for strokes (5%) and similar to Canadians Caucasians for myocardial infarctions (2%) (Anand et al. 2001).

In 1992, results showed that the blood lipid profiles of Inuit from Nunavik were healthier than those of Quebecers (Blanchet et al. 1992). However, with the expected increase in consumption of westernized food, researchers predicted a deterioration of the blood lipid profile. Twelve years later, there was no worsening of most of these CVD risk factors. Most of them improved and others were unchanged. This was particularly good news as these results were not due to selection bias (populations were not comparable).

For atherosclerosis, given the current low mortality rate, lower mmIMT was expected in this population from Nunavik compared to other Canadian Aboriginal populations who participated in a similar study (same equipment). This was clearly observed for both men and women age 46-55 years (mmIMT mean (SD) in women: 0.60(0.01) mm for Inuit vs. 0.71 (0.1) mm and men: 0.71 (0.03) mm vs. 0.78 (0.2) mm) (Anand et al. 2001). However, 10% of the population showed

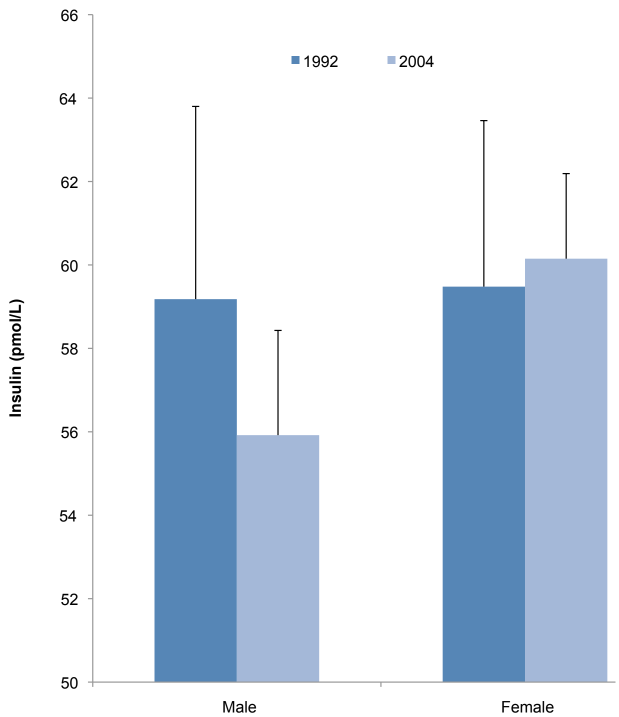


Figure 3. *Comparison of insulin concentrationa under fasting conditions, stratified by gender population aged 18 to 74 years, Nunavik, 1992 and 2004. Sources: Nunavik Inuit Health Survey 2004 and Santé Québec Survey 1992.*

a mmIMT equal or higher than 1 mm. Available epidemiological studies indicated that increased IMT (at or above 1 mm) represented a high risk of myocardial infarction and/or cerebrovascular disease (Simon et al. 2002). In light of these results, it was confirmed that this population is relatively well-protected against atherosclerosis. However, with the increase of risk factors such as the rates of smoking, glucose intolerance, obesity in general and abdominal obesity, an increase in the percentage of the population at risk of CVD events could be expected.

Whereas some modifiable factors such as blood lipid profiles showed improvement since 1992, similar enthusiastic conclusions could not be drawn for other modifiable factors such as tobacco smoking as detailed in another leaflet, and diabetes, obesity and insulin resistance as presented below.

Diabetes

In 1992, 8% of Inuit participants in the health survey reported they had diabetes and 2% glycaemia levels compatible with a diabetes diagnosis (Blanchet et al. 1992). Twelve years later, a similar prevalence of diabetes (2.4% according to fasting glucose measurement) was found for a global prevalence in Nunavik estimated at 5%. This prevalence was comparable to values observed in the rest of Canada (4.8% in people age 20 and over). However, in comparison with other Canadian populations, Inuit women 45 years and over had one of the highest prevalence of diabetes. Women also had the highest prevalence of diabetes risk factors such as obesity and hyperinsulinemia. This implied that a particular effort should be made to adapt prevention programs to this group.

As observed in other Aboriginal populations (Anand et al. 2001) and according to the 1992 "Santé Québec" Survey (Blanchet et al. 1992), diabetes and obesity were associated with low income and schooling. Anand and colleagues in 2001 suggested that improving the socioeconomic status might be reducing these cardiovascular risk factors. Nevertheless, the prevalence of obesity and cases of being overweight in Inuit population call for urgent action. Indeed, 28% of Inuit participants were obese. This proportion was higher than the one observed among the general Canadian population (14%).

As proposed earlier, the causes of the increase of diabetes and its related risk factors, such as obesity, are probably related to the epidemiologic transition that occurs in Nunavik and throughout the Arctic. Given the magnitude of socio-economic modifications in Nunavik and the increase of obesity in the last decade, a decrease in the prevalence of diabetes in Nunavik is not anticipated. Thus, maintaining and reinforcing prevention programs in order to reduce its main risk factors was encouraged. A prompt reaction is needed as diabetes may induce microvascular and macro-vascular complications.

Table 4

VARIABLES	TOTAL	MEN	WOMEN
Diabetes (yes)[a]	4.8	3.0E	6.6
Fasting glucose			
Normal (< 6.1 mmol/L)	91.8	93.9	89.7
IFBG (6.1-6.9 mmol/L)	3.4	3.2E	3.7E
DM (≥ 7.0 mmol/L[a])	4.8	3.0E	6.6
OGTT[b]			
Normal (< 7.75 mmol/L)	88.0	91.6	84.3
IGT or DM (≥ 7.8 mmol/L)	12.0	8.4	15.7
Glycaemia			
Abnormally high (> 5.8 mmol/L)	7.7	6.4E	9.0
Hyperinsulinemiac			
(> 90pmol/L)	12.7	10.2	15.2

DM: diabetes mellitus
IFBG: impaired fasting blood glucose
IGT: impaired glucose tolerance.

a Fasting glucose ≥ 7 plus people taking medication for diabetes, impaired fasting blood glucose (IFBG), impaired glucose tolerance (IGT).

b Non-weighted analysis.
c Restricted to participants who have not eaten for at least six hours.
E Interpret with caution.

Table 4. *Prevalence of diabetes by sex (%), population aged 18 to 74 years, Nunavik, 2004. Source: Nunavik Inuit Health Survey 2004.*

Until recently (around 1950), the Inuit could be considered both geographically and genetically isolated. For instance, the protection of the traditional Inuit from cardiovascular diseases (CVD), diabetes and some types of cancers could be the result of a particular genetic endowment and/or their traditional living conditions. However, because of the rapid societal transition resulting from the improvement of communication and transportation with southern regions, and with the settlement of Inuit populations into permanent communities, a shift away from traditional lifestyle and diet was observed. Traditional food system use is declining rapidly, though not uniformly across the Arctic, but for most circumpolar regions, dietary intake from market foods exceeds those from traditional foods.

The marine diet is primarily claimed to be protective against heart attacks but there are numerous other diseases that are likely to be affected by the diet and the dietary transition, in particular diabetes, CVD, cancer, immuno-mediated diseases. The Inuit dietary pattern is changing and has already for decades been composed of both traditional and imported food items. Currently, the young people eat much less traditional food than the elderly and there is a pronounced regional variation. For example the blood concentration of omega-3 fatty acids, the most important biomarker of fish consumption, is much lower in young Inuit compared to the adults and elders.

Furthermore, a gradual decrease in ice coverage, and thus in the abundance of ice algae may lead to a decrease in omega-3 fatty acids concentrations at all trophic levels. Alternatively, an increase in the production and biomass of phytoplankton in open waters could increase the amount of total lipids available to higher trophic levels. Finally, in the scenario where global warming of the Arctic favours the replacement of Arctic species by sub-polar and temperate species, the total and lipid PUFA content in the food web may decrease substantially. In all cases, spatial and temporal variations in water mass characteristics (e.g. light, temperature, nutrient content etc.) will largely influence the production and sustainability of PUFA in the marine food web.

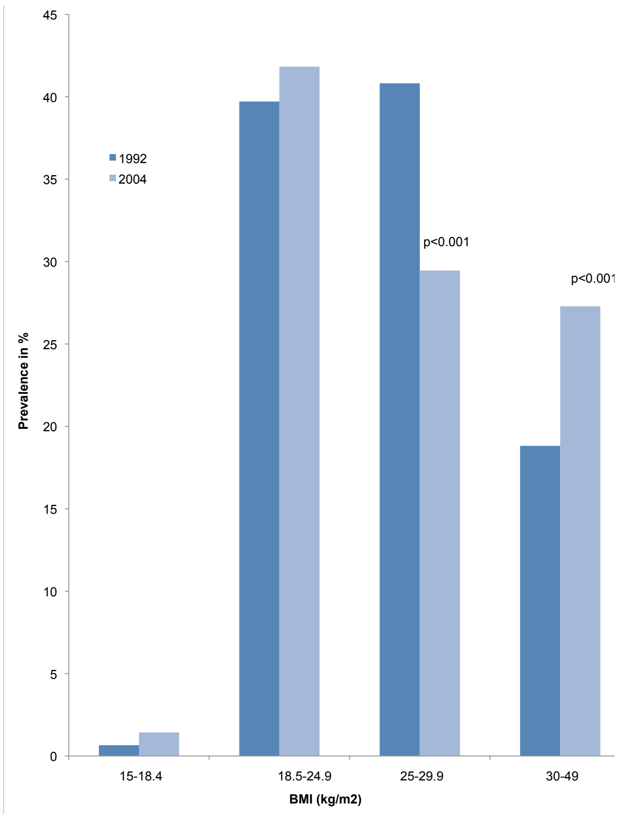


Figure 4. *Comparision of BMI prevalence between the health surveys (%), population aged 18 to 74 years, Nunavik, 1992 and 2004. Sources: Nunavik Inuit Health Survey 2004 and Santé Québec Survey 2004.*

Conclusions

Results were presented to the Nunavik population in late December 2006. Some results were also presented at ArcticNet Annual Scientific Meetings and NCP meetings. Media interviews with Nunatsiaq News, Toronto Star and Vancouver Sun were also carried out. A Film (Glacialis production) was produced and was presented at ASM 2006. This film was distributed in all Nunavik households. A thematic report on chronic diseases was also produced and edited in October 2007 and distributed to all health personnel and stake holders in Nunavik. A final presentation at the Annual Nunavik Government General Assembly was made in December 2007.

Table 5

	1992	2004	P-VALUE
BMI (kg/m^2)[a]			
< 25	39.7	42.0	0.29
25-29.9	41.3	29.8	< 0.0001
30-49	19.0	28.3	< 0.0001
Abdominal obesity[b]			
Men	8.2E	9.9	0.58
Women[a]	54.2	70. 8	< 0.0001

a Excluding pregnant women. E Interpret with caution.

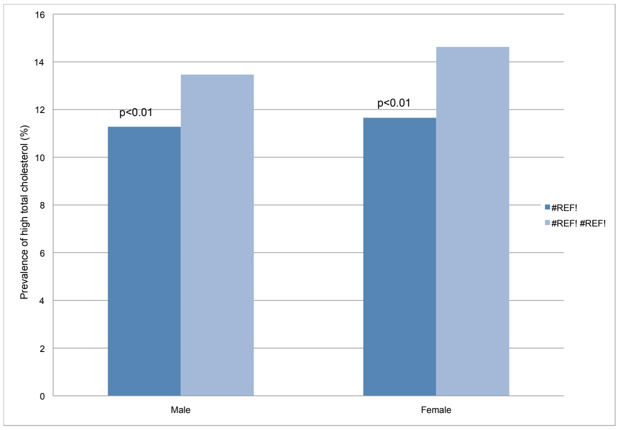
b Dimensionless.

Table 5. *Comparison of weight indicators between health surveys (%), population aged 18 to 74 years, Nunavik, 1992 and 2004. Sources: Nunavik Inuit Health Survey 2004 and Santé Québec Survey 1992.*

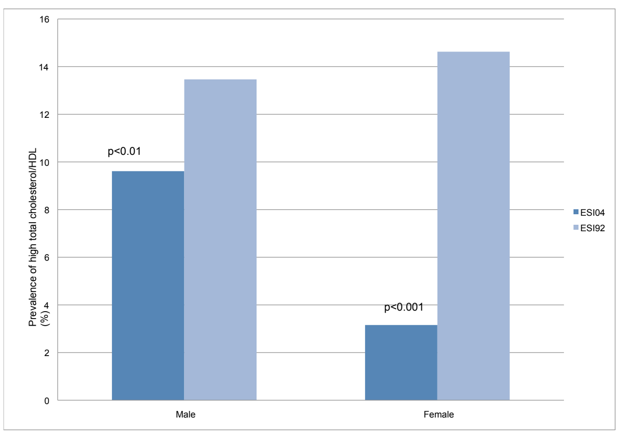
Results derived from the project will be mostly used by Public Health authorities of Nunavik in two ways. First, changes in dietary habits are important to know for public health but also for natural resources managers in order to adapt policies (inter-community trade, development of fisheries, etc.). Since there is a risk that TFAs and junk food in general persist for a long period of time in the Arctic, voluntary action from Territorial governments will need scientific input to support food policies (taxes, ban, etc.). Recently, and following articles in the media (i.e. Chan et al. 2006; Egeland et al. 2007), network investigators were contacted by policy makers from Nunavut to help them at decreasing the presence of junk food on the Territory. A Senior Economist at the Department of Finance in Iqaluit is working on a health policy plan to ban or tax some junk food based on the current and coming data.

4.5.8 Acknowledgements

The Nunavik Inuit Health Survey could not have be undertaken without the financial support of the "ministère de la Santé et des Services sociaux du Québec", the Nunavik Regional Board of Health and Social Services, the Department of Indian and

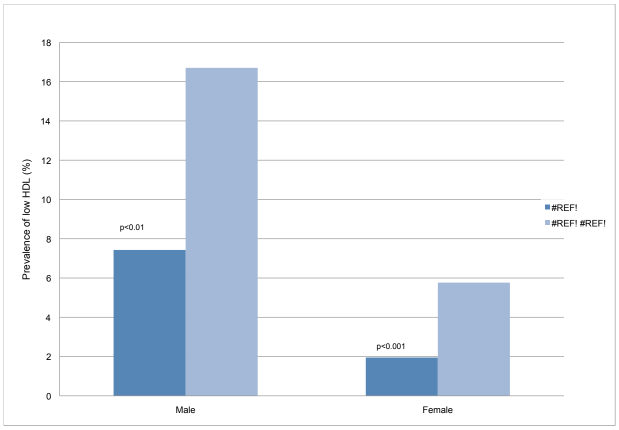


Appendix 1A. *Prevalence of high total cholesterol in men and women of Nunavik, 1992 and 2004.*



Appendix 2A. *Prevalence of high total cholesterol/HDL ratio in men and women of Nunavik, 1992 and 2004.*

Northern Affairs of Canada, the Canadian Foundation for Innovation (CFI), the Network of Centres of Excellence of Canada (ArcticNet), the Nasivvik ACADRE Inuit Centre and the Canadian Institutes of Health Research. The valuable assistance of Inuit representatives – both members of the survey advisory committee and Inuit leaders from each community – is gratefully acknowledged. We are also grateful to all of the professionals, technicians, students, interviewers and clerical staff who worked at each stage of the survey process. Our gratitude is also extended to the staff of the ice-breaker *CCGS Amundsen*. Finally, we wish to thank the Inuit people of Nunavik and Nunavut for their extensive cooperation with this survey. We would also like to acknowledge these special contributions: Public Health Research Unit (Laval University Medical Center-CHUQ): Suzanne Bruneau, Suzanne Côté. Nasivvik: The Nasivvik Center in collaboration with ArcticNet contributed to the training of Inuit so they could become Inuit Research Advisers. The following people participated to the training aboard the *CCGS Amundsen*: Sammy Tukkiapik, Jennie Ipirq, Elisabeth Ford, Donald Ross. Two other people participated in the training, but not onboard the ship: Barbara Armstrong and Shannon O'Hara. Students and postdoctoral fellows: Marie-Ludivine Château-Degat finished her PhD under the supervision of Éric Dewailly and began a post-doctoral training under the direction of Grace Egeland to process data from the survey pertaining to cardiovascular diseases and changes in diet. Twelve students (graduate and undergraduate) participated also to the 2004 cruise to work on various aspects of ongoing projects, including water quality and human health (Andrée Maheux, Caroline Lavoie, Chris Stamler, Guylaine Charbonneau, Joane Aubé-Maurice, Kattam Laraki-Côté, Sophie Kealan, Laurence Laperrière, Olivier Groulx, Sébastien Roy, Véronique Doutre-loux and Pauline Brindel). Technicians, nurses, interprets and interviewers: In order to build a team for the Inuit health survey, training was provided to several technicians, nurses and interviewers in order to carry-out the study. A total of 15 interviewers (Annie Alayco, Annie Augiak, Dalacy Augiak, Eric VanSpronsen, Johny Naktialuk, Josie Nappatuk, Pierre Lejeune, Julie Qinuajuaq, Maina Tukai, Minnie Akparook, Alasie Iqiquq, Johny Makaiuk, Norah Kokkinerk, Amalie Sivuak and Jennie Flemming) were trained to perform medical interviewing with Inuit participants. Among those, several were Inuit and acted also as interprets. Seven nurses (France Roy, Karina Olivier, Karine Lemay, Louise Billon, Michel Poulin, Solange Piché and Virginie Gargano) and six specialized technicians (laboratory, clinical, etc. – Jean-Sébastien Maguire,



Appendix 3A. *Prevalence of low HDL in men and women of Nunavik, 1992 and 2004.*

Louis-Fréderic Daigle, Tommy Bédard, Carmen Beauregard, Simon Bujold and Julien Fontaine) were also hired and trained for the specific needs of the cohort study. Institut National de la Santé Publique : Mélanie Anctil, Louis Rochette, Danielle St-Laurent, Michèle A. Dupont and Élisabeth Papineau. Nunavik Regional Board of Health and Social Services: Serge Dery. Funding: Québec's Ministry of Health and Social Services, Nunavik Board of Health, CIHR, ArcticNet, NCP. In 2007, we obtained IPY funding for the Nunavut Cohort Study and for the Urqsuk Program and a CIHR "Team in Circumpolar Chronic Disease Prevention" 5 year grant (2006-2011). In 2007, the Nasivvik Center grant was renewed for 3 years (2007-2011) within the CIHR NEAHR Grant competition.

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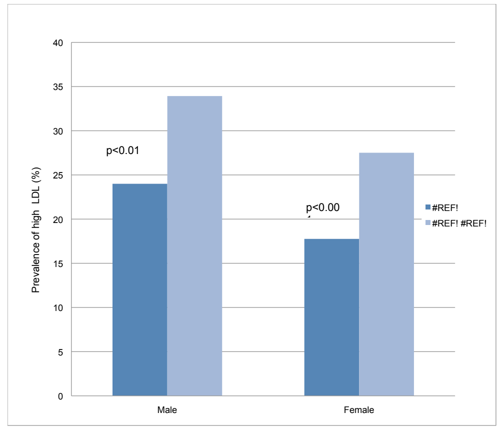
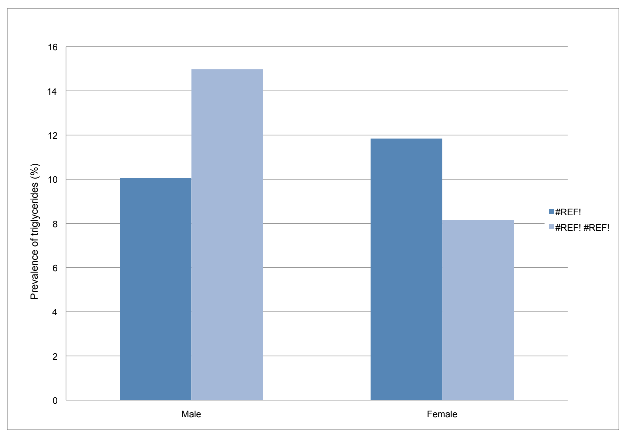


Appendix 4A. *Prevalence of high LDL in men and women of Nunavik, 1992 and 2004.*



Appendix 5A. *Prevalence of abnormally high triglycerides in men and women of Nunavik, 1992 and 2004.*

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4.6 The Opening of the Northwest Passage: Resources, Navigation, Sovereignty and Security (Project 1.6)

Project Leader

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4.6.1 Abstract

The central theme of this project was to collect seabed bathymetry and geologic data and provide the information derived from this data to make informed decisions on resource development, safe navigation, sovereignty, and security in the Canadian Arctic. The specific focus of the project was in the Northwest Passage where increased trans-continental shipping was envisaged. Four years of intense seabed mapping resulted in the creation of a series of maps that answered questions such as: a) What type of natural hazards exist that might impede the exploitation of natural resources?; b) Are there alternate safe navigational corridors to accommodate the expected increase in shipping?; c) Where can undisturbed sedimentary records be found that will provide an uninterrupted and undisturbed record of the past 15,000 years of climatic history of the Canadian Arctic?. The newly-acquired seabed mapping images revealed the location and extent of geohazards that might impede oil and gas development including gas-escape structures, slope instability and ice scouring. Analysis of the core sample data provided a preliminary record of the Arctic Island Archipelago past climate including, sea surface and bottom water temperatures, salinity and sea ice cover. The active engagement of both the Canadian government and the scientific community in mapping the Arctic waterways was a strong demonstration of Canada's intent to assert sovereignty over the region. The availability of new navigational charting products in areas, previously unmapped, is a necessary precursor to Canada implementing a naval security presence in the area.

4.6.2 Key Messages

Marine geohazards to hydrocarbon development: (serving the National Energy Board, Indian and Northern Affairs Canada, Inuvialuit, Oil industry, GNWT, Government of Nunavut, Parks Canada). Canada has potentially huge economic benefits to gain by having access to the natural resources of the Arctic Archipelago region. Exploitation in this manner however, can only proceed in a safe and responsible manner, by managing the potential detrimental impacts to the environment. A key requirement is to be able to assess potential natural hazards that might result in harmful affects both to persons and the environment. Natural hazards such as underwater landslides, collapse of offshore structures built on gassy seabeds and the impacts of glacial and sea ice must be known and their risk managed.

Opening new shipping lanes and improving navigational charting: (serving the Canadian Hydrographic Service, Coast Guard, Shipping Industry, Oil and Gas Industry, Mining Industry, Tourism, Insurance Industry). Despite previous focused mapping programs in the bottleneck regions (Dease, Victoria and Dolphin and Union Straits), the Archipelago region remains poorly mapped with shipping normally restricted to narrow singular corridors that may be ice covered. Because the *CCGS Amundsen* is operating a multipurpose mission throughout the region, there is a golden opportunity to simultaneously map uncharted regions to provide alternate pathways.

Past to present evolution of sea-ice regime: (serving the National Energy Board, Inuvialuit, Oil industry). Understanding past climatic history is the key to predicting potential future ramifications of a changing sea ice regime. To responsibly plan adaptation strategies, prediction future climatic responses and their consequences was critical. It was also the key to understanding the nature of these changes-i.e. are they part of a natural cycle or induced by present excess of greenhouse gases.

4.6.3 Objectives

This project mapped the bottom topography and geological structure of the Northwest Passage and other regions of the Canadian Archipelago as a first step towards the management of increased intercontinental ship traffic and resource exploration as ice conditions improve, and contributed invaluable information to assess the economic, sovereignty and security implications of an ice-free Northwest Passage.

The specific objectives of the project included:

- Compilation corridors of precise high resolution bathymetry, and seabed geomorphology;
- Improvement of mapping of the surficial geological environment of the Canadian Archipelago channels;
- Obtention of sediment cores and grabs of the Holocene record for paleoceanographic analyses at optimal sites in the region.

The following data gaps were filled by the work of Project 1.6:

- Geohazard mapping for regulatory needs as well as engineering design;
- Data for new navigation charts of the Northwest Passage;
- The frequency of which the Northwest Passage has been ice free in the past and other paleoceanographic characteristics (e.g. freshening of the surface water).

4.6.4 Introduction

Project 1.6 was directly developed in response to the possibility that, in the light of climate change, the Northwest Passage could become more viable as an international shipping lane, and a significant region for natural resource extraction. Historically the region has been predominantly ice-covered, providing barriers to both shipping and resource development. The same issue meant that there was little existing knowledge of the state of the seabed (both morphologically and geologically). Before responsible development of the region can proceed, these knowledge gaps (outlined in the project objectives above) had to be filled.

The Arctic Island Archipelago is part of Canada. The mapping and associated modelling work in this project (Figures 1 and 2) were a strong demonstration of both the state responsibility and the "stewardship" components that are seen as an

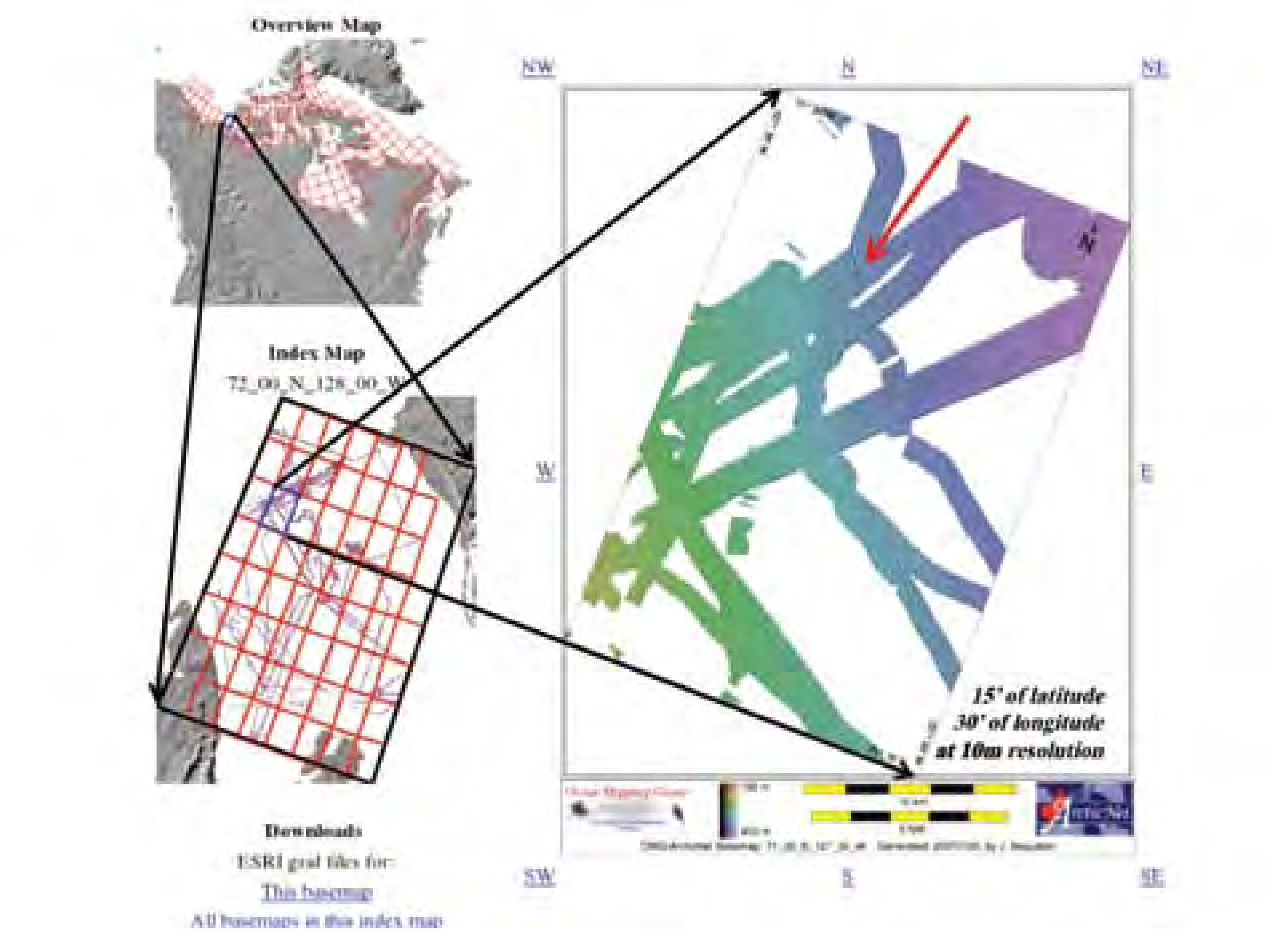

Figure 1. *Amundsen seabed mapping data distribution methodology. 1,958 separate mapsheets, each covering 15' of latitude by 30' of longitude at 10m resolution are available on-line for GIS ingestion. Each sheet potentially contains data from 5 years of transit or site survey data. Top left image shows full extent of map sheet coverage extending from Quebec City to the Beaufort Sea. Bottom Left shows a 2° latitude x 4° longitude subarea detailing the coverage (in this case the outer Amundsen Gulf). Right image reveals multi-year (2003-04-05-06) coverage from CCGS Amundsen collected just south of the summer limit of permanent sea ice. Individual tracks are diverted to avoid floating sea ice. Discontinuous corridors result from periods when ice-breaking. These data provide stakeholders with immediate access to full resolution seabed geomorphology, allowing interpretation of geohazard potential such as current or fossil seabed scour activity.*

essential part of asserting sovereignty. Any maritime security presence requires the ability to freely navigate the waters. Again the mapping component of this project provided the best, and often the only, quality charting information for much of the region.

Project 1.6 directly addressed the lack of seabed knowledge within the Arctic Island Passages (notably distinct from the Arctic Ocean region in which the offshore UNCLOS mapping focus lies). By combining the freedom of access only available through the use of icebreakers with the newest developments in seabed mapping (notably multibeam sonar systems) the Project 1.6 team took maximum advantage of the common scientific platform to compile knowledge of the seabed to serve Canadians.

4.6.5 Activities

Study sites and activities: Over the 2004-2007 period, Project 1.6 accomplished the following:

Collected multibeam and sub-bottom data over potential core sites to locate areas of Holocene sediment accumulation adequate for piston coring in Lancaster Sound, Barrow Strait, Victoria Strait, Dease Strait, and Amundsen Gulf.

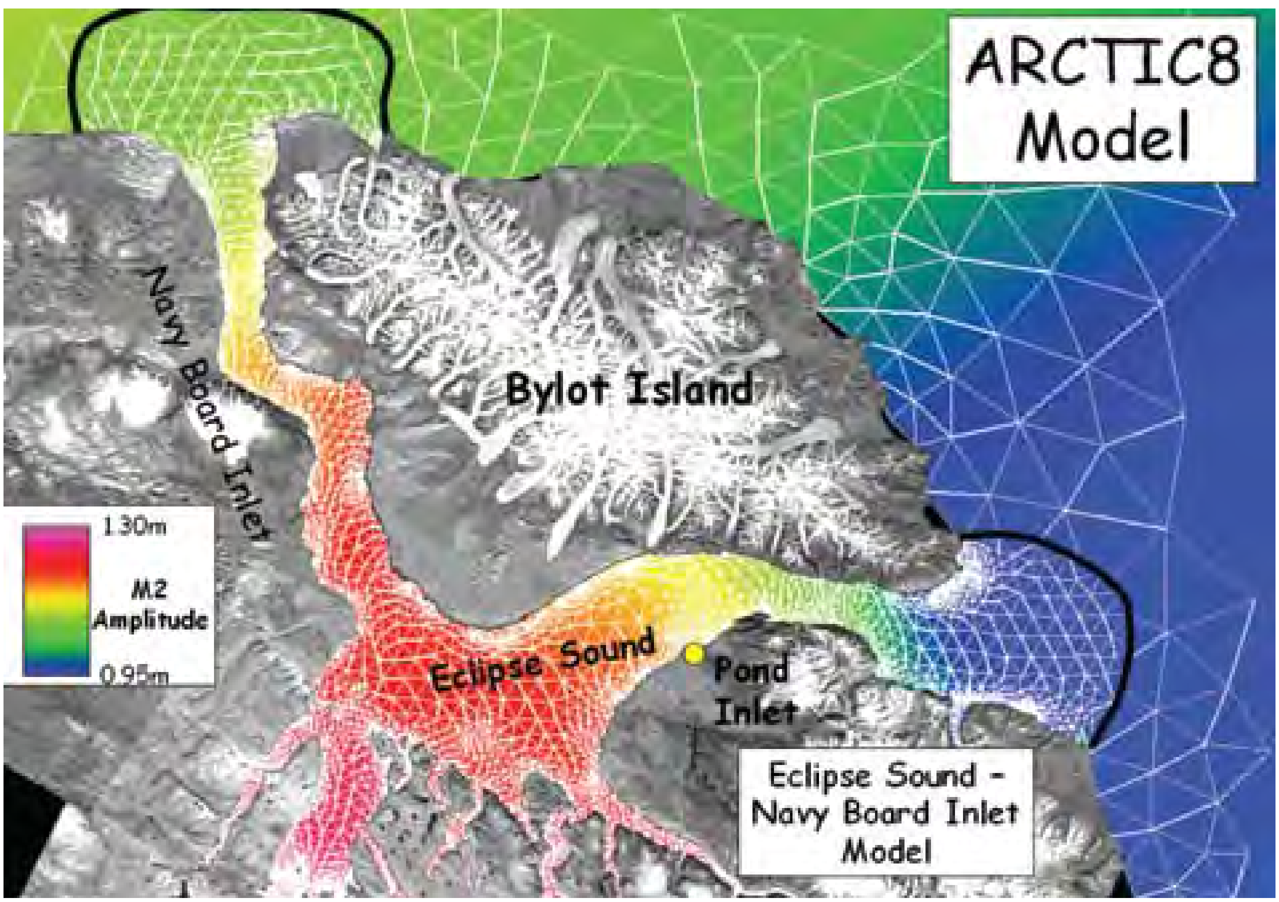

Figure 2. *Development of a nested 3D Hydrodynamic model for tidal prediction. It is operationally impractical to install tide gauges in remote areas of the Passage. A regional tidal model has been developed for whole Arctic Archipelago (Arctic8 – WebTide, DFO. 2005) but lacks the definition to properly predict tides in the narrow fjords of Baffin Island. The figure illustrates a nested high resolution model for the region around Pond Inlet*

Collected piston cores in Lancaster Sound, Barrow Strait, Victoria Strait, Dease Strait, and Amundsen Gulf, to meet the paleoceanographic objectives.

To enhance those same paleoceanographic objectives, box cores were collected in Oliver Sound, Kane Basin, Smith Sound, North Water Polynya, Lancaster Sound, Barrow Strait, Viscount-Melville Sound, M'Clintock Channel, Victoria Strait, Dease Strait, Amundsen Gulf, Beaufort Sea, Franklin Bay, Gulf of Boothia, Foxe Basin, Foxe Channel, and the Labrador fjords.

NRCan-funded multibeam survey blocks were collected with the *CCGS Amundsen* over sediment failure (slump), Ocean Action Plan (OAP) benthic ecosystem study area, and Resolute ice scour study area. Additional dedicated survey blocks were acquired over seabed features in Lancaster Sound (ice scours), Barrow Strait (pockmarks/gas vents), Pond Inlet (streamlined drumlins and bedrock structure), Amundsen Gulf (streamlined drumlins and ice scours).

Multibeam echosounder and sub-bottom profiler data were collected at all other times while the ship was transiting in the NW Passage, where ice conditions permitted. As an extension of this, the underway collection of multibeam and sub-bottom data were maintained outside Theme 1 areas to support all operations for Themes 2 and 3.

The CSL Heron – multibeam survey launch (new infrastructure addition to the *CCGS Amundsen*'s inventory) was utilized for the first time in 2006 using external funds. The launch was mobilized and completed a highly successful first survey season involving multiple inter-project, inter-theme and inter-agency (NRCan, DFO, Parks Canada) field surveys. CSL Heron was used to collect multibeam, sub-bottom, side scan sonar, and water column CTD data in: DeSalis Bay, Sachs Harbour, Beaufort OAP area, Resolute Bay, Belcher Glacier, Oliver Sound, and Labrador fjords.

CCGS Nahidik was used through contributions by NRCan to study geohazards across the Beaufort Shelf using multibeam echo sounder, seismic reflection, side scan sonar, and seabed sediment samples. Geohazards and processes addressed by the Nahidik field work include ice scour, near-surface gas, seabed foundation conditions, artificial island stability, sub-sea permafrost, and sensitive benthic ecosystems.

In keeping with the direct stated aims of Project 1.6 and as a critical underlying component of the Integrated Regional Impact Study (IRIS), innovative new on-line methods (Figure 1) were developed for disseminating the geological and geophysical mapping data collected from the underway operations of CCGS Amundsen and CSL Heron. Efficient management of these data was essential before the stated research program could be delivered. All the bathymetric, backscatter and sub-bottom data was processed, compiled and maintained on a publicly accessible web based server to support mapping of the bathymetry and geologic structure of the Northwest Passage. All data for 2003 through 2007 operations are available at: http://www.omg.unb.ca/Projects/Arctic/basemaps/index.html

As an extension of the data management model, all data up to the end of 2006 was delivered to one of the project's major clients, the Canadian Hydrographic Service. This was done in support of the update of national charting, essential to safety of navigation in the North.

Detailed analyses of the piston cores and box cores collected in the Northwest Passage were performed; analysis types included: paleomagnetism, foraminiferas, dinoflagellates and pollen, radio-isotopes, C total, N total, Cat-Scan, photographs, and spectrophotometry. Manuscripts were submitted to a special issue of Journal of Climate in November 2007.

Geological analysis of EM300 multibeam and sub-bottom for NW Passage was ongoing by NRCan and was used to plan

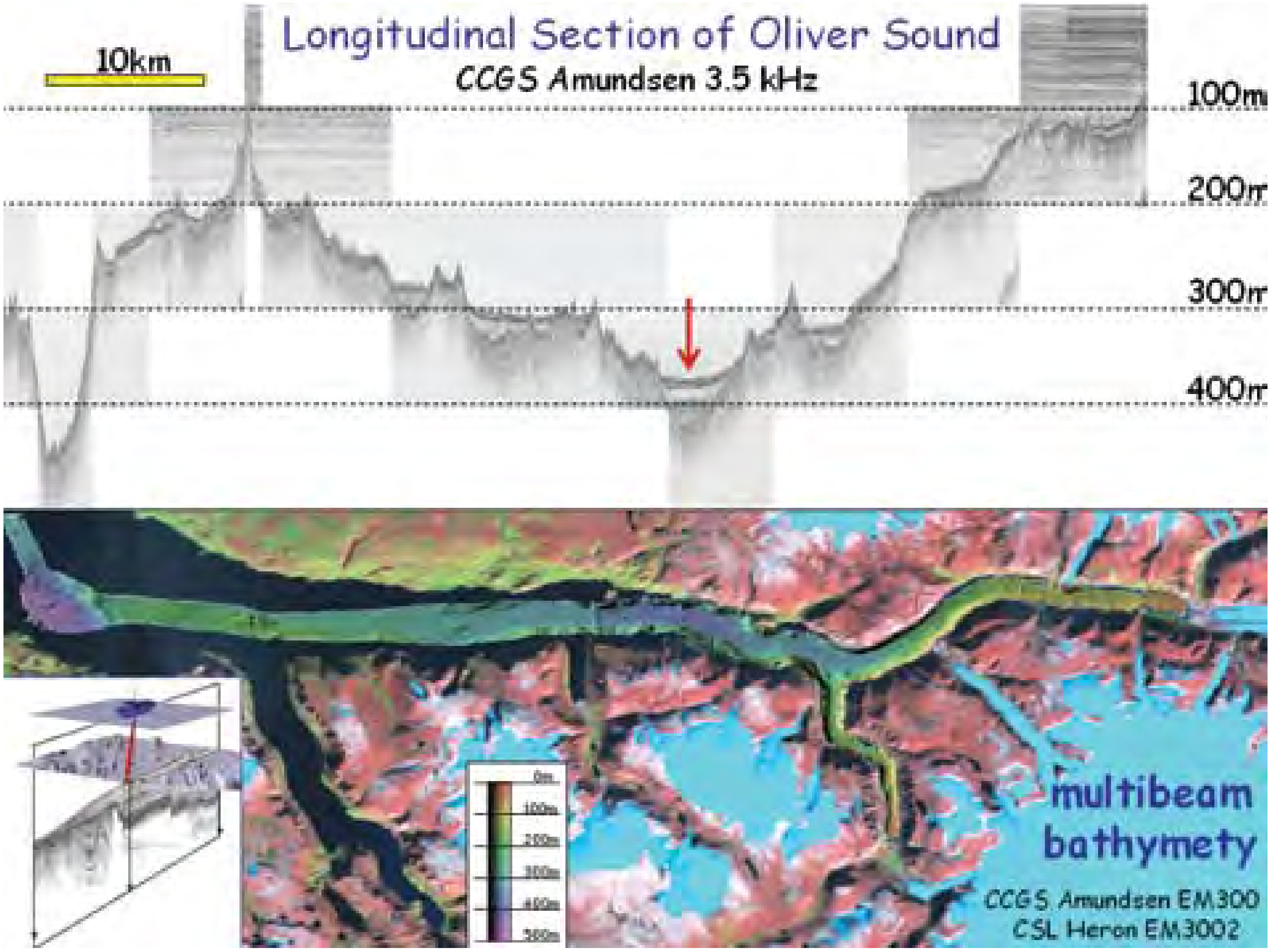

Figure 3. *Combined Multibeam bathymetric terrain model and 3.5 kHz subbottom profile of Oliver Sound. Sedimentary basins within the fjord floor, identified using the subbottom profile, potentially can provide a climatic history of the deglaciation of northern Baffin Island. The multibeam morphology provides clues to the modern sedimentary environment to establish the likely source of the deposited sediments. Background image is a Landsat 7 image from August 2000.*

subsequent year field operations (transit routes, site-specific surveys and locations for box-coring). Dedicated mapping programs directly addressed natural resource geohazards issues in the Northwest Passage, including oil seeps off Scott Inlet, iceberg scouring in Lancaster Sound, gas escape structures in Barrow Strait, ice-keel scouring in the Beaufort Sea and slope stability on the Beaufort Slope. Geological and Geophysical data, archived at the Bedford Institute of Oceanography, was compiled and maintained in a GIS database.

As well as meeting the stated aims of Project 1.6, the project personnel used external funds to supplement the *CCGS Amundsen* field operations including: Resource geohazard assessment work in Northern Labrador Sea; CHS Shipping Lane investigations – Coronation Gulf; CCGS Nahidik Surveys – NRCan collaboration in Beaufort Sea; Geoscience for Ocean Management (NRCan) – Beaufort Slope Slump surveys; Ocean Action Plan (NRCan) – Beaufort Shelf Corridor; UNCLOS test transects in the Beaufort and Labrador Seas; NSERC funded mapping of the Hudson Strait Slope area.

And as always, dialogue continued with potential partners in other ArcticNet projects on future collaborations, contributions and scientific input.

Personnel: Training of personnel on acquisition and processing of multibeam echosounder and sub-bottom profiler data was undertaken, as well as training of personnel on collection, processing, and sub-sampling of seabed sediment cores.

4.6.6 Results

Seabed mapping–Marine geohazards and opening new shipping lanes and improving navigational charting:

Using 5 years of continuous seabed mapping along transits and opportunistic site surveys, an unprecedented area of seabed throughout the Canadian Arctic Archipelago was imaged. In the almost complete absence of prior hydrographic and geophysical mapping data, this new coverage represented timely and critical data for Arctic navigation, resource extraction, climate science and asserting sovereignty.

While all data was made available for navigational chart compilation, specific areas have been recognized as needing particular attention. New multibeam data from dedicated surveys through the southern side of Coronation Gulf in previously uncharted waters represented the first step in opening up a new shipping route. This route provides an alternate and shorter transit between Kugluktuk and Dease Strait. Availability of such new routes was an essential precursor to economic development of the North. The same route allows us access to previously unexamined sedimentary basins that can provide an improved paleoceanographic record.

To be able to deliver navigational-quality bathymetric data in remote Arctic waters, the technical and logistical constraints of undertaking high latitude multibeam surveying need to be overcome. New methods for predicting tides using nested hydrodynamic models were developed and tested (Figure 2). Procedures for coping with incomplete knowledge of sound speed structure due to ice, instrument failure and limited ship time were also developed.

In the absence of coastal differential GPS base stations, the accuracy and reliability of GPS corrections from geostationary satellites had to be assessed (Wert 2004). Under certain conditions, ellipsoid heights derived directly from GPS could be used as a means of vertical control and tidal model validation.

In the absence of sufficient sound speed observations, a new method of combining archived oceanographic data bases and sparse underway sound speed measurements was implemented (Beaudoin et al. 2006). The EM300 multibeam onboard represents a new generation of use multi-sector multibeams that required development of new algorithms for post-processed integration of beam steering and ray tracing (Beaudoin et al. 2004b).

Imaging through polymer-titanium ice windows significantly alters the beam pattern of an EM300 multibeam sounder. This could have compromised the usefulness of the multibeam backscatter data which was key to the interpretation of the physical composition of the seafloor. New algorithms were therefore developed to predict and compensate for the resulting beam pattern distortions as a function of sector spacing and pulse length (Llewellyn 2005).

Taking advantage of these improvements in seabed mapping capability, geohazards of particular concern to the oil and gas development industry were imaged for the first time from the *CCGS Amundsen*. Ground water seeps, debris flows and landslides were identified off the Labrador margin. Sediment failure (or slumping) was identified on the upper Beaufort Sea slope. Active gas escape pockmarks were seen for the first time in Barrow Strait. Seabed scouring by ice keel activity in depths ranging from 20 to 400m was seen in the Amundsen Gulf. Scours in depths greater than 60m water depth were

recognised to be inactive through their scour morphology, repetitive seabed mapping on the Beaufort Shelf, and through an increased understanding of seabed glacial features revealed by *CCGS Amundsen* multibeam data.

While the CFI-funded instrument suite developed around the *CCGS Amundsen* represented a world class research platform (Bartlett et al. 2004), a significant deficiency was that it could not meet the needs of shallow coastal geoscience. A major outcome of Project 1.6 was the development and implementation of a unique coastal mapping capability (Bartlett et al. 2006). Using the infrastructure from UNB together with the technical expertise in Arctic geophysical mapping at UNB, a coastal field operational survey was implemented to meet the needs of ArcticNet marine geological researchers.

By utilizing the greater freedom of operation of the CSL Heron mapping platform, the seabed right up to the front of the retreating Belcher glacier was mapped. Despite a dedicated mapping effort in the 1980's, these waters were previously uncharted due to the more extensive ice then. This method allowed the evaluation of the rates and mechanisms of retreat of the last remaining major ice sheets in the Canadian Arctic.

Again, utilizing the ability to operate in shallower water, the CSL Heron allowed for the study of the sea level history, sedimentation and ice–seabed interaction in a number of coastal areas. In some cases, where deepwater was present close to the coast, as in Oliver Sound and Resolute, *CCGS Amundsen* and the Heron were able to work in tandem collecting data that was subsequently merged into a single mapping product.

In other cases, as in De Salis Bay and Sachs Harbour, the ship carried out more general marine geological surveys in the approaches while the Heron worked in to very shallow depths inside the bays. Significant new results included evidence for previously unknown submerged basins and terraces in De Salis Bay, imaging basin sediments in breached and submerged basins of Sachs Harbour and documenting a kettle-lake origin for these basins, which were cored from the late-winter ice surface in Project 1.2.

Multibeam data acquired at Resolute Bay using both the *CCGS Amundsen* and the Heron provided near complete coverage of the nearshore region, where sidescan surveys and diver observations had previously documented the impact and subsequent degradation of seabed ice scour features. The new multibeam data provided unprecedented imagery of this area and a new time slice of the seabed morphology. In addition, the Heron multibeam extended so close to the beach that seabed data could be combined with newly acquired high-resolution QuickBird satellite imagery and airborne LiDAR (acquired in collaboration with NASA under Project 2.4) to provide the first nearly seamless onshore-offshore mapping in Arctic waters. This proved useful in understanding aspects of the shoreline evolution and sensitivity to storm events and climate trends.

The project acquired the first seabed mapping data from Oliver Sound (Figure 3), a fjord on northern Baffin Island within Sirmilik National Park. The morphology of two proglacial fjord-head deltas revealed active slope failures on the steep prodelta slopes without channels. On the other hand, subaqueous fans from side-entry valleys were dominated by channel development and extended halfway across the basin at two locations. Large isolated mounds and craters several kilometres down-fjord from the fjord-head delta suggested that ice-rafting of large sediment blocks is an important process in the fjord. The deeper central floor of the fjord was imaged using the EM300 30 kHz multibeam and 3.5 kHz sub-bottom profiler on the CCGS Amundsen. A sequence of ponded basins was found to be bounded by sills at 25, 37, 50, and 63 km down-fjord. The maximum observed postglacial sediment thickness was approximately 60 m, much less than in some other Baffin Island fjords (cf. Syvitski and Hein 1991).

Past to present evolution of sea ice regime:

Using the same shipboard 3.5 kHz subbottom profiler, intact Holocene sedimentary basins were identified for the first time in the Western Arctic. From within these basins, piston cores were collected allowing the extraction and analysis of climatic records. The records from some of the Jones/Lancaster Sound cores provided the paleo data that linked the opening of the Arctic Channels with oceanographic changes as far south as Nova Scotia 5000 years ago.

Palynological analysis of cores from Lancaster Sound and Barrow Strait allowed identification of climate trends for the past ~15,000 years. Quantitative reconstruction of sea surface parameters (temperature, salinity, duration of sea-ice cover) from Lancaster Sound indicated important changes throughout the time-period covered by the records, especially around ~4000 years BP, where sea surface conditions were warmer by about 2°C and duration of sea ice cover less important by 1.5 months/yr (Ledu et al. 2008; 2010). This was followed by a gradual cooling of surface water until today. The warming and cooling trends did not occur sharply, but through a series of warm/cold intervals with a cyclicity of about 1800 years (Rochon et al. 2006). The meaning of this cycle has yet to be understood. Similar results were obtained on a nearby sediment core from northern Baffin Bay. Thus it appears that climate change over millennial scale in the eastern Canadian Arctic is driven, or strongly influenced, by this cycle (Mudie et al. 2005). The resolution of the sedimentary sequences did not permit to track recent climate change associated with the release of anthropogenic greenhouse gases.

Through the compilation of multi-year multibeam and subbottom coverage, the record of glacial ice-sheet retreat was examined. This was particularly critical in Amundsen Gulf where the multibeam images served to position a piston core just at the front edge of the former glacial margin and captured the glacial/de-glacial marine record for the first time in the Arctic, showing that the glacier in the Gulf started moving before those on land over Banks Island. Such information was critical to validate the ice-retreat hypotheses which are used in as input for the isostatic rebound models that predict the Holocene sea level history in the Arctic. The study of glacial ice dynamics and ice-sheet retreat using multibeam sonar also helped distinguish between active and inactive seabed processes in deep water (i.e. ice scour).

4.6.7 Discussion and Conclusions

Project 1.6 had a specific mandated focus on the Northwest Passage. To achieve this, it was necessary to install, operate and manage the data from the hull-mounted multibeam and subbottom profiler systems. These represented the single largest infrastructure cost in the Amundsen CFI project. While the proposed and funded focus was the Passage, it would have been a lost opportunity to not run these systems at all times in transit.

Using the core technical person funded through ArcticNet, together with externally funded personnel (an extra person year from CHS/NRCan) and graduate students funded externally, the sonar systems on the *CCGS Amundsen* were operated, and the data managed for all operational periods. As a result, a massive, on-line data set now serves Canadians. These data are requested, accessed, analyzed and published upon by non-ArcticNet and international researchers (e.g. Stokes et al. 2006). For example the data includes the Gulf of St. Lawrence which is the focus of a separate research project with NRCan and the province of Quebec. The *CCGS Amundsen* seabed mapping data is used to update the IBCAO compilation of Arctic bathymetry.

Multibeam mapping operations in ice-covered, remote and high latitude regions provided survey engineering challenges, not normally faced in the offshore mapping industry. New engineering research into technical solutions, including tidal modelling, high-latitude GPS analysis, sound speed compensation and ice-window beam pattern corrections was performed as part of Project 1.6 as a necessary precursor to the delivery of the mapping to the scientific community.

From the point of view of ArcticNet, this mapping effort provided extra information for other projects away from the Passage. Using existing resources, the prime technical support and implementation of all geophysical mapping programs in the Hudson Bay, Foxe Basin and Northern Labrador area (a newly emergent focus for the IRIS model) were provided. The core mapping seafloor component of Project 1.6 grew to become an essential stand-alone source of underlying framework information for Arctic researchers, nationally and internationally.

The paleoceanographic data resulting from the analysis of coring in small sediment basins in the Passage provided the constraint on predictive models of Arctic Climate. Over the course of ArcticNet we have developed several different proxies of past sea ice cover using dinoflagellates (Mudie et al. 2006; Rochon 2009), presence or absence of calcareous foraminifera (specifically planktics), and tintinnids (which only occur if there is fresh surface waterless sea ice). Stable isotope measurements were obtained from those same calcareous fossils that provide actual ice and sea surface salinities.

To have confidence in any forward climatic model predictions, these models can now be set to hindcast and checked and calibrated against the sea surface and seabed temperatures inferred from the paleoceanographic core data. Even ice cover can be estimated from the past and used as a check on ice-cover models.

There are several seabed-related constraints for resource development in the pristine Arctic environment and these were addressed by the research of Project 1.6. Knowing whether geohazards were considered relict (inactive) or contemporary was of huge importance for the development and regulation of natural resource extraction from the Arctic Seabed. ArcticNet Project 1.6 research revealed that ice scour is present in water depths out to 410m water depth, however only scours in 60m water depth or less can be considered contemporary. Naturally occurring levels of seabed disturbance (from ice scour) and hydrocarbons (from natural seabed oil seeps and gas vents) were necessary for regulation of resource development. This was addressed through mapping the distribution of ice scours and hydrocarbon vents throughout the Northwest Passage. The discovery and subsequent mapping of a large 14km wide slope failure on the Beaufort Shelf break revealed that this feature is likely several thousand years old which is valuable information to stakeholders concerned with seabed foundation conditions. These interpretations of seabed processes and the geohazard potential of the Arctic seabed were passed on to the oil and gas industry, regulatory stakeholders, and northern communities.

4.6.8 Acknowledgements

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4.7 Canada's Arctic Waters in International Law and Diplomacy (Project 1.7)

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4.7.1 Abstract

For decades, Canada has asserted the right to control activities in the straits and channels within its Arctic archipelago, which, since 1986, it claims as internal waters. Canada's claim has not often been put to the test. However, with rapidly melting ice and growing interest in Arctic shipping, Canada's claim to jurisdiction and control over the Northwest Passage will likely soon be physically challenged. This interdisciplinary project brought together experts in the Law of the Sea, sovereignty, the politics of international law, Canadian foreign policy, diplomacy, the science of climate change and sea-ice. Collaboratively, they analyzed the legal weight of Canada's claim to the Northwest Passage, the likely effects of changing ice conditions on the practical possibility of navigation, and the potential for persuading other countries, particularly the United States, to support the Canadian legal claim or otherwise cooperate in regulating the use of the Northwest Passage by vessels from all countries. The history of Canada's foreign relations concerning the issue is of considerable importance here, as well as the newly apparent openness of the United States (or at least former U.S. ambassador Paul Cellucci) to recognize the Canadian position.

4.7.2 Key Messages

- The current arrangement between Canada and the United States, whereby the two countries "agreed to disagree" over the legal status of the Northwest Passage, is no longer sustainable, given the rapidly changing ice conditions, increased shipping, and the inevitably of a challenge to Canada's claim from one or more non-U.S.-flagged vessels.
- Given the environmental and security risks associated with some non-state actors, including "rogue" shipping companies, smugglers and terrorist groups, it is not in the long-term interests of either Canada or the United States to have foreign shipping in an ice-free Northwest Passage subject to the relatively unrestricted legal regime of an "international strait".
- A new negotiated agreement between Canada and the United States is imperative, whereby Washington recognizes Ottawa's claim in return for concrete commitments, including open access to U.S. government vessels and reputable shipping companies complying with the highest international safety standards, and a serious enhancement of Canada's policing, search-and-rescue and navigation-assistance capabilities.

4.7.3 Objectives

- Analyze the legal weight of Canada's claim concerning the status of the Northwest Passage, as compared to competing claims.
- Consider the possible effects of changing ice conditions on the practical possibility of navigation through the Northwest Passage, in the context of a public policy approach based on risk (rather than a scientific approach oriented towards certainty).
- Analyze the potential for persuading other countries, particularly the United States, to support Canada's claim or otherwise cooperate in regulating the use of the Northwest Passage by vessels from all countries.
- Develop the outlines of a draft bilateral agreement between Canada and the United States on the Northwest Passage, whereby Washington recognizes Ottawa's claim in return for a serious enhancement of Canada's policing, search-and-rescue and navigation-assistance capabilities.
- Make recommendations as to those improved policing, search-and-rescue and navigation-assistance capabilities.

4.7.4 Introduction

Climate change is affecting the Arctic more dramatically than the rest of the planet, with the most apparent impact being on the sea ice, which is rapidly shrinking, thinning and changing composition in scientifically complex ways. While scientists focus on the changing character of the ice, political scientists worry about other consequences: 12,600 is the distance in nautical miles between Asia and Europe using the Panama Canal; 7,900 nautical miles is the distance using a navigable Northwest Passage.

For decades, Canada has asserted the right to control activities in the straits and channels within its Arctic Archipelago, which, since 1986, it claims as internal waters. Canada's claim has not often been put to the test. However, with rapidly melting ice and growing interest in Arctic shipping, Canada's claim to jurisdiction and control over the Northwest Passage will likely soon be physically challenged. The Government of Canada, in conjunction with other interested actors, will need to make some difficult policy choices that would benefit from the best interdisciplinary analysis possible.

Most of the research on the international law concerning the Passage dates back to the 1970s and 1980s, following the sailings of the U.S. vessels S.S. Manhattan and Polar Sea, and thus preceded the realization that changes to the sea ice will greatly facilitate near-future navigation. It also preceded the conclusion of the 1993 Nunavut Land Claims Agreement and its affirmation that "Canada's sovereignty over the waters of the Arctic Archipelago is supported by Inuit use and occupancy." Given these fundamental developments, the time was ripe for a re-evaluation of the international legal status of the Passage.

This project also analyzed the possible effects of changing ice conditions on efforts to navigate through the Northwest Passage, and the likely time frame involved before transits become commercially viable. For example, changing conditions could result in more rather than less ice being pushed into the western approaches to the Passage. At the same time, however, that ice could be single rather than multi-year ice and thus more conducive to transits by icebreakers and ice-strengthened vessels. Without a reliable prediction of the effects of climate change on shipping conditions in the various straits and channels, it was difficult to provide advice on the appropriate timelines for diplomacy, adjudication or arbitration, equipment procurement, and the construction of ports or military bases.

The loss of 1.2 million square kilometres of Arctic Sea ice between September 2006 and September 2007, along with the opening of the Northwest Passage that summer (including the historically ice-choked M'Clure Strait) suggested that the time frame for all of this is significantly shorter than most scientists and policy-makers had anticipated. And, of course, public policy decisions are generally made on the basis of risk assessment —rather than waiting for scientific certainty — making rapid decision-making pretty much imperative here.

On diplomacy, this project analyzed the potential for persuading other countries, particularly the United States, to support the Canadian legal claim or otherwise cooperate in regulating the use of the Northwest Passage by vessels from all countries. The history of Canada's foreign relations concerning the issue was of considerable importance here, as is the newly apparent openness of the United States (or at least former U.S. ambassador Paul Cellucci) to recognize the Canadian position.

Finally, the project addressed the question of enforcement, for, irrespective of the outcome of the legal debate regarding the status of the Northwest Passage, Canada must have the will and the means to enforce those rights conferred upon it by international law. Even if Canada's claim does not hold up, it will still have important regulatory powers and prerogatives as a coastal state under the 1982 United Nations Law of the Sea Convention. How would it best exercise those rights, and what sort of planning and investments now need to be made?

This multidimensional project addressed these complex and interrelated issues. It resulted in a comprehensive report in early 2008, and thus promoted constructive discussion, debate and (hopefully) better-informed policy-making.

4.7.5 Activities

This project researched numerous laws and regulations, conducted interviews with law-makers/community/medias, and led conferences and workshops.

Time frame and activities:

Research / interviewing visits

August 29-31, 2007: Interviews with territorial, municipal and Inuit leaders in Iqaluit (Paul Okalik, Premier of Nunavut, Paul Kaludjak, President of Nunavut Tunngavik Inc., Elisapee Sheutiapik, Mayor of Iqaluit), Pangnirtung (Mayor Manasa Evic), Rankin Inlet (Mayor Lorne Kusugak) and Cambridge Bay (Mayor Michelle Gillis). While in Cambridge Bay, interviews were conducted concerning the recent interdiction and arrest of five Norwegian adventurers who sought to challenge Canada's authority over the Northwest Passage in their yacht, the Berserk II.

August 25, 2007: Interview with Thomas Berger, conciliator between the Government of Nunavut, the Government of Canada, and Nunavut Tunngavik on the implementation of the 1993 Nunavut Land Claims Agreement, Vancouver.

March 27, 2007: Interviews with Government of the Yukon officials, Whitehorse, Yukon Territory.

February 8, 2007: Interviews with U.S. State Department and U.S. Coastguard officials responsible for the Northwest Passage file, and with Canadian diplomats at the Canadian Embassy, Washington, DC.

October 21-30, 2006: Northwest Passage transit, Kugluktuk to Iqaluit on the *CCGS Amundsen*, with interviews in Kugluktuk, Igloolik and Iqaluit and of Canadian Coast Guard personnel on board. Considerable time was spent with members of the ArcticNet seabed mapping programme and thus gained a much fuller understanding of the feasibility of large ships navigating through the so-called "shallow water" routes of the Northwest Passage in ice-free (or largely ice-free) conditions. While the *CCGS Amundsen* was anchored off Iqaluit, numerous Northern politicians, civil servants and elders who were flown on board were met for a lunch meeting.

July 2006: Interview the President of the United Nations' Law of the Sea Tribunal, Rüdiger Wolfrum, one of the leading authorities on the questions of international law relevant to the Northwest Passage, at the Max-Planck-Institute for Public International Law, Heidelberg, Germany.

November 23-24, 2005: Arctic Security Intergovernmental Working Group, Canadian Forces Northern Area headquarters, Yellowknife, Northwest Territories.

Conferences and Workshops Organized

February/March 2008: "Solving the Northwest Passage: Towards a diplomatic resolution of the Canada-U.S. dispute," model negotiation in Iqaluit, Nunavut, with a follow-up dissemination conference in Ottawa. The model negotiation involved teams representing the interests of Canada, the United States, Nunavut and the Inuit.

"Canada's Arctic Waters in International Law and Diplomacy": National Arts Centre, Ottawa, June 14, 2006. This international conference included among its participants John Amagoalik (Nunavut); Christopher Joyner (Georgetown University), Bernard Oxman (University of Miami); Donald Rothwell (University of Sydney), Erik Franckx (Free University of Brussels). Diplomats from Russia, the United States and the United Kingdom were present, along with numerous

Canadian officials, industry representatives and members of the national and international media. Four of the speakers at the conference were Inuit.

October 29, 2005: "Les eaux de l'Arctique," Université de Montréal. This workshop took place entirely in French. Participants included Jean-Maurice Arbour (Université de Laval); Isabelle Duplessis (Université de Montréal); Louis Fortier (Université de Laval); Frédéric Lasserre (Université de Laval); Col. Pierre Leblanc (Forces Armées Canadiennes); Donat Pharand (Université d'Ottawa); Stéphane Roussel (Université du Québec à Montréal).

Media Interviews

Multiple interviews on National Public Radio, Al Jazeera (English), BBC Newsnight, BBC World Service, Washington Post, Die Zeit, Le Monde, CBC & Radio Canada, CTV Canada AM, Question Period & Newsnet, Globe and Mail, Toronto Star, National Post, La Presse, etc.

Opinion pieces. ArcticNet research has been widely disseminated via public as well as academic media. In this project, M. Byers contributed many opinion pieces to newspapers and reviews, including the following:

22 January 2008:
Selling out sovereignty in orbit and the North.
Toronto Star.

11 August 2008:
Sovereignty will solve the Northwest Passage dispute.
The Globe and Mail.

29 July 2008:
Canada's Arctic race with Russia. *The Toronto Star.*

27 October 2006:
ByCanada must seek deal with U.S.: Vanishing ice puts Canadian sovereignty in the far north at serious risk.
The Toronto Star.

7 October 2006
True North strong and… free to give up our sovereignty?
The Globe and Mail.

6 April 2007:
Our next frontier: the Arctic Ocean. *The Globe and Mail.*

21 May 2005:
When the Ice Melts. *The Guardian.*

4.7.6 Results

The accelerating loss of Arctic sea-ice has already created a seasonally open Northwest Passage — at least during the summer of 2007. This indicated that public policy — which is based on risk assessment rather than scientific certainty — must immediately respond, before Canada's sovereignty claim is challenged, probably by a merchant vessel carrying a "flag of convenience" from Liberia, Panama or some such state.

Results obtained in 2008 suggested that the Canadian position is legally defensible, but that pro-active diplomacy is urgently required to persuade the United States to recognize Canada's claim.

As Paul Cellucci, the former U.S. ambassador to Canada has argued, the post-September 11, 2001 threat posed by non-state actors (which can include rogue shipping companies, smugglers and terrorists) can best be dealt with through the application and enforcement of Canadian domestic law. For this reason, it would be in the U.S. national interest to recognize Canada's claim, provided that a number of commitments are made by Canada in return—including assured access to the Northwest Passage for U.S. governmental vessels and reputable shipping companies applying the highest international safety standards.

A draft bilateral treaty was produced on the Northwest Passage, in an effort to demonstrate that a diplomatic solution is possible. This process culminated in a model negotiation in Iqaluit in February / March 2008, followed by a dissemination conference in Ottawa. Representatives from Canada, the United States and Nunavut were involved throughout.

4.7.7 Discussion and Conclusions

Planet Earth lost 1.2 million square kilometres of Arctic sea-ice between September 2006 and September 2007. The Northwest Passage was fully open in September 2007. The implications for the global climate system are serious. So too are the implications for Canadian policy in the North. The tacit Canada-U.S. "agreement to disagree" over the status of the Northwest Passage cannot survive now that the ice is disappearing and international shipping is on its way. A new, negotiated solution is required, one that makes Canadian sovereignty work for both countries, protecting the North — and all of North America — against a variety of environmental and security risks.

4.7.8 Acknowledgements

We are grateful to the Social Sciences and Humanities Research Council of Canada for providing the grant that supported our initial work on the Northwest Passage, to the universities of British Columbia, Montreal, Victoria, Manitoba and Winnipeg for in-kind contributions, to the many individuals, organizations and governments who facilitated our work, and — of course — to ArcticNet itself.

4.7.9 References

(ArcticNet generated references in italics)

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5. Theme 2 Project Compendium

Theme 2 was entitled "Food, water and resources in the shifting north-south thermal gradient of the terrestrial eastern Canadian Arctic" and was composed of eight projects, extending from Nunavik and Nunatsiavut to the northern limit of Nunavut.

5.1 Changing Food Diversity, Wildlife Patterns and Exploitation (Project 2.1)

Project Leaders

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MSc students: Guillaume Szor, Marie-Andrée Giroux, Marie-Claire Bédard, Manon Morrissette, Maude Graham-Sauvé, Cassandra Cameron, Édith Sénéchal, Vincent L'Héreault, Catherine Gagnon (UQAR), Marie-Hélène Dickey, Nicolas Gruyer, David Duchesne, Mylène Marchand-Roy (Université Laval), Stacey Jarema, Troy Pretzlaw, April Kinghorn-Solver, Heather Milligan, Sonja Ostertag (McGill University), Isabel Butler (Carleton University), Kerrith McKay (University of Guelph).

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Technical and project staff: Ilya Klvana, Diane Leclerc, Jimmy Pitseolak (UQAR), Denis Sarrazin, Marie-Christine Cadieux, Ivan Koonoo, Joassie Otoovak (Université Laval).

5.1.1 Abstract

Ten study sites in the Eastern Canadian Arctic were surveyed. More than 30 populations of wildlife species, mostly tundra wildlife and marine birds, were monitored. These monitoring data provide an important benchmark against which to compare future changes in wildlife patterns and ecosystem dynamics. The relations between climate and some wildlife populations were also studied in detail. Even small variations in climate affect the ecology of populations, and climate strongly structures wildlife communities. Climate warming and changes in climatic variability will thus have profound effects on the distribution and abundance of Arctic wildlife, including traditional food supplies. Field work and a synthesis of literature showed that, even in the Arctic, ecosystems are too complex to allow reliable long-term projections of the effects of climate change on wildlife populations. Yet it is clear that in a warmer climate there will be losers and winners within the wildlife populations. There will be more losers among species that have evolved with the most specialized adaptations to the harsh Arctic environment. For the animal species that are the most important in the diet of Aboriginal populations, there is a general trend of predicted increases in species with more southerly distributions, like moose and lake trout, and predicted decreases in species with largely Arctic distributions, such as caribou, Arctic char, ringed seal, and beluga. However there are many uncertainties, especially at the local scale. A sustained monitoring program coupled with a good understanding of ecosystem dynamics are key to conserve Arctic biodiversity, and to design sound strategies in relation to interactions between humans and wildlife in the changing Arctic.

5.1.2 Key Messages

- **Effects of climate warming on species:** A general northward movement of wildlife species is ongoing and should amplify in the next decades. This was mostly detected at the southern margin of the Arctic, in more temperate and boreal environments. Consequences of climate warming on wildlife appear to be at times negative and at times positive, depending on the species considered. Species that are most specialized for Arctic environments (e.g. Peary caribou, polar bear, Arctic fox, and snowy owl) are expecred to be the most negatively affected. In the short term, increases in weather variability (rain in winter, heavy wet snowfalls in early spring) may have more negative influences than climate warming per se.
- **Changes in wildlife communities:** As the abundance of some species increases while that of others decreases, some major shifts in wildlife species assemblages are expected. Species that play a key role in the organization of ecosystems (and thus influence ecosystem services such as subsistence for human communities) will likely change in many parts of the Arctic.
- **Importance of wildlife monitoring:** Because animals are continuously interacting with their environment, monitoring a set of key wildlife species is of formidable value to assess ecosystem changes occurring in the Arctic. More than 30 wildlife populations from the Arctic tundra and marine ecosystems are now monitored. This provides Canada with an important warning system regarding ecosystem changes in the Arctic.
- **Relations between humans and wildlife:** Wildlife exploitation and food diversity of Arctic human communities depend on the composition and health of ecosystems. Consequently, assessing the vulnerabilities of ecosystems and wildlife is an important component to assessing the vulnerability of human communities.

5.1.3 Objectives

- To measure the effects of climate change on Arctic wildlife.
- To predict future trends as wildlife is facing a warmer and more variable climate.
- To investigate the effects of changing wildlife patterns on human diet, health, and culture.

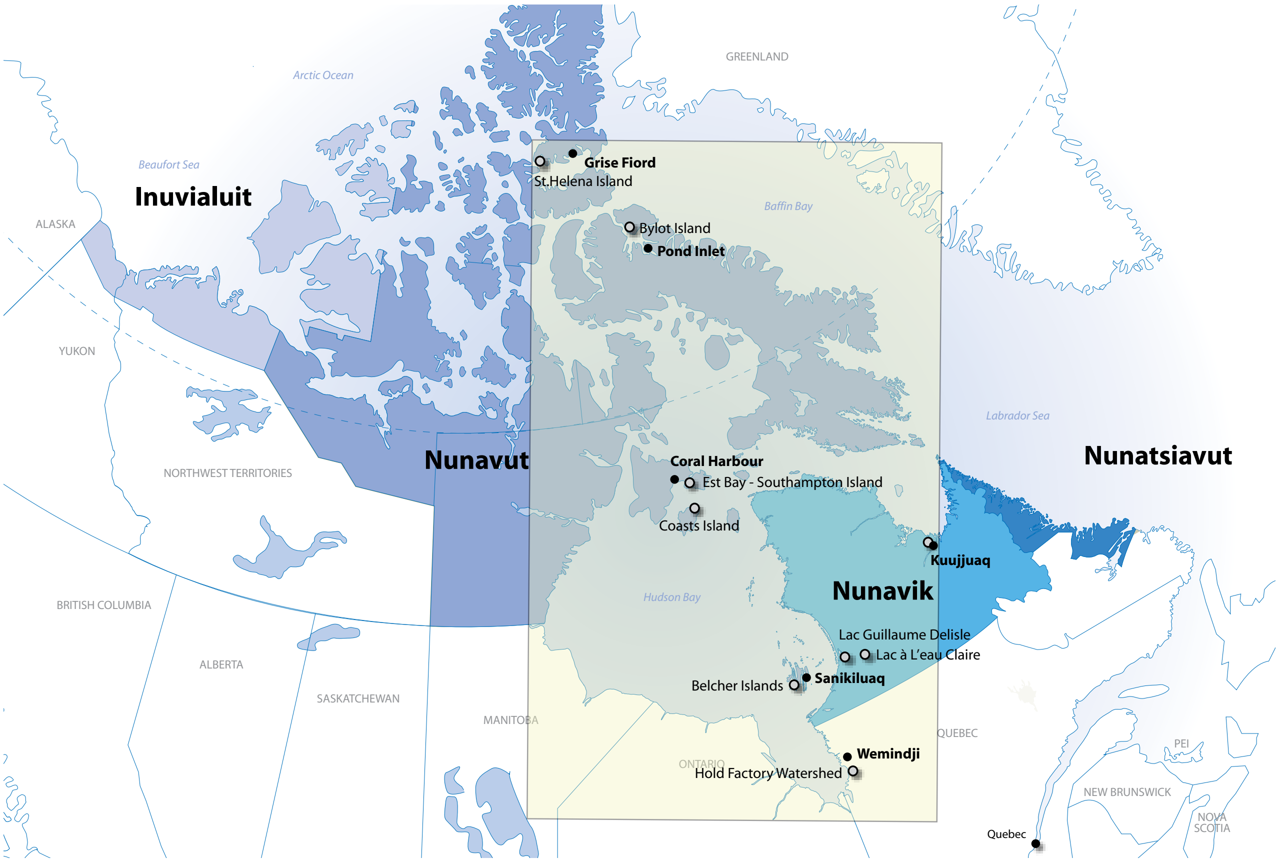

Figure 1. *Locations of main study sites (and nearby communities) used by Project 2.1 for wildlife studies and meteorological monitoring. The Koksoak River study site, located in the Yukon, does not appear here.*

5.1.4 Introduction

The increase in Arctic surface temperatures over the last decades has generated major concerns on the future of Arctic wildlife, traditional hunting activities, and the health of the indigenous people of the Arctic. Effects of climate change on the phenology of populations, the distribution of species, and the trophic dynamics of wildlife communities are now apparent. Yet, as Arctic climate continues to warm, the capacity to measure and predict the responses of biological systems and their cascading effects through food webs, and ultimately their effects on humans, remains very limited. Baseline data on natural systems are lacking in order to fully understand the complex interactions between wildlife and humans.

Phenology of populations:

Wildlife species are sentinels of environmental change and the first effects of climate change on species can be detected in the timing of biological events (their phenology) (Berteaux et al. 2004). Eider ducks and greater snow geese were the focal species studied because of their significance to the Inuit and because extensive data sets already existed on these species. The phenology of long distance migrants like shorebirds was also monitored as they represent a relevant component of Arctic biodiversity.

Distribution of species:

The northward progression of isotherms in the Arctic will have wide-ranging impacts on the distribution of wildlife

(Humphries et al. 2002), with cascading effects on the functioning of ecosystems. Many Arctic species could undergo population declines in response to warming. This is not because they cannot tolerate more benign environmental conditions, but rather because they will be out-competed by southern invaders in these new environments. The latter are less tolerant of harsh conditions, but have better growth potential under more benign conditions. Invading species come from the southern boundary of the Arctic, where the distribution and abundance of wildlife species along a forest-tundra gradient in the low Arctic, were surveyed in order to determine the factors currently limiting their distribution. In addition, detailed investigations of the mechanisms leading to range expansion and its effect on other species were done using as models red and Arctic foxes on Bylot Island, and shorebirds in northern Hudson Bay.

Food web dynamics of wildlife communities:

Climate imposes a rough structure to wildlife communities through its effects on local primary productivity. However, the interactions between plants, herbivores, and predators (the food web dynamics) shape the fine-scale structure of communities (Krebs et al. 2003). It is not known yet how the relative influences of climate and biotic factors vary geographically. Therefore, it cannot be anticipated where the effects of climate change on the functioning of the tundra will be greatest. The studies on the interactions between plants, herbivores, and predators on Bylot Island (High Arctic) and Southampton Island (Low Arctic) were expanded to all components of the food web (e.g. lemmings and avian predators) to better understand climatic impacts on food web dynamics.

Diet and health impacts of changes in wildlife:

Humans and wildlife are closely connected to each other in the Arctic. Country food is vital for communities, but also exposes humans to contaminants or parasites. The contribution of a changing climate to health in northern communities was assessed according to one parasite, Toxoplasma gondii, which can be of animal origin and can have catastrophic consequences when contracted by pregnant women. The potential impacts of climate change on several traditional food species across the Canadian Arctic were also examined.

Figure 2. *Photos of some of the most intensively monitored wildlife species in Project 2.1. Clockwise from upper left: snow goose (photo: G. Gauthier), arctic fox (photo: D. Berteaux), snowy owl (photo: G. Gauthier), common eider (photo: G. Gilchrist), brown lemming (photo: G. Gauthier), Baird's sandpiper (photo: L. McKinnon), black guillemot (photo: M. Mallory), Long tailed jaegger (photo: G. Gauthier).*

5.1.5 Activities

Study sites: Field work was conducted at Bylot Island (73° 08' N, 80° 00' W and 72° 53' N, 79° 55' W), St. Helena Island (76° 16' N, 89° 08' W), East Bay-Southampton Island (64° 01' N, 81° 46' W), Coats Island (62° 59' N, 82° 15' W), Belcher Islands (56° 22' N, 79° 59' W), Koksoak River (58°32'N, 68°10'W), Lac Guillaume-Delisle (56°15'N, 76°17'W), Lac à

L'Eau Claire (56º10'N, 74º25'W), and Old Factory Watershed (52º 30' N, 78º 40' W). See Figure 1 for a map of study sites and nearby communities.

Activities: Numerous wildlife species were monitored (see Figure 2 for a subset of the species monitored). On Bylot Island, the breeding activity of Arctic and red foxes, arrival dates and breeding activity of geese, nesting activity of other birds (shorebirds, lapland longspurs, jaegers, glaucous gulls, raptors), and lemming and arthropod abundance were monitored. On Southampton and Coats Islands, the nesting activity of common eiders, large gulls, and shorebirds was monitored as well as for gulls, eider ducks, and black guillemots on St. Helena Island. Beaver ecology at Old Factory Watershed was monitored. To accurately relate wildlife breeding activity and abundance to climate, automated weather stations at four field sites (Bylot, St. Helena, Southampton, and Coats) were maintained.

In addition, intensive studies on various aspects of the ecology of key wildlife species were conducted. On Bylot Island, the demography of both Arctic foxes and lemmings was studied through intensive trapping and marking programs, and the impact of climatic factors on lemming demography was examined. The diet of predators was analysed using various techniques (foxes: stable isotopes; avian predators: food pellets and camera recording at nests). Plant-herbivore interactions in geese were studied by sampling plant production in wetlands used by geese and by measuring the impact of goose grazing with exclosures. The migration strategies of Arctic-nesting snow geese and shorebirds were studied through direct observation and the use of satellite telemetry. The seasonal changes in food (arthropod) abundance of shorebirds were also monitored and associated with weather data. On Southampton and Coats Islands, studies comparing the influence of predators on shorebird reproduction between a site where lemmings are present (East Bay) and a site where they are absent (Coats Island) were pursued. On the Belcher

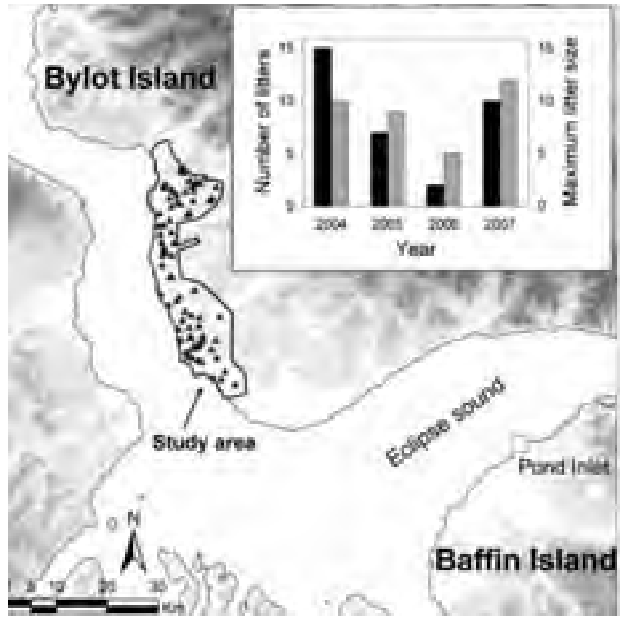

Figure 3. *In this representative example of wildlife monitoring, every den used by arctic foxes has been mapped in a 600 km² study area in Sirmilik National Park of Canada (Bylot Island, Nunavut). The fox population is closely monitored by systematically visiting each den every year. Triangles in the study area indicate location of dens. The histogram shows yearly variations in the number of dens with fox families (left axis, dark bars) and in the largest litter found in a given year (right axis, grey bars). The years 2004 and 2007 were high lemming years.*

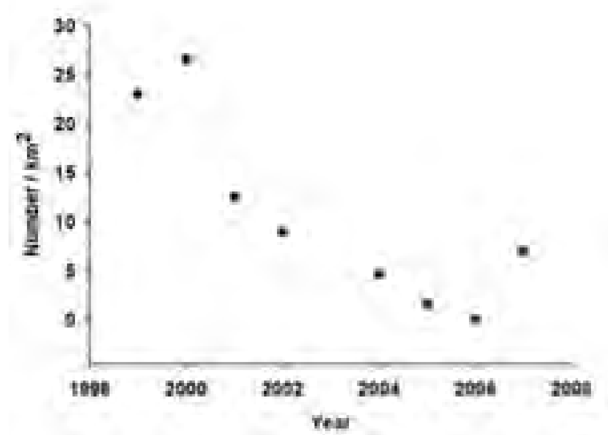

Figure 4. *The number of nesting red phalaropes observed in a 2.6 km² study plot at East Bay, Nunavut, has declined three-fold since 1999. Note the spike in abundance recorded in 2007, the first year of lemming abundance at East Bay in a long time.*

Islands, movements, foraging ecology and marine habitat use of eider ducks wintering in Hudson Bay were examined using direct observation and underwater photography. At East Bay, eider duck colony attendance, adult survival, and reproductive success in relation to weather and the presence of avian cholera (a newly emerging disease affecting birds in the Eastern Arctic) were investigated. In the Old Factory Watershed, the relevance of aquatic vegetation to beavers was investigated and the distribution and abundance of beaver were surveyed in Nunavik to develop models of climate and land cover determinants of beaver range limits and to generate climate change projections of beaver distribution across Nunavik. Finally, the collection of biological samples from birds along a latitudinal gradient in the Arctic was expanded to establish baseline information on avian disease (e.g. avian cholera), and from mammals in Nunavik and Hudson Bay for the presence of zoonotic pathogens (e.g. *Toxoplasma gondii*).

Other activities away from the field were also conducted. A conceptual model allowing examination of the role of sea ice on the ecology of terrestrial Arctic wildlife was developed as well as a model integrating foraging energetics of eider ducks and constraints imposed by sea ice and currents. The literature on the effects of climatic variability on Arctic wildlife, including six key traditional food species (moose, caribou, Arctic char, lake trout, ringed seals, and beluga whales) was reviewed in order to produce a synthesis of the effects of climatic variability on mammal ecology.

Time frame: Most of the field work involved intense and repeated sampling over several years at the same study sites (longitudinal studies), rather than extensive and single sampling at many study sites (transversal studies). Therefore, most studies ran throughout the whole project period, and were pursued afterwards. Field work was typically conducetd during the summer, when wildlife is most active and reproducing. One exception was the winter study of the relation between eider ducks and sea ice in the Belcher Islands.

Methods: A wide variety of sampling designs, field techniques, and analytical procedures were used throughout this project. Several of the detailed field protocols used in this project can be found at www.cen.ulaval.ca/Arcticwolves/en_project_descrip_CAN_info.htm. Additional details can be found in Gruyer 2007, Lecomte 2007, Perkins et al. 2007, and in Smith et al. 2007a, 2007b.

5.1.6 Results

Hereafter are presented a subset of findings to support the main messages delivered by this project.

Wildlife monitoring:

Monitoring proved to be the easiest and most efficient way to study wildlife when species used the same nests, dens, colony sites, or general breeding areas every year. For most monitored populations, yearly variations in the density and reproductive success of individuals and the phenology of biological events were observed. Accumulation of standardized data through the years thus allowed detecting directional trends, fluctuations, and cycles. This can be illustrated using the following two examples. First, monitoring of the most important tundra predator (Arctic fox) over 600 km^2 in the heart of Sirmilik National Park of Canada showed large annual fluctuations in the abundance and reproduction of this predator (Figure 3) in relation to the lemming cycles (Gauthier et al. 2004). These fluctuations observed in the high Canadian Arctic are not observed anymore in sub-Arctic Scandinavia, where lemming cycles have disappeared, partly due to climate warming. Second, the number of red phalaropes (a shorebird) observed at East Bay declined three-fold since 1999, in a 2.6 km^2 study plot where an exhaustive sample of line transects was conducted for 8 years (Figure 4). This decline is representative of the general decline usually observed in many shorebirds throughout the Canadian Arctic.

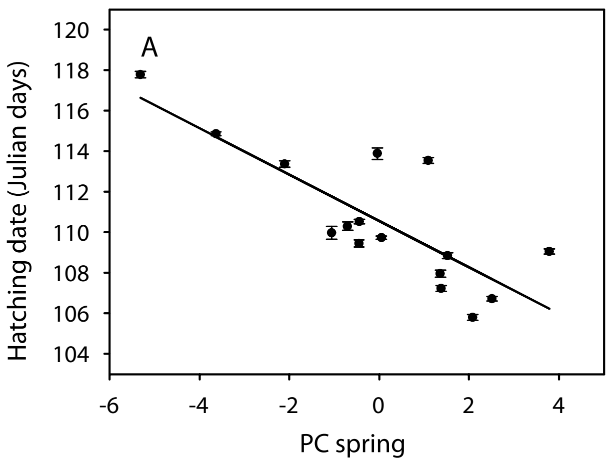

Figure 5A. *Example of relationships between climate and wildlife. Hatching date of snow goose nests (Julian days relative to vernal equinox) as a function of an index of warm spring temperature and low snow cover (PC spring) over a 16-year period.*

Effects of climatic variability on wildlife:

It was found that climate was a key factor affecting the ecology of populations and that wildlife thus responded strongly to climatic variability (e.g. Szor 2006; Szor et al. 2008). However, analyses revealed that these interactions were complex and could be both positive and negative for the same species. This is illustrated with the following examples related to snow geese and shorebirds.

Warm springs with early snow melt are strongly associated with early egg laying dates for geese, and hence early hatching dates of goslings (Figure 5A). Geese that lay their eggs early in the season benefit from a longer period to raise their goslings, and thus enjoy a high reproductive success (Lepage et al. 2000). However, in years with very warm spring, the phenology of plant growth advances more rapidly than the phenology of goose nesting, leading to a time lag between hatching dates of goslings and date of peak nitrogen concentration in plants, an index of food quality (Figure 5B). Thus, during very warm springs, goslings hatch up to three weeks after the peak in food quality, which can have a strong negative impact on their growth and survival during their first year (Lepage et al. 1998; Dickey 2006; Dickey et al. 2008).

Shorebirds are influenced strongly by spring weather conditions including snow depth, temperature, and precipitation. It was found that the spring climate in the Arctic is a key factor determining the date of nest initiation of ground-nesting shorebirds at Hudson Bay and Bylot Island. However, shorebird species vary in their response to late snow conditions in relation to their mating strategy, body size, and migration routes. Shorebirds migrating northward over-sea are less affected by continental late-spring snow conditions than those migrating over-land. By networking with other shorebird monitoring sites in Hudson Bay, recent changes were detected in the breeding range among several species, reflecting the documented warming conditions in northern Hudson Bay. Dunlin and semi-palmated sandpipers have moved northward in Hudson Bay to nest commonly on Coats and Southampton Islands (Smith et al. 2006).

Some of the correlates of spatial variability in climate were also analyzed. It was noted that wildlife in the forest-tundra transition is sorted into four discrete assemblages; three of them are strongly affiliated with boreal, taiga, or tundra habitats. Habitats belonging to these categories are distributed along the latitudinal gradient and depend on the topography. However, there is little overlap between the wildlife species assemblages. Thus, species richness is not higher at sites within the forest-tundra transition than in boreal and tundra sites. Instead, diversity declines as one moves north in the transition zone. Ordination analyses showed that vegetation cover (particularly conifer vs. herbaceous cover) is the best predictor of species composition across the transition while climate (seasonality and precipitation) plays a secondary but significant role.

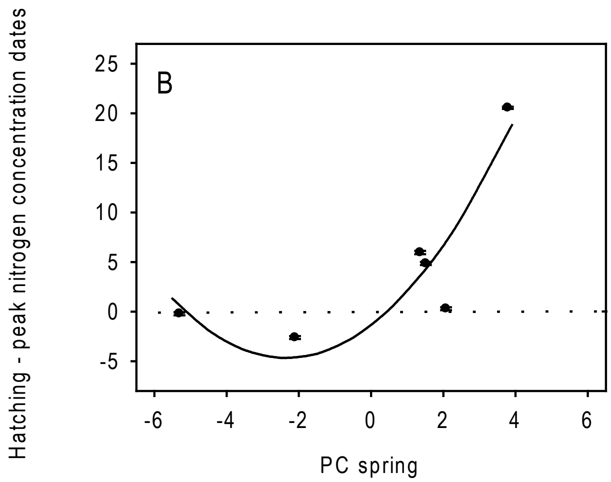

Figure 5B. *Relationship between the difference in hatching date of goose nests and date of peak nitrogen concentration in plants, and an index of warm spring temperature and low snow cover (PC spring) over a 6-year period. Sirmilik National Park of Canada, Bylot Island, Nunavut (from Dickey 2006).*

Predicted effects of climate variability on wildlife:

Projections are required to detect the major vulnerabilities of a system and to elaborate adaptation strategies. Two approaches were explored to provide projections of the impacts of climate change on wildlife. First, an extensive review of the literature was performed to synthesize existing knowledge on the relations between climate and Arctic wildlife. Second, an international symposium (Berteaux and Stenseth 2006a; 2006b) was organized to evaluate the specificities of wildlife ecology regarding the ability to anticipate the future effects of climate changes. It was found that even for the best known Arctic species, existing knowledge is often scarce regarding the links between climate and population ecology. Quantitative predictions are extremely difficult, given that climate often interacts with other variables to create complex biological responses at the population level (Krebs and Berteaux 2006), yet some qualitative predictions can be made (Table 1).

Relations between wildlife and humans:

Following the previous results, it was established that the availability of data regarding the effects of climatic variability on animals consumed by Aboriginal populations in the Canadian North range from mediocre to poor. There are therefore many uncertainties; however, there is a general trend of predicted increases in species with more southerly distributions, like moose and lake trout, and predicted decreases in species with largely Arctic distributions, such as caribou, Arctic char, ringed seal, and beluga. Preliminary results also suggested that the prevalence of toxoplasma infection in seals can be high (e.g., up to 20% on Belcher Islands) and the effects of climate change on these high infection rates need to be evaluated.

5.1.7 Discussion and Conclusions

Main contributions:

The main contributions of this project were (1) the establishment of a network of wildlife monitoring programs in the Canadian Arctic; (2) the elucidation of some of the relations between climate variability and Arctic wildlife; (3) a better grasp of the possibilities and limitations of projecting the effects of climate change on Arctic wildlife; and (4) the synthesis of available literature pertaining to wildlife and climate in the Arctic, including potential effects of climate change on traditional food supplies. These contributions provide a strong platform to assess expected changes and will facilitate the development of adaptation strategies in the wildlife/biodiversity sector.

The value of the monitoring network established by this project is tremendous considering that detailed data on wildlife populations are very scarce (non-existent for many species) in the Canadian Arctic. Such a reliable benchmark is crucial to evaluate future changes due to climate change and modernization.

SPECIES	RELATION BETWEEN CLIMATE VARIABILITY AND SOME ASPECTS OF THE ECOLOGY OF SPECIES
Terrestrial ecosystems	
Lemmings	Increased winter mortality and dampened cyclicity due to reduced quality of snow cover and increased frequency of thaw/freeze cycles and icing events in winter (Aars & Ims 2002).
Snow goose	Expansion of breeding range as new habitats become available due to warming (Jensen et al. in press). Reduced gosling growth and survival due to a mistiming between hatching date and the peak in plant food quality (Dickey 2006).
Peary caribou	Increased winter mortality due to negative effects of winter freezing rain limiting access to lichen and vegetation under the ice (COSEWIC 2004)
Common raven	Warming and modernization should increase availability of food, most notably carrions, and fuel population increases (Downes and Collins 2003).
Red fox	Warming allows increased tundra productivity and thus northern range extension (Killengreen, Ims et al. 2007)
Arctic fox	Warming favours red fox, a fierce competitor to the arctic fox (Killengreen, Ims et al. 2007)
Snowy owl	Reduced reproductive success if lemming cycle is disrupted due to climatic-induced winter mortality and the invasion of alien, generalist predators
Marine ecosystems	
Thick-billed mure	Earlier ice breakup and higher spring temperatures favour reproduction in high Arctic colonies but have negative effects on chick growth and survival in low Arctic colonies (Gaston, Gilchrist et al. 2005)
Ivory gull	The strong year-around association of Ivory Gull with pack ice suggests likely effects of climate change, but knowledge is too scant to enable even weak projections (Gilchrist and Mallory 2005).
Polar bear	Negative effects of decreasing sea ice on foraging opportunities and population size (low Arctic). Possible positive effects of decreasing sea ice on foraging opportunities and population size (high Arctic) (Desrocher et al. 2004). There is currently more evidence for negative effects than for positive effects.

Table 1. *Likely effects of 21st century climate warming on the abundance of selected species (blue: positive effects, red: negative effects, black: unknown effects). Effects were inferred from knowledge of the relationships between climate and some aspects of the species ecology (right column). Opposing effects sometimes occur within a single species. Knowledge is often scant, and complex ecological relationships will sometimes modify the anticipated direction of effects. Surprises will thus occur.*

It is relevant to stress that this project was very successful largely due to the long-term data sets acquired on several Arctic wildlife species, which were available at the beginning of the project. This further highlights the value of maintaining these long-term programs considering the large natural annual variability in the climate, the periodicity of some phenomena (e.g. lemming population cycles) and the relatively long lifespan of several wildlife species.

The numerous field studies conducted within this project started to unravel some of the relations between climate and Arctic wildlife. They also revealed the complexities of these relationships in unexpected ways. For instance, the direct and positive effect of warm temperature on nesting phenology of snow goose was not surprising and suggested a positive effect of future climate warming on this species. However, trophic interaction studies also revealed a negative impact of climate warming on goose reproduction due to a difference in the response times of plants and herbivores, which leads to a time lag in the events in the annual cycle of geese. The nest outcome of these opposing effects is difficult to predict and requires experimentation. So far, the Eastern Canadian Arctic warmed at a slower pace than other regions such as the Western Canadian Arctic and Northern Europe, where many bird species are not able to track the recent changes in climate (Møller et al. 2004). Therefore, it is expected that the anticipated temperature increase in Eastern Arctic will lead to still greater mismatches between food availability and wildlife breeding phenology.

Despite the intensive efforts to study the impact of climate variability on several wildlife species, this project only focussed on a very limited subset of the Arctic fauna. In order to fill our knowledge gaps and broaden our vision, a large synthesis of the literature pertaining to Arctic wildlife and its relationships to climate was undertaken. In particular, a question asked was "How much can be predicted?". The field work and this literature review revealed that the knowledge about the population ecology of Arctic wildlife is generally very sparse, especially concerning their winter ecology. Information on the status and trends of Arctic fauna is very fragmented (CAAF 2003; Berteaux 2005). The ability to predict the future state of wildlife populations is limited because basic data on population demography and ecology is lacking (clearly, this is due to the logistical difficulties associated with field work in the Arctic), ecological phenomena are very complex and rely on stochastic processes that greatly influence the demography of wildlife populations (Berteaux et al. 2006). However the literature does show that climate change will have significant impacts on food security in the North, given that the most prized country food species will be affected by the changing climate. Answering when and how much climate will impact each population is out of reach at the moment, but results can at least be used as a blueprint for northern communities to develop local monitoring efforts and adaptation strategies. Nonetheless, the limits of current knowledge must be recognized. Much more monitoring is required to track trends in basic environmental parameters in the Arctic, and more research is needed to document the ways that species interact locally and across ecosystems.

Three conclusions can be derived from these results. First, wildlife monitoring is critical to assess the trajectories of populations in the short to mid-term scale because it allows calibrating previous projections. Second, a few well-known populations may serve as models from which generalisations can be drawn. Third, long-term projections at the community and ecosystem levels are more likely to be informative than those at the population level. Future research should therefore combine a good monitoring strategy (at the population level), some detailed work on a few well-known populations, and work at the community and ecosystem level.

Impact on stakeholders:

Collectively, this project made significant progress toward the production of region-specific assessments of climate change effects on wildlife. Parks Canada and the Canadian Wildlife Service already use some of the project's results in the management of Arctic parks or wildlife populations. For example, management decisions for some waterfowl (e.g. eiders, geese) and seabird populations have been partly based on data gathered during this project. Similarly, the Nunavut Field Unit of Parks Canada incorporates some of the monitored variables in their Ecological Integrity monitoring program. Some of the information provided is relevant for decision making related to the impacts of climate change on Inuit health and food supply, which are closely linked to wildlife ecology. In addition, a large number of highly qualified persons, including northerners, have been trained during this project. Finally, several workshops were organized and numerous brochures were distributed in northern communities to disseminate results and discuss them publically.

Future work:

Future research is needed to identify the main vulnerabilities of Arctic biodiversity in the context of a warming climate. The best way to do this is to continue documenting past and present responses of animal populations to climatic variability based on the ongoing research, the available literature, and the considerable expert knowledge available in Inuit communities, universities, governmental agencies, and interest groups. In addition to maintaining monitoring programs, future research is needed to identify climate indicators and thresholds. Such variables listed in a metadatabase such as the ArcticNet Polar Data Catalogue represent an invaluable resource and a barometer of the Canadian Arctic ecosystems. Finally, further modelization efforts are needed to better predict the consequences of climate change and modernization.

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5.2 Water Quality, Supply and Indicators of Change (Project 2.2)

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5.2.1 Abstract

Lakes and rivers are major features of the circumpolar Arctic, and are diverse and vital resources that provide many essential services including habitats for aquatic wildlife, drinking water supplies for northern residents, and water for industries such as mining and hydroelectricity generation. These aquatic resources are likely to be vulnerable to future climate change and also provide records of change in the past and present that will help guide environmental management strategies. The main objectives of ArcticNet Project 2.2 were to develop, assess and apply indicators of climate, water quality and water supply in lakes and reservoirs of the eastern Canadian Arctic. Paleoclimate indicators including lake sediments, ice cores and dendrochronological measurements (tree-ring analysis) were used to study annual precipitation, air temperature fluctuations, air-sea interactions, lake water level changes, melting patterns, and changes in snow geese populations. Present climate indicators and their relationship with limnological variables and sedimentation processes were studied by installing climate stations and underwater data loggers (thermistors) in lakes and ponds and by maintaining other meteorological stations along the IRIS region transect, compiling modern data from climate stations, profiling lakes and fjords on Ellesmere Island, and undertaking detailed microbiological and limnological analyses. Indicators of water quality included coliformic and other pathogenic bacteria, cyanobacteria, diatoms, freshwater crustaceans (cladocera, ostracods), pigments and insects (chironomids) and chemical indicators for drinking water. Results obtained from a major drinking water survey in Nunavik and a pilot survey in Nunatsiavut were used to make general recommendations to Nunavik residents and to initiate projects pertinent to drinking water quality. Upon completion of the analyses, results were communicated to community health centers.

5.2.2 Key messages

- Freshwater is a vital resource for the Arctic, with implications that cut across the health, social and all natural science sectors. The monitoring of aquatic resources in the eastern Canadian Arctic as past and present indicators of climate change is critically important for predicting current and future trends, a central objective of the network.
- Multiple indicators are required to assess the regional patterns of environmental change throughout the vast, north-south range of the eastern Canadian Arctic. This project employed many standard approaches, including the establishment of new climate monitoring stations, monitoring of lake and fiord ice by RADARSAT, and the paleo-analysis of ice cores, lake sediments and tree-rings. It also allowed the development and application of new approaches, such as the use of lake and fiord profiles as climate indicators, the application of DNA-based techniques to assess aquatic biodiversity, and the analysis of fossil bacterial pigments as paleo-indicators of lake ice and snow cover.
- Results from northern Ellesmere Island show that the northern limit of Nunavut is a region that is already experiencing severe climate change. Analyses of lake sediments show evidence of an abrupt onset of warming sometime within the last two centuries that was unparalleled relative to previous millennia. Modelling of lake water profiles and analysis of ice shelf dynamics indicate that the region was strongly affected by climate warming in the 1930s and 40s. Monitoring of ice-related features along the coastline shows evidence of accelerated change over the last five years, including the break-up and ongoing loss of the Ward Hunt Ice Shelf and its associated ecosystems, and the complete break-out and loss of the Ayles Ice Shelf during record minimum sea ice conditions and record maximum air temperatures.
- Analyses of drinking water in the context of environmental change show the urgency of setting up both an effective environmental monitoring system and an effective health monitoring system to detect and deal rapidly with health problems related to water quality.

5.2.3 Objectives

The central objective of this project was to develop and apply environmental and health indicators for water resources in the eastern Canadian Arctic sector. This vast region encompasses a 30 degree span of latitudes from Hudson Bay to Ellesmere Island in which there appears to be a striking north-south disparity in climate trends and sensitivity (Saulnier-Talbot et al. 2003; Antoniades et al. 2008). The specific objectives of Project 2.2 were the following:

- To develop and use paleoclimate indicators (lake sediments, ice cores and dendrochronological data) to reconstruct histories of snow accumulation, air temperature, melting patterns, lake water level changes within this IRIS transect region.
- To investigate influences of changing sea ice conditions and patterns of atmospheric transport on snow accumulation and aerosol deposition on the ice caps.
- To maintain and increase the northern climate station network in order to document the present climate patterns and their relationships with the limnological variables and the sedimentation processes.
- To assess and apply health indicators of drinking water quality in order to evaluate drinking habits that may place northern residents at an increased risk of gastroenteric diseases in the context of climate change.
- To determine the impact of the animal populations on the water quality of lakes and ponds of Bylot Island, Nunavut and to develop and test paleolimnological techniques for the reconstruction of past animal population dynamics.

5.2.4 Introduction

The most successful strategies for long-term sustainable management of aquatic ecosystems are those combining global perspectives and knowledge with a local understanding of cultural, environmental and economic factors (Kumagai and Vincent 2003). Although this integrative approach towards aquatic resource management has been applied with success in several parts of the world, it has been little considered at high northern latitudes where environmental change is likely to have major repercussions for the supply of safe drinking water, freshwater habitats for aquatic wildlife and water resources for industrial needs, including mining and hydro-power generation (Prowse et al. 2007; Wrona et al. 2007; Vincent and Laybourn-Parry 2008). The central objective of this project was to develop and apply a broad suite of environmental indicators for water resources in the eastern Canadian SubArctic-Arctic sector, a 30 degree span of latitudes from Hudson Bay to Ellesmere Island in which there appears to be a striking north-south disparity in climate trends and sensitivity (Saulnier-Talbot et al. 2003; Antoniades et al. 2007) and a variety of issues concerning the sustained use of these resources.

This project brought together a diverse team of northern scientists to develop and apply regional indicators of environmental change with emphasis on water and ice, and to encompass sites across the full north-south range of eastern Canadian Arctic. This ecoclimatic gradient provided a variety of paleo-indicators of climate fluctuations in the past. At the southern limit, boreal forest grades into tundra, providing the opportunity to use tree-ring data to assess variability in water supply, a question of vital relevance to the powerful hydro-power industry in subArctic Québec. The abundant lakes and ponds at tundra sites further to the north, specifically on Southampton Island and Bylot Island, provided sediment records to assess changes not only in climate, but also in trophic status and other ecological shifts. Due to protection measures and changes in the overwintering habitat, the population of breeding Greater Snow Geese (*Chen caerulescens atlantica*) on Bylot Island has increased dramatically over recent years. By retrieving short cores in enriched and unenriched lakes and ponds, it was possible to study several proxies to determine the evolution of the trophic status of these small freshwater ecosystems in response to variations in goose densities. Further to the north, the glaciers and ice caps provide records of chemical deposition, sea-land transport and sea-ice conditions, and analyses focused on drilling and analysis of ice cores from the ice cap on Devon Island and the Prince of Wales Icefield on Ellesmere Island.

At the northern extremity of this eastern Arctic sector, the 'Ward Hunt Island Observatory' was established in partnership with Parks Canada as a monitoring station and logistic base for ArcticNet operations along the northern Ellesmere coastline. Paleo-climate analyses focused on lake and fiord sediments, historical records of ice, and the development of a geophysical model of long-term solar heating in the perennial ice-covered lakes of the region. The research at this site also addressed environmental conditions in the present by way of studies on aquatic biodiversity, food webs, contaminants and ice conditions, and included experimental analyses of nutrient control of primary production.

Another key component of project 2.2 was a comprehensive assessment of drinking water quality for northern residents. The first phase of this work was undertaken as part of the Nunavik Health Survey via the *CCGS Amundsen* in 2004 in which 14 Inuit communities were visited. This subsequently involved considerable analysis and synthesis and extensive reporting back to northern communities by way of community presentations. The second phase was a pilot study to begin the same analyses in Nunatsiavut, and similar work is planned for Nunavut in the longer term.

5.2.5 Activities

1) Paleoclimate indicators

Tree-ring samples were taken at more than 100 sites in the eastern James Bay-Hudson Bay region from field studies in each of the four years, with comparative measurements of tree growth rates using automated dendrometers to calibrate the records. This sampling encompassed the vast La Grande watershed, and covered an area of 320,000 km^2 (800 km of longitude by 400 km of latitude). Dendrochronological analyses were conducted on these samples and the data were synthesized into models to reconstruct the past 1000 years in terms of spring water supply, temperature, snow depths, and flood peaks.

For the paleolimnological studies in tundra, two visits were made to the "Goose Camp" on Bylot Island during the summers of 2005 and 2006 for the paleo-analysis of fluctuations in Greater Snow Goose populations and their influence on water quality in lakes and ponds. In August 2007, a survey of lakes and ponds was completed within the East Bay Bird Sanctuary on south-eastern Southampton Island, and water samples and short sediment cores were taken from three lakes located within dense nesting habitats of another migrating bird, the Lesser Snow Goose, and a study on the diatom-inferred environmental changes on Southampton Island was completed.

The glaciological analyses over this period involved sub-sampling of five short cores from the Devon Island ice cap, two short cores from the Prince of Wales Icefield (Ellesmere Island) and the top 50 m of a long core from the Prince of Wales Icefield (this record spanned ca. 100 years). Analyses were completed for anion chemistry, oxygen isotopes, annual layer thickness and net accumulation rates. In related work, an analysis was undertaken on the relations between the mass balance of glaciers and ice caps on the Queen Elizabeth Islands since 1960 and the behaviour of the summer Circumpolar Vortex.

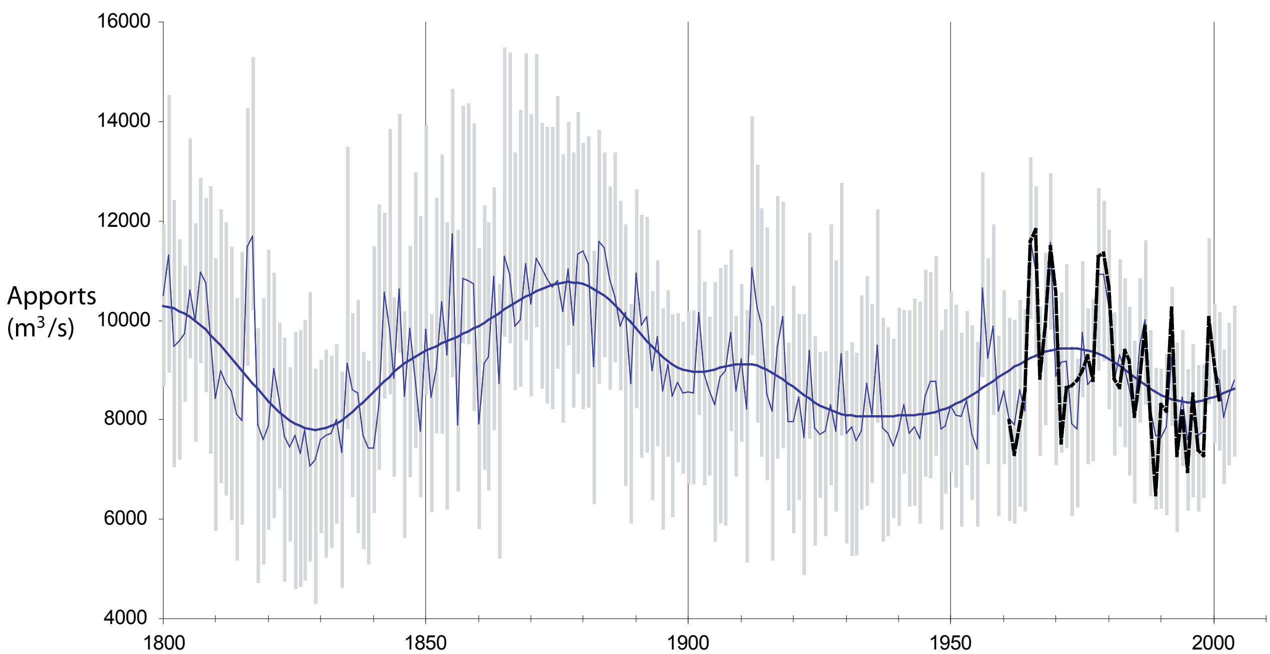

Figure 1. *Reconstruction of the annual inflows to the La Grande reservoir (Caniapiscau) for the last 300 years using a model based on dendrochronological data collected under the auspices of ArcticNet and partners.*

Field studies were undertaken during each of the four years along the northern coast of Nunavut, based out of Ward Hunt Island. Sediment cores were retrieved from Disraeli, Markham, and Ayles fiords, records that spanned several millennia each, and initial geochemical and paleolimnological analyses were completed. A sediment core from Ward Hunt Lake, Canada's northernmost lake, was analyzed and brought through to publication. Several sediment cores from the bottom of Lake A and C1 were also retrieved. A geophysical model was developed to describe the long-term solar heating in Lake A and to determine past variations in ice cover.

2) Present indicators

Research on Bylot Island aimed to provide an assessment of the impacts of increasing pressure from expanding animal populations on freshwater ecosystems (lakes, ponds) in Sirmilik National Park, Nunavut. The field visits in 2005 and 2006 allowed sampling for a broad range of water quality variables. Similar measurements were made from the survey by this team of lakes and ponds within the East Bay Bird Sanctuary on southeastern Southampton Island, Nunavut.

Over the 2004-2007 period, present climate variations and their relation with limnological variables and sedimentation processes were studied using the construction of a 10-m climate station on Ward Hunt Island (integrated into the CEN SILA Network, in collaboration with ArcticNet partner Parks Canada), and a satellite 3-m climate station was installed next to Lake A on Ellesmere Island. Related work was undertaken on Southampton Island by installing temperature data loggers and sediment traps in several lakes along with measurements of limnological water quality variables.

Pilot-scale work was funded by this project on Arctic char populations in 2005-2006. This was a preliminary project of ArcticNet that led to more similar projects in Nunavik, Nunatsiavut, Nunavut and the Inuvialuit region on the life history characteristics, phenology, and biological characteristics of char populations in relation to climate variability (see project 2.7).

A broad range of limnological and microbiological measurements were conducted on lakes of the Ward Hunt, Northern Ellesmere region each year. These included stable isotope food web analyses (with comparative analyses at Resolute Bay and Kuujjuarapik), molecular analyses of microbial biodiversity as biological indicators of ecosystem properties and detailed water column profiling. Changes in ice along this coastline, including the dramatic loss of the Ayles Ice Shelf, were documented by RADARSAT and by in situ observations. Analyses were also made of the ablation stake network on both the Ward Hunt Ice Shelf and Ice Rise to determine the amount of melt that had occurred in the last year, and snow depth and ice thickness measurements were made at all of the sampling sites to add to the ArcticNet database of changing environmental conditions in this sensitive, far northern region of Canada's Arctic.

3) Indicators of water quality

Over the last 4 years, studies of the current contaminant levels in Arctic freshwaters focused on Lake Hazen, the deepest water body in Nunavut, by sampling melt waters entering the lake and surface waters of the lake itself (see project 2.7 for details); on northern Ellesmere Island by sampling of snow, lake water, sediment and biota for perfluorinated contaminants; and on Southampton Island, Nunavut, by sampling several lakes for contaminant analysis of water and sediments.

Field studies for the assessment of drinking water took place during the ArcticNet 2004 cruise of *CCGS Amundsen*. Fourteen villages in Nunavik were visited to sample drinking water reservoirs (household tanks and water jugs) and adjacent lakes and rivers where the water originated. Microscopy, HPLC, molecular techniques and chemical analysis were used

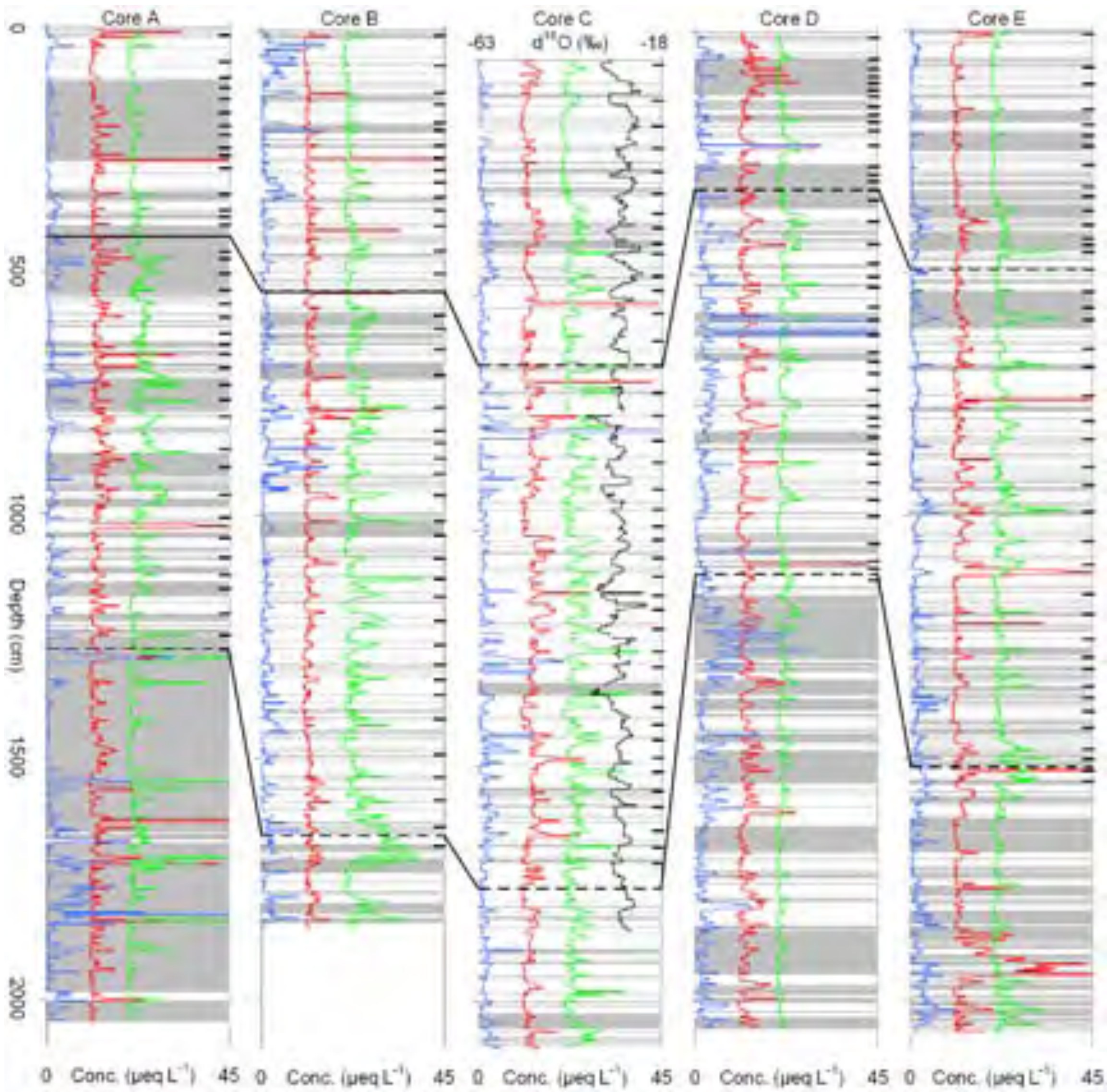

Figure 2. *Chemical stratigraphy of ice cores from the Devon Island ice cap. MSA (blue), Cl^- (red), SO_4^{2-} (green) and δ18O (black) records with depth are given for each of the five shallow firn cores. To facilitate interpretation, in each core, MSA concentrations have been multiplied by 100 and Cl^- and SO_4^{2-} concentrations have been translated from zero by 10 and 20 μeq L^{-1} respectively. Grey shading indicates the portions of the cores composed of ice, both clear and bubbly, as opposed to firn (white shading). The 1963 ^{137}Cs 'bomb' horizon and the 1989 annual layer are connected between cores (dashed lines). The annual layers are identified in each core (dashed marks). Sharp et al. (unpublished).*

to detect the presence of coliforms and other pathogenic bacteria, cyanobacteria and chemical indicators of water quality. At the beginning of October 2006, the second run of water microbiological testing (raw water, tap water and water stored in plastic containers) was completed in two Nunatsiavut communities, Nain and Rigolet. At the same time, extensive consultation processes were held in both communities, with stakeholders and local population, as in the Nunavik health

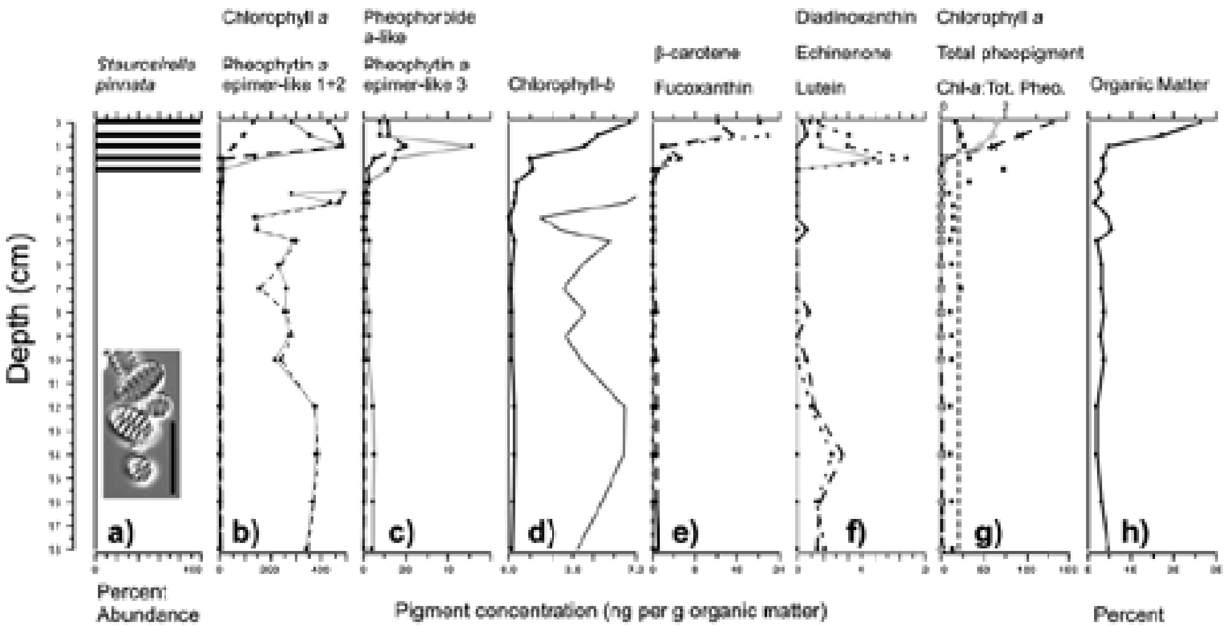

Figure 3. *Evidence of abrupt climate change in Canada's northernmost lake. The profiles extend over the last eight millennia in Ward Hunt Lake: (a) diatom stratigraphy; inset, photo of the excusive dominant* Staurosirella pinnata*; (b) Chl-a: solid grey line; Pheophytin a epimer-like 1: dashed line; Pheophytin a epimer-like 2: dotted line. The lines at right represent the same pigments with horizontal scale exaggerated 80x to show trends dwarfed by the magnitude of the scale of recent changes; (c) Pheophorbide a-like: solid line; Pheophytin a epimer-like 3: dashed line; (d) Chl-b, with 10x exaggerated horizontal scale at right; (e) β-carotene: dashed line; Fucoxanthin: dotted line; (f) diadinoxanthin: solid line; lutein: dashed line; echinenone: dotted line; (g) total chl-a (grey line, crosses) and total pheopigments (dashed black line, x-symbols) expressed as molar concentrations; black squares represent the molar ratio of chl-a:total pheopigment, and the vertical line the mean ratio (h) Percent organic matter determined by LOI (Antoniades et al. 2007).*

survey. Some initial measurements were also made on Char Lake, the drinking water supply for Resolute Bay, Nunavut.

As noted above, water quality in lakes was also studied in terms of contamination from migratory birds. Surface sediment samples from 19 Bylot Island lakes and from the eastern part of Southampton Island were analyzed for sediment characteristics, chemical composition, contaminants, and microfossils in order to investigate the impacts of growing snow geese populations on nutrient status and contamination.

5.2.6 Results

1) Paleoclimate indicators:

The dendrochonology studies in the La Grande River catchment allowed the development of high resolution models to construct detailed historical records of water supply (Bégin et al. 2007; Lemay et al. 2007). These records show evidence of 25% natural fluctuations in water supply over the last 300 years (Figure 1) and these data reveal information that must be taken into account when predicting the supply of hydro-electricity from northern reservoirs, even in the absence of anthropogenic climate change.

All of the proxies studied in a long sediment core from Southampton Island revealed a relatively stable environment during the last millennium, but also an environment that was perturbed by short-lived events that drove changes in the entire lake ecosystem. The chironomid-based paleo temperature record revealed high amplitude variations that were also associated with changes in the sediment density and chemical composition of the core. The core section that revealed higher inferred temperatures corresponded to the Medieval Warming Period (ca. AD 1160 to AD 1360), whereas the following period with lower temperatures was likely related to Little Ice Age cooling (ca. AD 1360 and AD 1700). This study provided new insights into the timing of known climatic events and allowed climate models for the Foxe Basin region and the eastern Canadian Arctic to be refined.

Analyses of Bylot Island sediment cores revealed recent changes in diatom species composition, as well as increases in diatom concentrations and organic matter content. The results suggested a slight increase in productivity in recent times, which led to a recent increase in the organic matter content found in the sediments and changes in community structure. On the other hand, analyses of elemental C and N and the stable isotope results did not show significant changes through time, and the C/N ratio also indicated that nutrient inputs from external sources remained constant through time. A more detailed analysis is now required to reconcile these results, and to fully evaluate whether changes in goose populations had a significant impact on the trophic state of these ecosystems.

The results from analyses of eight ice cores (Devon Island ice cap and Prince of Wales Icefield, Ellesmere Island) showed significant increases in summer air temperature and melt since the early 1980s and a clear reduction in snow accumulation since 1989 (Figure 2). The latter change is linked to an increase in sea ice concentration in the summer in the North Open Water Polynya and a reduction in atmospheric transport from northern Baffin Bay to the Devon Island ice cap, both of which reduce the moisture flux to the ice cap from local sources. Sulphate deposition on both ice masses increased from the mid-twentieth century until the late 1980s after which it decreased. Pollutant-derived sulphate has been the dominant source of sulphate deposition since ca. 1970. Nitrate deposition also increased from the mid-twentieth century and it continues to increase at Prince of Wales Icefield. It has decreased over the last decade on the Devon Island ice cap, but less rapidly than sulphate, with the result that nitrate has become a more significant component of acid deposition in the past decade. Deposition records of MSA and chloride correlate with variability in sea ice concentration in the Arctic as a whole in summer (MSA) and in the Beaufort Sea and southern Baffin Bay in fall (chloride), suggesting that these species could be used as proxies for past sea ice variability in the long core record.

Results from an analysis of diatoms and fossil pigments in a sediment core from Canada's northern-most perennially ice-covered lake revealed striking changes in diatom communities and sedimentary pigment concentrations over the last two centuries (Antoniades et al. 2007). Diatoms were found only in the upper 2.5 cm of the sedimentary record of Ward Hunt Lake at latitude 83 °N in Nunavut, and where present, diatom assemblages were composed almost entirely of a single species (Figure 3). Photosynthetic pigments varied slightly in the lower sections of the core, and began to increase gradually at the 4 cm horizon followed by an increase of two orders of magnitude in the uppermost stratum. The changes observed in the sedimentary record of Ward Hunt Lake had similar trajectories to those observed post-1850 elsewhere in the circumpolar High Arctic, and implying that aquatic communities even in the most extreme northern lakes have been impacted by recent climate warming. In a related study, a novel paleo-indicator of climate change based on bacteriochlorophyll-e concentrations in the lake sediments was developed. Results from the Lake A sedimentary record on northern Ellesmere Island indicated large shifts in bacterial productivity and the similarity of the overall trend to the melt record of the nearby Agassiz Ice Cap suggested that reconstructions using bacteriochlorophyll are recording a regional climate signal.

Figure 4. *The detached Ayles Ice Shelf, observed by the ArcticNet expedition to northern Ellesmere Island in May 2006. This image was subsequently reproduced by many newspapers and TV stations including BBC, CBC and Radio Canada, and in a news item in Science (19 Jan 2007, vol 315, p. 309) about the calving event. This ice island was about 40 m thick, with a total mass of 2 billion tonnes.*

2) Present indicators of change

Limnological research on Bylot Island and Southampton Island provided a comprehensive data set that can be used to assess future changes. This has included biodiversity analysis of aquatic microinvertebrates. On Bylot Island, micro-crustaceans were found in the sediment samples using a flotation technique. In addition, plankton samples were taken at each locality and analyzed for invertebrate species. The present ostracod species list includes *Cyclocypris ovum*, *C. ampla*, *Candona neglecta*, *C. harmsdorfii*, *Eucypris foveata*, and *Tonnacypris glacialis*. The zooplankton community of these lakes is often dominated by single groups or species (e.g., copepods, *Holopedium gibberum*, *Bosmina* sp. or *Daphnia middendorffiana*) of up to 95% (monospecific). The species list of invertebrates currently includes *Alonella nana*, *Bosmina* cf. *longirostris*, *Chyodorus brevilabris*, *C. sphaericus*, *Eurycercus glacialis*, *Daphnia middendorfiana*, *D. pulicaria*, *D. tenebrosa*, *Holopedium gibberum*, and *Polyphemus pediculus*.

From 2004 onwards, under the auspices of ArcticNet, climate-related observations have be undertaken at the northern coastline of Ellesmere Island, Nunavut. The operations were based each year out of Ward Hunt Island Observatory (WHIO), with the base camp located at latitude 83 °N at the northern limit of Quttinirpaaq ('Top of the World' in Inuktitut) National Park. One of the first steps was to establish, in partnership with Parks Canada, a 10 m tall automated climate station, the northernmost station in the Canadian Arctic. A smaller climate station was also installed on the edge of Lake A, a remarkable meromictic (freshwater over saltwater), ice-covered lake about 10 km to the southeast of Ward Hunt Island, in which past and present changes in temperature are measured. This has allowed the development a geophysical model of energy exchange in Lake A to assess the extent of recent change. The results showed that the lake experienced unusually warm conditions in the 1930s and 40s, and that its unique water column structure and ecosystem properties will likely be destroyed by ongoing climate change in the region (Vincent et al. 2008).

Climate records were also examined from studies elsewhere in this eastern Arctic sector. For example, in conjunction with water quality analyses in Labrador, historical data revealed a small increase (0.2°C) in temperature between 1953 and 2006 in Goose Bay. After a noticeable decrease between 1987 and 1993 (2.6°C for Goose Bay and 2.7°C for Nain), temperatures increased rapidly (3°C at Goose Bay and 3.5°C at Nain) between 1993 and 2006. Historical data for Goose Bay showed also that precipitation levels decreased during the same period: about 100 mm over 53 years (2 mm per year). A decrease in the level of precipitation between 1985 and 1993 (about 200 mm at Goose Bay) was noted along with an increase between 1993 and 1999, mainly due to rain.

In parallel with direct climate observations, the ice dynamics of this northern coastline was followed closely, including the ablation of the six ice shelves (Mueller et al. 2006). These likely formed several thousand years ago as part of a larger ice shelf, which in the early 1900s extended 400 km along the Ellesmere coastline. One of these features, the Ayles Ice Shelf, broke away from the coast of Ellesmere Island within a one-hour period on the afternoon of August 13, 2005. This dramatic event occurred after a summer of anomalously warm air temperatures and a period of off- and along-shore wind (recorded at WHIO) that pushed the Arctic Ocean sea ice away from the coast and allowed the detached ice island (weighing two billion tonnes) to move off to the west. Observations and commentary on this event by the ArcticNet team (Figure 4) were widely reported, including on the front page of more than 60 newspapers and of many websites, including CBC, BBC, and MSN. Water column profiling in the fiord showed that the epishelf lake (a thick layer of freshwater floating on sea water) had been completely lost as the surface layer drained away, no longer retained by the thick ice shelf and multiyear sea ice. Several other major changes accompanied this break-up in August 2005, including the loss of a vast expanse of thick, perennial sea ice in Yelverton Bay, calving of the Petersen Ice Shelf, and disintegration of the Nansen and Sverdrup Ice Plugs.

Many microbiological and limnological studies in the High Arctic, supported partially by ArcticNet, were published or submitted for publication including analyses of bacterial activity (Mueller et al. 2004) and biodiversity (Bottos et al. 2008) on the Arctic ice shelves, analyses of ice shelf ablation processes (Mueller et al. 2006b), analysis of the long-term evolution of chemical and physical properties of northern Ellesmere lakes and fiords (Van Hove et al. 2006), experimental studies of lower food web processes in northern lakes (Rautio and Vincent 2005; 2006) and experimental analysis of the factors controlling primary production in northern lakes (Bonilla et al. 2005).

3) Indicators of water quality

During the CCGS Amundsen cruise in fall 2004, raw water from the most frequently visited collection sites (brooks, lakes, rivers) was found to be of good quality in most of the villages. Of particular concern was the water from the individual storage containers, which was much more contaminated than the water at the collection sites. Upon completion of the analyses, results were communicated to community health centers. In February 2005, a workshop gathering drinking water managers and people involved in public health (scientists and physicians) was held in Kuujjuaq (Nunavik). In April 2005, a final report was presented to the mayors of the 14 communities in Nunavik (Figure 5).

Evaluations of tap water in Nain and Rigolet (Labrador) revealed that it was of good microbiological quality and safe to drink, at the time of the research visits (in both cases, water is chlorinated). On the other hand, some contamination was observed in water sampled from the plastic containers used to store raw water.

5.2.7 Discussion and Conclusions

1) Paleoclimate indicators:

The climatic changes observed in the Devon Island ice cap and Prince of Wales Icefield, Ellesmere Island conflict with the observed thickening of the interior regions of the Devon Island ice cap from 1995-2000 and suggest that this thickening is likely due to reduced ice outflow from the ice cap – perhaps due to cooling of ice at depth in response to Neoglacial or Little Ice Age atmospheric cooling. The isotope record from the long core clearly shows the centennial-scale temperature variability apparent in other ice core records from the High Arctic, but the amplitude of the variability is nearly double that it is in any other record. This suggested a role of the North Open Water Polynya in the amplification of climate changes in this part of the Arctic – perhaps involving changes in the sea ice concentration in the Polynya that are likely controlled by variability in sea ice advection and ice bridge formation in Nares Strait. This in turn may be linked to changes in the intensity of the quasi-stationary low pressure system over northern Baffin Bay.

Further research is required on Bylot Island to determine if there is a correlation between our biostratigraphic data and the known changes in bird population size over the past 30 years. More diatom counts are needed to achieve a higher temporal resolution in order to apply transfer functions and reconstruct the past animal population change on the island. The results have the potential to give a better understanding of the impact of increasingly intensive use of lake shorelines by wildlife. The carrying capacity of lacustrine habitats is such that they can withstand the effects of such a presence, but only up to a certain point, and that this critical threshold is not known for Arctic environments. In addition, the anticipated climate change will, according to the ACIA report (2004), cause more wildlife species to migrate towards northern regions to find suitable habitat. As a result, lakes, including the open-air water reservoirs of the Inuit communities of Nunavut and Nunavik, will be much more intensively used than is currently the case, since they provide critical habitat for several wildlife species.

Analyses of lake temperature profiles, and of pigments of photosynthetic sulphur bacteria, suggest novel indices of climate-related change, as well as potential impacts of future change. The Lake A energy balance model is highly sensitive to changes in the variables that affect photosynthetically available radiation (the forcing term): incoming radiation, attenuation by snow and ice, and Kd, the diffuse attenuation coefficient in the water. This is an important bio-physical feedback effect, where growth of pigmented microbes affects the local absorption of PAR, thereby causing an increased accumulation of heat in their surrounding waters. Boundary

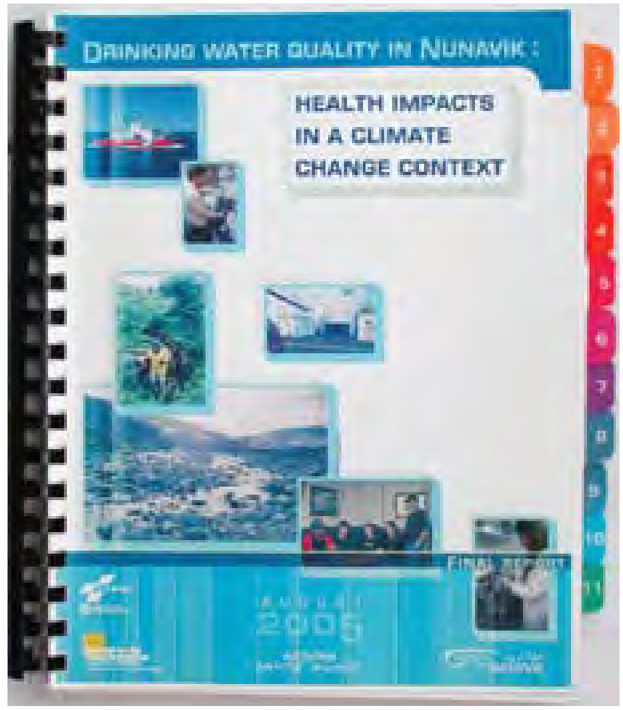

Figure 5. *The final report presented to the mayors of 14 communities visited during the Nunavik drinking water survey in 2004 (Martin et al. 2005).*

conditions such as heat loss through diffusion to the atmosphere, latent heat and wind-driven cooling of the snow have minimal but non-negligible effects on the overall dynamics. The loss of ice cover due to climate change would have a drastic effect, however. More than a decade of ice-free summers would mean that the unique temperature profile would be completely lost due to wind-driven mixing. Ironically, the increased greenhouse warming on a planetary scale may bring about the collapse of the greenhouse effect in Lake A and other ice-covered polar lakes, thereby altering these ecosystems through cooling and completely disrupting their unique bio-physical structure. It was hypothesized that the community of deep-living green sulphur bacteria in Lake A is limited by light availability. As the penetration of light into the lake's water column is directly related to ice and snow cover, which is itself controlled by climate, the dynamics of green sulphur bacteria are likely

controlled by changes in climate. Warmer climates would cause reductions in ice cover, which would in turn permit increased light penetration and higher bacterial productivity. Further work is subsequently underway to produce a rigorous chronology for the sedimentary record in order to strengthen the inferences of past climate change.

2) Present climate indicators:

The break-up of ice in the Ayles Fiord region followed another major event just 3 years earlier in which the Ward Hunt Ice Shelf fractured in half, draining the largest epishelf lake in the Northern Hemisphere (Mueller et al. 2003). This ecosystem contained a unique mixture of marine and freshwater zooplankton, and similar conditions were likely in the epishelf lake behind the Ayles Ice Shelf prior to its break-up. The ice shelves themselves are also living ecosystems that contain a rich biodiversity of microscopic species. These environments and their biota, like the other remarkable, ice-dependent aquatic habitats of northern Nunavut, are endangered ecosystems and highly vulnerable to the ongoing effects of a warming climate. (Veillette et al. 2008).

3) Indicators of water quality:

Regular monitoring of drinking water is necessary, and the public should be warned when the sites become contaminated. To develop or improve the climate change adaptation strategies in this area, it was proposed: 1) to establish an appropriate environmental monitoring system, 2) to improve wastewater disposal and municipal water systems, 3) to involve nursing staff in microbiological testing of the water at community sites,

4) to raise public awareness of the risks related to raw water consumption, and 5) to gather strategic health information during the periods of the year when cases of gastroenteric diseases are most frequent, in order to establish whether there is a link between these disorders and water quality.

In one or two communities where weather information does not exist (like Rigolet), it would be interesting to install small weather stations to study possible correlations between extreme events and drinking water quality. One of the major objectives of this project will be, in the near future, to recruit people in each community to monitor, on a regular basis, water quality (at raw water sites) and local weather conditions. Analysis of enterococci, total coliforms and *E. coli* should also be done in each community. In Nain and Rigolet, raw water from rivers, lakes and brooks could be at risk and should always be boiled (for 1 minute) before drinking. Raw water stored in plastic containers is often contaminated. Containers should be cleaned on a regular basis and water should always be boiled before drinking.

5.2.8 Acknowledgements

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5.3 Emerging New Infectious Diseases in Humans and Wildlife (Project 2.3)

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5.3.1 Abstract

Climate change has the potential of affecting infectious diseases through a variety of mechanisms. Possible climate-related impacts include changes in the range, abundance, seasonality and activity of insect vectors and animal reservoirs, the appearance and extent of infectious agents as well as modifications in the availability, production and use of food and water supplies. Hence, it is important to gather data in order to establish a baseline for infectious diseases that are related to the environment. As a result of their intimate contact with the environment and their nutritional habits, Inuit are considered to be at high risk for acquiring zoonotic infections (infections transmitted by animals to humans) and food borne and waterborne diseases. The first three years of research activities of this project (2004-2007) were concentrated on Nunavik, given the strong existing links between researchers, communities and public health authorities in that region. However, the study of the seroprevalence of zoonotic infections has been expanded in 2007-2008 to Nunavut. The project has essentially been aimed at i) describing the prevalence of exposure to various zoonotic infections (four parasites; *Trichinella*, *Toxoplasma gondii*, *Toxocara canis*, *Echinococcus granulosus* and four additional pathogenic bacteria; *Leptospira sp.*, *Brucella sp.*, *F. tularensis*, *Coxiella burnetii*) and of gastroenteritis among Inuit from Nunavik, ii) describing the perceptions and habits of Inuit with regard to drinking water, and iii) evaluating the health risks related to the consumption of bivalve molluscs in different communities. Results showed that a portion of the Nunavik Inuit population has been exposed to the pathogenic micro-organisms responsible for some of the zoonotic diseases investigated, particularly to *Toxoplasma gondii*. The overall prevalence of gastroenteritis in the Nunavik population has been estimated at 9.6%, with the extreme age groups being particularly affected. Frequent cleaning of the domestic water reservoir does seem to have a protective effect. Approximately one third of the population of Nunavik consumes untreated water, a practice even more frequent among individuals aged 50 and over. Mussels from five communities were investigated and were of good microbiological quality relative to human consumption. These data have enabled the gathering of important baseline information regarding diseases related to the exposure to fauna. In a context of climate change which could have an impact on future transmission of these diseases, it is important to continue supplying information on zoonoses and safe procedures for handling animals (population, hunters and trappers), and to support clinicians and medical staff in the management of zoonoses. It is also advisable to reinforce personal hygiene in preparing food or cutting up game meat, to boil untreated water before consumption, and to avoid the consumption of raw and insufficiently cooked meat. Moreover, further research is needed in order to identify the sources of *T. gondii* infection, and determine the microbiological risks associated with surface and drinking water.

5.3.2 Key messages

- A portion of the Nunavik Inuit population has been exposed to pathogenic microorganisms responsible for some of the zoonotic diseases investigated, particularly to *Toxoplasma gondii*. The sources of exposure to *Toxoplasma gondii* should be investigated.
- In a context of climate change, it is important to continue supplying information on zoonoses and safe procedures for handling animals (population, hunters and trappers), and to support clinicians and medical staff in the management of zoonoses.
- The prevalence of diarrheic episodes was greater among children less than 5 years of age and among individuals aged 50 and over.
- Approximately one third of the population of Nunavik consumes untreated water. Further research is needed in order to determine the microbiological risks associated with surface and drinking water.

5.3.3 Objectives

The general objective of the project for 2004-2007 was to collect and gather baseline data on zoonotic, waterborne and food borne human diseases in Northern Canada in order to document the actual health status of Arctic human populations with the potential of monitoring the effects of climate change.

The specific objectives of this project were:

- To describe the prevalence of different zoonotic infections in Nunavik;
- To describe the variables related to different zoonotic infections in Nunavik;
- To describe the prevalence and incidence of the infection by Toxoplasma gondii obtained during the surveillance program for pregnant women in Nunavik from 1990 to 2003;
- To describe the data on congenital toxoplasmosis in Nunavik from 1990 to 2003;
- To describe the prevalence of gastroenteritis in Nunavik;
- To describe the factors related to the prevalence of gastroenteritis in Nunavik;
- To describe the habits and perceptions of Nunavik Inuit regarding drinking water;
- To evaluate the health risks related to the consumption of bivalve molluscs in Nunavik.

Table 1.

	Trichinella sp.	*T. canis*	*E. granulosus*	*T. gondii*	*Brucella sp.*	*C. burnetii*	*Leptospira sp.*	*F. tularensis*
Positives	F	3.9	8.3	59.8	F	F	5.9	2.6E
Negatives	98.9	95.2	89.6	37.2	99.6	99.0	81.7	81.1
Equivocals	F	0.9E	2.1E	2.9E	F	F	12.4	16.3

E. Coefficient of variation between 16.6 and 33.3%, to be interpreted with caution.
F. Coefficient of variation higher than 33.3%, insufficient precision.

Table 1. *Seroprevalence of* Trichinella sp., Toxocara canis, Echinococcus granulosus, Toxoplasma gondii, Brucella sp., Coxiella burnetii, Leptospira sp. *and* Francisella tularensis *(%), population aged 18 to 74 years, Nunavik, 2004.*

5.3.4 Introduction

Emerging infectious diseases are those that have recently appeared for the first time, while re-emerging infectious diseases are those that have increased significantly in the last twenty years (Higgins 1999; Woolhouse and Gowtage-Sequeria 2005). Climate change in the Arctic could have many potential indirect impacts on the epidemiology of infectious diseases in both humans and wildlife, resulting in re-emergence of endemic infectious diseases, and emergence of infectious diseases for the first time in the Arctic. These impacts are related to the effects of climate on range, abundance and activity of vectors, reservoir hosts and infectious agents, changes in the local ecology of waterborne and food borne infectious agents, changes in food and drinking water availability, productivity, storage and use, and finally, rises in sea level, which could potentially increase the risk of certain infectious diseases.

Given the traditional diet, hunting and fishing activities and isolation of people in the Arctic, the occurrence of zoonotic, food borne and waterborne diseases could be significantly affected by any impact a changing climate may have. Indeed, the Inuit way of life and the special relationship they have with animals and the land during traditional activities of hunting, fishing and trapping result in the Inuit people being highly exposed to pathogenic agents present in the environment and among wild animals. In Northern Canada, common practices such as the consumption of untreated water and raw meat, fish, shellfish and both marine and land mammals, increase the risk of infection by a variety of micro-organisms associated with this environment.

There is little documentation regarding zoonotic diseases (or zoonoses: infections transmissible from animals to humans) among the Inuit. For a number of these diseases, little is known as to specific hosts and modes of transmission in the Arctic environment. Additionally, their clinical presentation is often unspecific and can render diagnosis extremely difficult. All of these factors thus make it difficult to determine the significance of these infections for Inuit people.

Moreover, the presence of permafrost and the absence of water systems have led to a striking difference between methods of distributing drinking water and managing sewage in the Arctic in comparison to those prevailing elsewhere in Southern Canada. For example, in most Nunavik Inuit communities, drinking water is obtained from unfiltered chlorinated surface water, although about 30% of the Inuit population in Nunavik still uses untreated water. Treated water is distributed daily by tanker truck and stored in reservoirs inside homes. Sewage is generally dumped not far from the village in ponds reserved for this purpose.

This brief portrait provides a glimpse of a variety of factors and mechanisms favouring exposure to zoonotic pathogens

Table 2.

T. canis	• Age: being 50 years and older • Living in the Hudson Bay region
E. granulosus	• Female gender • Schooling: high school not completed • Frequent cleaning of water reservoir (≥ once a month)
Leptospira sp.	• Being 50 years and older
F. tularensis	• Being 50 years and older • Living in the Ungava Bay region
T. gondii	• Age: being 30 years and older • Female gender • Schooling: high school not completed • Annual consumption of seal meat • Annual consumption of feathered game • Frequent cleaning of water reservoir (≥ once a month) • Exposure to "high risk" water[a]

[a]*Water exposure index*

- *Low risk : consumption of bottled water OR boiled / filtered water only*
- *High risk : consumption of natural water OR water from municipal system / water plant – no additional treatment*

Table 2. *Variables significantly associated ($p \leq 0.05$) with the seroprevalence of* Toxocara canis, Echinococcus granulosus, Leptospira sp., Francisella tularensis *and* Toxoplasma gondii *in multivariate analyses.*

and to food-borne and water-borne diseases, particularly gastroenteritis. Prior to this study, few data on the prevalence of these infections among this particular population group were available. Moreover, it is recognized that the number of cases declared to health authorities via the passive surveillance system for Mandatory Reportable Diseases is well below the actual number of cases occurring in the population. Due to their way of life and geographic location, the Inuit communities in Northern Canada are probably among the most highly exposed to infection risks related to the environment. In a context of climate change and in view of these risks, together with the fact that little information is available, there is a genuine need for both increased monitoring of infections and a better knowledge of risk factors so that appropriate means of prevention may be implemented.

5.3.5 Activities

At the outset, four sub-projects were planned with the collaboration of the Nunavik Public Health Department. The first sub-project focused on seroprevalence of zoonoses in Nunavik and was completed during the Qanuipitaa study (collection of data was conducted aboard the *CCGS Amundsen*) and results were presented to the authorities and communities of Nunavik (Messier et al. 2006a). The Qanuipitaa study also yielded data on the prevalence of gastroenteritis and regarding the habits and

Table 3.

CHARACTERISTICS	NUMBER OF PREGNANCIES	NUMBER OF IMMUNE WOMEN	PREVALENCE (%) ADJUSTED FOR AGE
Year of pregnancy			
1994	164	91	56
1995	172	96	54
1996	196	104	55
1997	192	99	54
1998	197	98	52
1999	201	104	58
2000	229	112	57
2001	214	93	47
2002	194	81	48
2003	101	51	58
Birthplace of the child			
Ungava	773	298	42
Hudson	1034	610	65
Unknown	53	21	

Table 3. *Age-adjusted prevalence of toxoplasmosis in Nunavik.*

perceptions of Inuit with respect to drinking water (Messier et al. 2006a). The second sub-project focused on seroprevalence of infections by *Toxoplasma gondii* in pregnant women (Lavoie et al. 2008). The third sub-project aimed to determine the prevalence and incidence of gatroenteritis in Nunavik. From the data of the Qanuipitaa study, the prevalence of gastroenteritis was determined on a random sample of Inuit from Nunavik. The fourth sub-project focused on health risks associated with shellfish consumption in Nunavik and as completed in 2007.

For the first three years (2004-2007), research activities were concentrated in Nunavik given the existing strong links between researchers, communities and public health authorities in that region. However, in 2007-2008, a sub-project based on the model of the seroprevalence study already conducted in Nunavik (see below) was conducted in Nunavut.

5.3.6 Results

Seroprevalence of zoonoses in Nunavik:

To determine human exposure to assorted microorganisms, it is possible to verify the presence of antibodies related to these microorganisms in the blood. Table 1 presents the seroprevalence of antibodies determined on a random sample of the Inuit population in Nunavik against the eight microorganisms responsible for the different human infections under study (n=917). The results showed a low seroprevalence for *Trichinella sp.* (trichinellosis), *C. burnetii* (Q fever) and *Brucella sp.* (brucellosis) (≤ 1.0%), and rates inferior to 10% for *E. granulosus* (echinococcosis) and *T. canis* (toxocariasis). However, high percentages of equivocal results were detected for *Leptospira sp.* (leptospirosis) and *F. tularensis* (tularemia), with an especially high seroprevalence for *T. gondii* (toxoplasmosis).

The low number of positive or equivocal results ($n \leq 5$) for *Trichinella sp.*, *Brucella sp.*, and *C. burnetii* did not allow to further pursue statistical analyses for these pathogens.

Table 2 shows the results of the multivariate analysis in determining the variables related to the exposure to the various microorganisms investigated. The infection transmitted by *T. gondii* is usually benign in humans but can lead to severe clinical manifestations in cases of congenital infection (Dunn et al. 1999). A toxoplasmosis outbreak among pregnant women during the 1980's (McDonald et al. 1990) led health officials to institute a screening and control program for T. gondii infection (Proulx 1999). To this day, this northern territory remains the only region in Canada in which a toxoplasmosis prevention program is currently in effect. This program contains a serological screening, even if the effectiveness of such screening still remains to be demonstrated (Peyron et al. 1998).

The crude prevalence of *T. gondii* infection for pregnant women in Nunavik was 50% between 1994 and 2003. The seroprevalence of *T. gondii* significantly increased with the age of the mother during early pregnancy ($\chi 2$ tendency; $p<0.0001$), i.e. 42% for mothers under the age of 20 and 70% in mothers 40 years old and older ($\chi 2$; $p<0.0001$). Age-adjusted rates were relatively stable over time ($\chi 2$ tendency; $p= 0.271$), although higher in Hudson than in Ungava ($\chi 2$; $p<0.0001$) (Table 3). A total of 16 cases of recent infections were observed among the 931 negative pregnancies for a cumulative incidence of 2% for the study period. The annual incidence was relatively stable throughout the follow-up ($\chi 2$ tendency; $p= 0.5972$). There was a statistically significant difference between the Hudson region (3.1%) and the Ungava region (0.7%) ($\chi 2$; $p=0.0073$).

All the medical charts of the mothers and their children identified as potentially infected from 1994 until 2003 were verified and the application of the prevention program was evaluated (Table 3). In general, potentially infected women and their children were identified and taken in charge by the local health care system; no consequence of congenital toxoplasmosis was identified during the study period (Lavoie et al. 2008).

Prevalence of gastroenteritis:

Table 4 presents the bivariable analysis of the significant associations between the prevalence of gastroenteritis episodes and explanatory variables related to socio-demography, nutrition, drinking water, promiscuity and the presence of children under five in the home. These variables are based on data from the Nunavik Inuit Health Survey conducted during the 2004 expedition aboard the CCGS Amundsen (Messier, V., Lévesque, B., Proulx, J.F., Ward, B.J., Libman, M.D., Couillard, C., Martin, D. and Hubert B. 2006. Zoonotic diseases, drinking water and gastroenteritis in Nunavik: a brief portrait. Inuit Health Survey, Institut national de santé publique du Québec, Québec, 37 p.). Among those affected, the proportion of individuals who presented a prolonged episode of diarrhea (three days or more) is also given for these variables. The results showed a significant difference amongst age categories, with children under five and persons aged 50 and over being more frequently affected by gastroenteritis during the month preceding the survey. There were also more episodes of prolonged diarrhea in the extreme age groups. Moreover, the prevalence was significantly lower in the Hudson region as well as among individuals who clean their domestic reservoir more frequently. In multivariate analysis, all these variables were also significant ($p< 0.05$) and the risk seemed more important for female ($p= 0.02$) and curiously for people living in houses with less than 2 persons by room ($p= 0.05$).

However, no relationship was observed when the prevalence of gastroenteritis episodes was examined relative to either i) the source of water used in winter and summer, ii) the treatment performed on water consumed in the home (boiling, filtering or other treatment), or iii) the customary manner

Table 4.

	PREVALENCE [a]	PROLONGED EPISODES (3 DAYS AND MORE) [a]
Total	9.6	38.9
Age group		
0-4 years	15.1	47.7
5-14 years	5.9E	22.2 E
15-49 years	8.6	34.6
50 years +	16.0	53.7
P-value	**< 0.001**	**0.008**
Region		
Hudson	7.1	42.1
Ungava	12.9	36.7
P-value	**0.001**	0.445
Frequency in cleaning the domestic reservoir		
Once a month	5.3	44.6 E
Once every 2 to 6 months	6.8	51.2
Once a year or less	14.8	31.2 E
P-value	**< 0.001**	0.052

[a] *P-values indicated in bold are significant below the 0.05 threshold.*
E *Interpret with circumspection.*

Table 4. *Variables significantly associated with episodes of gastroenteritis (%), members of Inuit households, Nunavik, 2004.*

of preparing meats and fish, eaten cooked (fried, boiled or roasted) or uncooked (raw, frozen or dried). The presence of children under five in the home (for individuals aged five and over) did not show a significant association with the prevalence of gastroenteritis. Similarly, as a whole, the principal occupation of participants aged 15 and over during the two weeks preceding the survey displayed no association with gastroenteritis episodes.

Drinking water:

Likewise, from the data of the Inuit Health Survey, nearly 60% of households primarily consumed water from the municipal system or from the tap of the treatment plant. However, about one third of households normally used water from natural sources (lake, river, stream, melted snow or ice), while a small percentage, about 6%, primarily consumed bottled water. With regard to cleaning the home water reservoir, which involved disinfecting the walls of the tank with bleach, 27% of respondents stated doing so every month, 31% every two to six months, 42% once a year or less.

Respondents aged 15 to 49 had a greater propensity to use the municipal water system or the tap of the treatment plant than those aged 50 and over, while a greater proportion of elders opted for water taken from natural sources ($p<0.001$ in summer and winter). Moreover, respondents with a secondary school education drank significantly less natural water and more bottled water than those who had not completed elementary or secondary school ($p<0.005$ in summer and winter). Also, more people consumed natural water in the Hudson sector than in the Ungava sector, with approximate proportions reaching 40% versus 25% respectively ($p<0.001$ in summer and winter).

Health risks related to bivalve molluscs:

Bivalve molluscs have regularly been implicated in the transmission of enteric diseases worldwide (Romalde et al. 2002). Moreover, Nunavik Inuit have been known to eat raw bivalve molluscs in the past. A report from Environment Canada describing mussel beds in Nunavik was used to identify communities for the study (Lamontagne, Y. 2003. Le programme de salubrité des eaux coquillières au Nunavik : campagne de terrain 2002 caractérisation et évaluation des risques. Environnement Canada, Montréal, 64 p.). Samples were collected in five communities, Salluit, Aupaluk, Tasiujaq, Kangirsuk and Quaqtaq. Two Kg samples were collected in Salluit, one in a site presumably under the influence of waste water, while one sample was collected in each of the other two communities. Mussels from Salluit were analyzed for the following indicators by enumeration methods (fecal streptococcus, E. coli, F-specific coliphages, *Clostridium perfringens*) and for pathogens (Norovirus, *Salmonella sp.*, *Campylobacter sp.*, *E. coli O157:H7*, *Shigella sp.* and *Yersinia enterocolitica*) by molecular identification. For the other communities, in addition to the aforementioned list, the presence of three parasites (*Giardia duodenalis*, *Cryptosporidium spp.*, *Toxoplasma gondii*) was also investigated by microscopy and molecular methods in two different laboratories.

Table 5 presents the pathogens and indicators analyzed in mussels from the contaminated and non-contaminated sites in Salluit. These analyses revealed a presence of coliphages (2625/100g in mussels of the contaminated site and 850/100g in those of the non-contaminated site) and Yersinia enterocolitica (positive/25g but only for non human pathogenic strains, in both sites). Other assessed agents remained below the detection limit.

For the other communities, apart from small quantities of *Clostridium perfringens* in two samples, no bacterial or viral pathogens were identified in the mussels. Toxoplasma gondii was also not detected. However, Giardia duodenalis and *Cryptosporidium* spp. were present in 18% and 73% of the samples investigated for these pathogens respectively. When considering the indicators and the viral and bacterial pathogens investigated, the mussels examined were of good microbiological quality, but considering the presence of potentially zoonotic protozoa, it should be recommended that consumers cook the molluscs well before eating them.

5.3.7 Discussion

Seroprevalence of zoonoses in Nunavik:

The results of this serosurvey revealed that there is no or very infrequent exposure to *Brucella sp.*, *C. burnetii* and *Trichinella sp.* (≤ 1%). The low seroprevalence of *T. canis* (3.9%), *Leptospira sp.* (5.9%), *F. tularensis* (2.6%) and *E. granulosus* (8.3%) is also encouraging. In the case of the latter pathogen, people with strongly reactive serologies were investigated and found to be asymptomatic. Nonetheless, for *Leptospira sp.* and *F. tularensis*, past exposure could possibly explain some of the high percentages of equivocal results.

On the other hand, the high seroprevalence of *Toxoplasma gondii* (~60%) appears to be of major concern. The results show an association with the consumption of seal meat and feathered game (see seroprevalence data among some of these species in Table 6). The potential association with the supply of drinkable water in Nunavik was unexpected. The distribution of unfiltered chlorinated surface water, associated with the resistance of parasites and protozoa to chlorination as performed in Nunavik, could allow the transmission of parasitic infection through this route. However, because of the extremely low population of domestic felids in this region, and expected low densities of wild felids such as lynx, the

Table 5.

PATHOGEN/INDICATOR	CONTAMINATED SITE	NON-CONTAMINATED SITE
Fecal streptococcus	< 10 cfu[1]/g	< 10 cfu/g
E coli	< 10 cfu/g	< 10 cfu/g
F-specific coliphages	2625 pfu[2]/100g	850 pfu/100g
Clostridium perfringens	< 100 cfu/g	< 100 cfu/g
Norovirus	negative[3]	negative[3]
Salmonella sp.	negative[3]	negative[3]
Campylobacter sp.	negative[3]	negative[3]
E coli O157:H7	negative[3]	negative[3]
Shigella sp.	negative[3]	negative[3]
Yersinia enterocolitica	positive/25g, only for non pathogenic strains	positive/25g, only for non pathogenic strains

[1] *Colony forming units* [2] *Plaque forming units* [3] *Detection limit =1/25g.*

Table 5. *Pathogens and indicators analyzed in mussels from the contaminated and non-contaminated sites in the village of Salluit, Nunavik.*

only definitive hosts identified to date, this hypothesis remains to be definitely confirmed.

The results from the study for pregnant women further confirm the presence and activity of *T. gondii* in Nunavik. Age-adjusted seroprevalence data as well as cumulative incidence of infections during pregnancy were stable throughout the period 1993-2004. As anticipated, there was an increase in seroprevalence as a function of age of the mother during early pregnancy. Nevertheless, potentially infected women and their children were generally identified and taken under care by the local health care system. No consequence of congenital toxoplasmosis was identified during the period of study.

Table 6.

Seal	14.0 %
Goose	4.2 %
Ptarmigan	2.5 %

Table 6. *Seroprevalence of* Toxoplasma gondii *among Nunavik species. Data from the Nunavik Research Centre.*

Prevalence of gastroenteritis:

The data revealed a crude prevalence of gastroenteritis cases of 9.6% over a 30-day period, with higher rates among extreme age groups. In a Québec study of the risk of gastroenteritis in families using water from a domestic well, the overall prevalence of diarrheic episodes over a period of 14 days, using a definition similar to ours, was found to be 3.4%. Age constitutes an important risk factor for gastrointestinal infections. As in other studies (Payment et al. 1991; Scallan et al. 2005), our results showed a greater prevalence of diarrheic episodes among children under 5 years of age. However, in our study, the strong prevalence among individuals aged 50 and over was strikingly different from rates measured in four industrialized countries – Canada, Australia, Ireland and the United States – where, to the contrary, the lowest rates were among persons aged 65 and over (Scallan et al. 2005). These data seem to indicate that way of life and certain environmental factors peculiar to the inhabitants of Nunavik could influence the epidemiology of gastrointestinal infections among Inuit over 50 years of age. With respect to drinking water supplies, the prevalence of diarrheic episodes is distinctly lower among households that clean their domestic water reservoir at least every two to six months, comparatively to those who do so less often. These data suggested that the chlorination used during cleaning of the reservoir, despite being of limited effectiveness against protozoa, appears nevertheless to be effective against bacteria and viruses generally responsible for acute episodes of gastroenteritis.

Drinking water:

About a third of the population of Nunavik consumes untreated water, a risky practice considering that this water originates from various sources of surface water that are subject to contamination by a variety of micro-organisms. Nonetheless, there are significant variations between practices in the Ungava region and those in the Hudson region. Ungava households consume less natural water and make greater use of filtration, whereas cleaning of the domestic reservoir is less frequent. These data suggested that practices and perceptions with regard to drinking water differ between the two sectors. The use of natural water, considered traditional as much as hunting and gathering, is more frequent among those aged 50 and over, who no doubt are more accustomed to this method than to recent infrastructures for the treatment of drinking water. Moreover, some Inuit find that natural water has a better taste and is cooler, clearer and less contaminated than water in a domestic reservoir. On the other hand, individuals in the more educated category (who have completed secondary school) are apparently more aware of the risks associated with untreated water, since they use less natural water and more bottled water.

Health risks related to bivalve molluscs:

There were few variations between the two sites tested (contaminated vs. non-contaminated) for the molluscs collected in the village of Salluit. While F-specific coliphages appeared to be present in larger quantities in molluscs from the potentially contaminated site compared to the non-contaminated site, this difference was not significant due to the precision of the method used. For the other communities, *Giardia duodenalis* and *Cryptosporidium spp.* were present in 18% and 73% of the samples investigated for these pathogens respectively.

Giardia sp. is a well known contaminant of molluscs (Grackzyk et al. 1999) and *Cryptosporidium spp.* has been regularly identified in molluscs in North America (Fayer et al. 2002; Fayer et al. 2003; Miller et al. 2005) and in Europe (Gomez-Bautista et al. 2000). *Salmonella sp.* (Wilson and Moore 1996; Martinez-Urtaza et al. 2003) and especially *Campylobacter sp.* (Wilson and Moore 1996; Endtz et al. 1997) have also been documented by many authors in various species of molluscs.

There are very few data regarding the microbiological quality of molluscs in Arctic communities, with further research needed to fully assess their microbiological content in these Nordic regions especially vulnerable to climate change. Nevertheless, in comparison with data collected in other areas, the mussels harvested at this moment from Nunavik were of good microbiological quality. However, considering that mussels are filtering organisms and especially susceptible to microbiological contamination, it is advisable to cook them prior to consumption.

5.3.8 Conclusion

The Inuit population is exposed to microorganisms from the fauna, particularly to *T. gondii*. Therefore, particularly in a context of climate change, which could have an impact on future transmission of these diseases, it is important to continue supplying information on zoonoses and safe procedures for handling animals (population, hunters and trappers), and to support clinicians and medical staff in the management of zoonoses. It is also advisable to reinforce personal hygiene in preparing food or cutting up game meat, to boil untreated water prior to consumption, and to avoid the consumption of raw and insufficiently cooked meat, especially for seronegative pregnant women and immunodepressed individuals. Moreover, further research is needed in order to identify the sources of *T. gondii* infection, and determine the microbiological risks associated with surface and drinking water, particularly in regard to the use and the cleaning of domestic water tanks.

These data have enabled to gather important baseline infor-mation with respect to diseases related to the exposure to fauna, namely gastroenteritis and eight different zoonoses. They have also allowed obtaining useful information on the microbiological quality of shellfish, an important cause of outbreaks of infectious diseases, as well as regarding the perceptions and the habits of Nunavik inhabitants in relation to drinking water. These results were obtained in collaboration and transmitted to the Nunavik Public Health Department. The Nunavik Research Centre was also a collaborator in some research activities and the Kativik regional advisory Committee was also aware of the results, particularly concerning drinking water.

Finally, this project generated new projects focusing (1) on the sources of exposure to *Toxoplasma gondii* in Nunavik, (2) on the seroprevalence of parasitic diseases in Nunavut and (3) on the importance of cleaning the in-home drinking water storage reservoirs in Nunavik in order to maintain water quality.

5.3.9 Acknowledgements

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5.4 Climate and Coastal Landscape Instability: Socio-economic and Ecological Impacts (Project 2.4)

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5.4.1 Abstract

The researchers of this project measured the changes that are taking place in the coastal regions of the Arctic where Inuit communities are located. They provided analyses of the terrain conditions and the geomorphological processes that are driven by climate forcings. Numerous field campaigns across the Canadian Arctic were done and 21 communities were both consulted and involved in the research process. Field methods included surveying, shallow drilling of permafrost, soil and sediment sampling, use of terrestrial, marine, and airborne geophysics (ground penetrating radar, electrical resistivity, chirp sonar, multibeam echosounding, and airborne lidar), core sampling from lake bottoms and the sea bed, and the use of dating techniques to asses rates of changes in order to extract information, and map coastal changes and permafrost conditions. Rates of coastal change were measured. Processes of permafrost degradation (thermokarst) through thermal and mechanical erosion were analyzed and were related to sedimentary changes. The rate of permafrost thaw in the discontinuous zone was also precisely measured at a site in Nunavik. Applicable assessments of the impact of climate change on coastal, permafrost dominated systems are now available locally and regionally in the form of map products and reports. Knowledge on how the changes are taking place (processes) is greatly improved and already being transferred to the science community and to concerned communities and authorities to help formulate adaptation strategies.

5.4.2 Key Messages

- Coastal retreat in ice-rich and deep permafrost of the Beaufort Sea leaves partial preservation of massive ice and ice bonding below formerly subaerial transgressed seabed. A mosaic of permafrost conditions develop in the transitional submergence phase under shore platforms, lagoons and spits.
- A reduction of permafrost area by over 35% occurred in the discontinuous permafrost zone east of Hudson Bay between 1957 and 2005, leading to the generation of hundreds of thermokarst lakes and shrubby hollows. The impacts on ecosystems are extensive.
- Most of the communities in Nunavik are not totally confined onto exiguous land areas with difficult permafrost conditions. Despite the fact that some tracts of land are unsuitable for construction due to adverse terrain conditions, space for expansion on low sensitivity permafrost does exist and, often, communities have already avoided problematic soils.
- A new remote sensing method has been established to map and monitor surface temperatures at a resolution of 1 km^2, including permafrost terrain, over the Arctic territory.
- The majority of research conducted by project 2.4 directly addressed concerns specific to coastal communities. Communities and regional governments were key stakeholders in this research program.

5.4.3 Objectives

The primary objective of this project was to quantify the potential impact of climate change on coastal permafrost systems. Regions around communities and areas of traditional land use were emphasized in order to evaluate the impact of landscape change on the activities of northern people, communities, and resource use. The project also more generally aimed at the prediction of environmental change in the coastal zone induced by climate warming in order to provide the northern residents, governments, and industry the knowledge necessary to develop adaptation strategies. Environmental change at the core of this project was related to a critical abiotic component of the ecosystem: ground that is made highly sensitive because of the presence of ice-bearing permafrost.

Other specific objectives of the project were to:

- Measure the changes that occur along the coastline through erosion, be it directly in ice-rich coastal permafrost or in the catchment of rivers in the coastal regions.
- Assess the rates and processes of changes through analyzing and dating the past and recent sedimentary record in coastal water basins such as inlets, bays and fjords as well as in some lakes in the coastal regions. This included assessing the fate of mobilized organic carbon, nutrients and sediments from eroding or thawing permafrost in the coastal marine system.
- Map geotechnical permafrost conditions and coastal (terrestrial, shoreline, and subtidal) processes and sediments on the territory of Inuit communities to support the planning of community expansion and adapt the practice of traditional activities in the search and harvest of natural resources.
- Document the processes of permafrost degradation through heat transfer from a warming atmosphere and oceans, and the processes of degradation thereby generated (thermokarst) that are manifested in features such as thaw ponds, active layer slides, retrogressive thaw slides, thermo-erosion, and so on.
- Monitor the change in climate and its impact through the use of a widespread network of instrumentation consisting of meteorological stations and thermistor cables (e.g., the CEN SILA Network), GPS sites, tide gauges, etc.
- Use the acquired data and information as a base for forecasting future changes and planning adaptation strategies.

5.4.4 Introduction

Climate change has become the overwhelming environmental issue facing the North today because it is fundamental to all other issues, ranging from the dynamics of species and ecosystems and to the impact of industrial projects such as oil, gas, and mining development. In the Arctic, landscapes, ecosystems and human activities are particularly vulnerable to its effects (ACIA, 2005). Four years down the road since the start of the project and of ArcticNet as a whole, international reports and new observations have made it clear that impacts of warming in the form of reduction of marine ice cover, shorter snow cover duration and widespread degradation of permafrost are already occurring at a rate faster than initially expected. The international community of climate modellers now agrees that the worst case scenarios of climate warming are likely to occur over the coming decades. Coastal regions are further affected by the worldwide sea level rise, a factor that enhances erosion, reduces sea ice duration, and increases storminess. The central Canadian Arctic, however, escapes this facet of impacts because of postglacial isostatic uplift; but land emergence due to uplift is also an inexorable factor of change acting in our country. As the climate warms up, northerners are confronted by a series of fundamental problems including the paucity of recovered and structured information about how Arctic terrestrial and coastal systems are responding to these climatological and geophysical forcings. More than ever, there is a pressing need to understand the reported impacts of landscape (ecosystem) change on communities and on man-made infrastructures. These impacts must also be integrated into a comprehensive scheme in order for the communities and their leaders to take on adaptation strategies suited to their socio-economic and cultural aspirations.

Along these lines of thinking, the members of this project have made a series of measurements and observations in regions of the Arctic where the impacts are felt. An array of methodologies including mapping permafrost conditions, coring, sampling, ground temperature measurements, and lake sediment sampling were undertaken in addition to the analysis of permafrost conditions and processes of thermokarst formation (permafrost degradation that disturbs the terrain and the ecosystems). Researchers have measured the rate of coastal retreat in ice-rich permafrost and measured the amount

Inset 1. Reports on Urgent Community Issues.
In addition to published work, an important output of ArcticNet has been the production of reports in response to specific environmental management concerns. These have provided practical information of immediate use to the local community, as well as models for similar applications elsewhere in the circumpolar North, for example:

- Allard, M., Fortier, R., et Gagnon, O. (2004) Problématique du développement du village de Salluit, Nunavik. Rapport final. Salluit, Nunavik, une communauté en croissance sur un terrain sensible au réchauffement climatique. Ministère de la sécurité publique du Québec., 100 p.
- Allard, M., Calmels, F. Fortier, D., Laurent, C. L'Hérault, E. et Vinet, F. (2007a) Cartographie des conditions de pergélisol dans les communautés du Nunavik en vue de l'adaptation au réchauffement climatique. Université Laval, Centre d'études nordiques, Rapport remis à Ouranos et à ressources Naturelles Canada, 51 p.
- Allard, M., Fortier, R., Sarrazin, D., Calmels, F., Fortier, D., Chaumont, D. Savard, J.P., et A. Tarussov. (2007b). L'impact du réchauffement climatique sur les aéroports du Nunavik : caractéristiques du pergélisol et caractérisation des processus de dégradation des pistes. Université Laval, Centre d'études nordiques, Rapport remis à Transports Québec, Ouranos et Ressources Naturelles Canada. 192 p.

of carbon released; they have also mapped parts of shallow sea-floor zones near several communities. New regional studies of surficial geology and relative sea level history in key areas of the Canadian Arctic have been produced. Scientific papers contributing to the understanding of poorly known processes, such as heat transfer to permafrost from both running water and ground water, have been published. The project also studied how surface erosion processes linked to a warming ground and melting glaciers have affected the rate at which sediments and soil chemicals are fed into lakes. The areas studied by the project members cover a wide range of Arctic environmental settings from the erosional ice-rich sedimentary coast of Beaufort Sea, across the central Arctic to the rocky and uplifting shores of Nunavik, thus providing a strong base of knowledge for the general objectives of ArcticNet. At least 21 Inuit communities were involved during the project. For many of them, helpful practical reports for their management of and expansion over permafrost terrain were released.

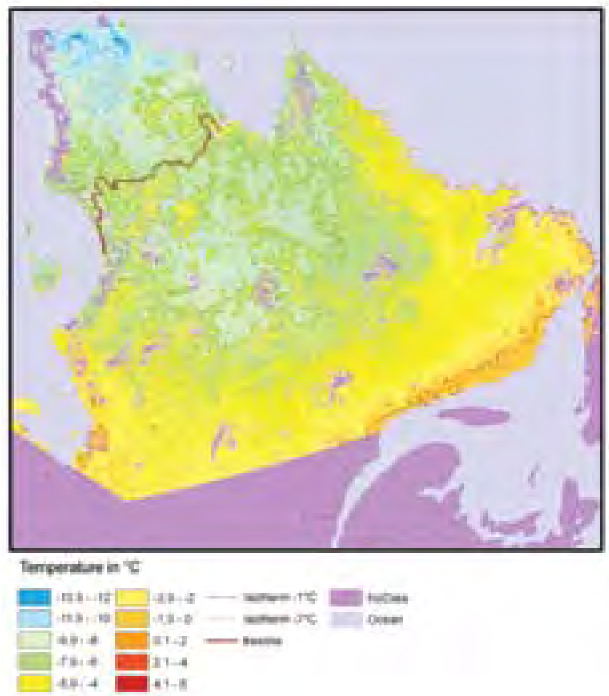

Figure 1. *Mean annual surface temperatures over Nunavik, 2002-2007, mapped from Modis data.*

5.4.5 Activities

In order to quantify the impact of climate change on permafrost coasts and to evaluate the impact of these effects, project members took one of five approaches outlined in the sections below, and their activities during the 2004-2008 period included the following:

Permafrost characterization and mapping:

- In the High Arctic, carried out aerial reconnaissance of the coast in the Eureka Sound area of Ellesmere Island in 2004 to identify regions with massive ice or active thermokarst. Conducted shallow drilling on Axel Heiberg and Ellesmere Island in 2005 and 2006 in support of ice content analyses. In 2006 and 2007, collected aerial imagery and ground truth data at Expedition Fiord and around Eureka Sound to help in quantifying and categorizing ice wedge polygon geometry. Geophysical surveys (ground penetrating radar (GPR) and capacitive coupled resistance) were used to map ground ice. An analysis of ice wedge polygon patterns and their relationship to surficial geology and ice contents was carried out.
- Carried out both types of geophysical surveys (GPR and resistivity) in the western Arctic to map ice distribution. Collected permafrost cores along the Yukon coast from seven sites in 2004 and 18 more in 2005, for analysis of ground ice and organic carbon content. Sampled natural exposures of ground ice at several Yukon sites including Herschel Island, King Point, and Komakuk Beach for cryostratigraphic analysis. Samples collected in 2006 were analyzed by collaborators at the Alfred Wegner Institute in Germany for pollen, crystallography, and stable oxygen and hydrogen isotopes in order to reconstruct environmental conditions at the time of formation. Collected organic material from these exposures for dating.

- Using data acquired in 2004 through GPS surveys and seismic and multi-beam surveys of the nearshore, examined the geomorphology of the rivers flowing into Lac Guillaume-Delisle through analysis of stratigraphic sections in terraces. Documented Holocene landscape and permafrost evolution in the Umiujaq-Lac Guillaume-Delisle region along Hudson Bay, using both offshore and onshore surveys carried out in 2004.
- Carried out surveys in support of 3-D geological and thermal modelling of the Salluit valley along the coast of Hudson Straight. In the Ungava Bay area, similar surveys and mapping were conducted in 2004 around the communities of Tasiujaq, Aupaluk, Kangirsuk, and Quaqtaq.

Observations and measurements of coastal changes:

- Carried out annual surveys of shoreline features, including block failures and thermo-erosional niches. Mapped annual shoreline changes along the Yukon coast and at selected sites on Axel Heiberg and Ellesmere Island using high resolution GPS.
- Carried out work on vertical motion and sea-level rise using continuous GPS and tide-gauges at a number of sites throughout the Arctic. Response to sea-level change and varying sea-ice conditions included studies on modern and relict (raised) gravel beaches, in part through detailed topographic (RTK-GPS) and sedimentological analyses of raised beaches. These investigations were assisted by seamless mapping across the shoreline, combining high-resolution satellite and airborne mapping tools on land with multibeam bathymetric surveys of the seabed in the Resolute Bay and Oliver Sound areas using the *CCGS Amundsen* and the Heron launch. Extensive ground validation surveys were completed in the Resolute area to supplement the onshore component.
- In 2005, mapped and C-14 dated landforms and Quaternary deposits at Coral Harbour, Resolute Bay, and in two regions in Nunavik (Biscarat River and Tasiujaq) to assess how uplift, tidal range, and past climates shape morphological development of the coastline. Raised beaches and deltas were investigated and datable material was collected from Coral Harbour in order to construct an emergence curve for the region to show sea level trends.

Figure 2. *Seamless mapping of onshore and seabed geomorphology at Resolute Bay, NU, combining QuickBird satellite imagery and multibeam bathymetric surveys acquired by CCGS Amundsen and the Heron launch in 2006.*

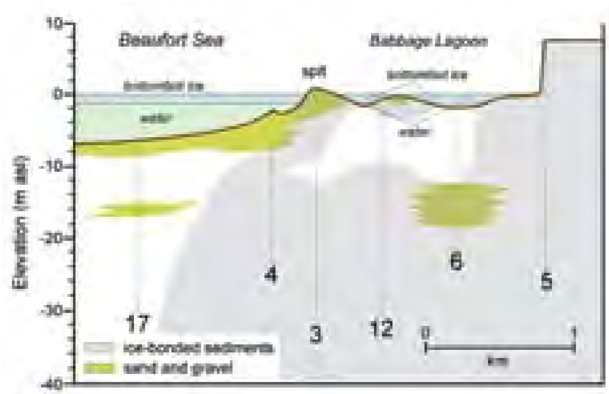

Figure 3. *Distribution of permafrost (ice-bonded sediments) under a receding coastline. Banks Island (Numbers refer to drill holes).*

- Conducted field work near Umiujaq in 2006 in support of a project to map Quaternary geology, and to reconstruct deglaciation and sea-level history. Work was also done for a study of soil wedge polygons in recently emerged coastal sediments which included mapping, GPR profiling, drilling, and C-14 dating of organics to define the rate at which permafrost evolves on newly emerged terrain and how wedge activity varies in relation to climatic changes.

Figure 4. *Permafrost degradation landforms in the forest tundra of Nunavik. Permafrost areas have decreased by more than 35 % in the past 50 years and new ponds and shrubland have formed. The arrow shows the BGR monitoring site.*

- In 2006, conducted bathymetric surveys at selected sites along the Beaufort Sea for inputs to a wave energy model. Sampled nearshore sediments to determine the source of organic carbon in order to better understand how sediments are being transported along the coast.
- Installed a water level recorder in Pauline Cove at Herschel Island in 2007 and collected data for constructing a digital elevation model. These data were used to help in assessing threats to historic infrastructure on the spit where the main settlement is located.

Research on basic processes of thermokarst formation:

- Performed detailed mapping of thermokarst features at selected sites on Axel Heiberg and Ellesmere Island and in the Yukon using high resolution GPS to track their development over time.
- Completed mapping of coastal morphologic features on all of Banks Island and a GIS was developed to help characterize the sensitivity of coastal areas.
- Visited all Nunavik communities to map permafrost degradation due to ground instability related to climate warming and to evaluate how this is affecting infrastructures. Large scale soil maps of Nunavik communities were produced in support of adaptation strategies for urban planning.
- Instrumented and closely tracked internal temperatures of a lithalsa near Umiujaq to gain insight into its thermal regime and how it is affected by external forcings.
- Instrumented an ice wedge network on Bylot Island in support of a study on thermal erosion of the wedges.

Monitored active-layer development at all sites.

- Assessing watershed mass and nutrient transfer processes and rates of changes through marine and lacustrine sedimentary records:
- Collected and analyzed 20 cores collected from Hudson Bay and Hudson Straight in 2005. Additional gravity and

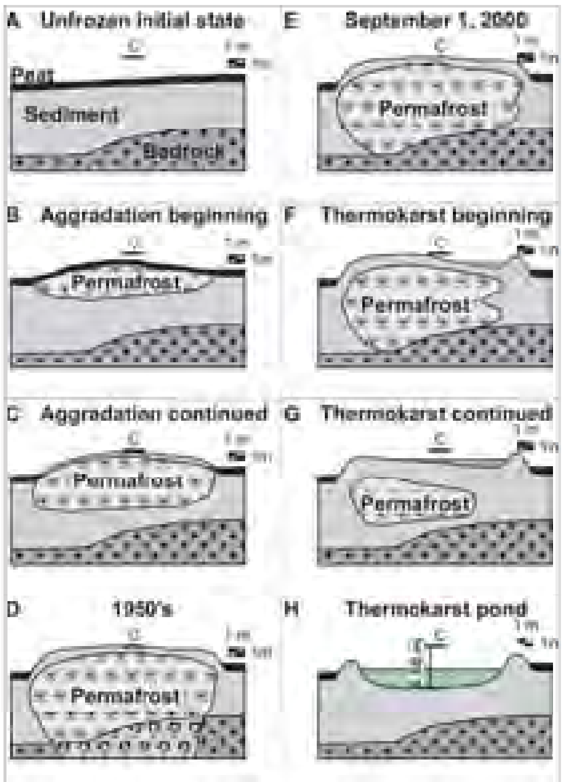

Figure 5. *Model of permafrost growth and decay in the BGR site (from Fabrice et al. 2008).*

box cores of recent sediments were collected during the CCGS Radisson cruise from Cape Dorset to Kuujjuarapik. Conducted multibeam sonar and subbottom profiler surveys of Hudson Bay and Hudson Strait. Integrated the data into a GIS and produced a DEM. The geophysical data was combined with the sediment database to reconstruct Holocene environmental changes and sedimentation rates.

- In 2004, obtained 6 cores of bottom sediments through the sea-ice cover at Lac Guillaume-Delisle for sedimentary, diatom and pollen analysis to reconstruct past changes related to climate and gradual isolation from marine conditions due to post-glacial uplift.
- Took sediment cores at two sites near Ward Hunt Island to determine annual sediment delivery and linkages to climate history.
- Collected cores in support of glacial runoff studies on Devon Island in 2005.
- Carried out geomorphological surveys on Devon Island in 2004 to characterize several lacustrine basins.
- Conducted detailed investigation of two watersheds at Cape Bounty, on Melville Island. This included quantifying the fluxes of water, suspended sediment, dissolved organic carbon, and nitrogen from the main tributaries over from 2005-2007, and in four subcatchments in 2006 and 2007. Active layer detachment sliding and precipitation events were documented in support of studies on the impact on the watershed fluxes.

Improving the monitoring infrastructure:

- Project members have set up an extensive network of automated meteorological stations throughout Nunavik, on Melville Island and Devon Islands, along the Yukon coast and on Axel Heiberg and Ellesmere Islands. This commitment included establishment of new equipment as well as regular site visits to both new and existing stations to download data and perform equipment maintenance. Where possible, community members have been involved in manual data reading and keeping watch on fixed instrumentation.
- Installed and maintained additional instrumentation for monitoring of environmental parameters, including ground temperature cables, soil moisture sensors, tide gauges and water level recorders, sediment transmissivity sensors, soil suction lysimeters, and snow fencing.

Human impacts and adaptation to changing environmental conditions in coastal settings:

- Since project inception, project members have held consultations with community leaders to discuss the impacts of climate changes on infrastructure and on access to land resources. Data from meteorological stations maintained by various researchers have been regularly provided to nearby communities or other stakeholders.
- Examined Inuit perceptions of the land-water interface through a series of interviews in 2004 and 2005 with

more than 35 community members in the village of Kangiqsualujjuaq. A primary goal was to assess how traditional knowledge of the land-water interface is transmitted between generations.

- In 2005, initiated an investigation into how climate-related hazards in the coastal zone impact community members in the eastern Arctic, particularly those involved in the resource harvesting sector.
- Extracted meteorological data on extreme climatic events (e.g., floods linked to rapid spring thaw, damaging winds) that affect both modern and traditional activities such as travel on snow and ice or by boat. These data, in combination with the Canadian Regional Climate Model, were used to forecast the frequency of future events.
- Instrumented two field monitoring sites in support of a project to assess the increasing risk of active layer detachment slides triggered by warming.
- Following consultation with communities of Clyde River and Hall Beach, established multidisciplinary research programs in 2007 to specifically address the issue of coastal hazards.

5.4.6 Results

The key findings and outputs of this project are as follows:

- Most of the communities in Nunavik are not totally confined onto exiguous land areas with difficult permafrost conditions. Salluit is an exception, being located on ice-rich clay soils in the bottom of a narrow valley. Despite the fact that some tracts of land are unsuitable for construction due to adverse terrain conditions, space for expansion on low sensitivity permafrost do exist and, often, communities have already avoided problematic soils. However the maps produced were a useful planning tool as most communities are expanding fast due to demographic growth. Potential problematic areas or sites that require further geotechnical characterization were identified for further municipal planning.
- The thermal importance of snow cover redistribution around man-made infrastructure is best demonstrated by the case of the Tasiujaq airport, one of the most affected by permafrost degradation. Snow accumulation along the embankment of the runway locally generates mean annual soil surface temperatures above the freezing point (up to 3°C) and provokes the thawing of the permafrost. Being important in the natural environment as well, changes in snow cover thickness related to topographic changes and shrub growth are keys to thermokarst in the discontinuous zone. Snow cover as the main driving factor of ecosystem changes needs to be appraised in greater details.
- A newly produced surface temperature map of Nunavik shows that some wide areas with mean air temperatures above 10 °C for the warmest month (thermal boundary for the tree-line) existed well north of the tree-line in the period 2005 to 2007 (Figure 1). Implications for permafrost distribution in the landscape and for ongoing and future ecological changes will be important to assess..
- In the Western and the Eastern Arctic (and maybe on the Labrador Coast and eastern Ungava Bay), eustatic sea level rise due to global warming is either partially or completely compensating for the isostatic crustal uplift, therefore increasing coastal sensitivity to storm surges and erosion.
- Coastal retreat in the carbon-rich sedimentary permafrost of the Yukon coast contributes to the release of carbon into the coastal marine ecosystem. Preliminary rates of delivery have been assessed at 2.13×10^6 tonnes/year.
- Coastal retreat in ice-rich and deep permafrost of the Beaufort Sea left partial preservation of massive ice and ice bonding below formerly subaerial transgressed seabed. A mosaic of permafrost conditions developed in the transitional submergence phase under shore platforms, lagoons and spits (Figures 2 and 3).
- The morphology of a series of raised beaches reflected alternating past periods of shore ice activity and ice-free wave-dominated conditions, therefore providing clues to past coastal changes driven by climate variations.
- An original bathymetric map, marine geophysical surveys and cores extracted from the bottom of Lac Guillaume-Delisle (formerly named Richmond Gulf) were key contribution to regional knowledge. Results showed that this structural estuary has depressions deeper than Hudson Bay.

A new emergence curve has been produced which indicated an actual rate of emergence on 1.2 cm/year. The information is already used for marine infrastructure planning on the eastern coast of Hudson Bay by Makivik. The map of Richmond Gulf was a key contribution to the governmental proposal for the creation of Nunavik provincial park Lac-Guillaume-Delisle-Lac-à-l'Eau Claire.

- C/N ratios and $\delta^{13}C$ measurements of organic carbon from cores from Lac Guillaume-Delisle, Hudson Bay and Late glacial lacustrine sediments allowed the differentiation between the similar looking fine-grained sediments detected by chirp sonar and obtained from shallow cores. This will guarantee proper discrimination of these sediment types in future marine studies of Hudson Bay.
- An analysis was performed to examine the microclimatic amplification of thaw processes within retrogressive thaw slumps in the High Arctic. Results suggested that under peak radiation, there is an increase of in-slump temperatures on the order of 2-4°C and an increase in radiation on the order of 10% at the ice face. Over a four-week period, five to six metres of retreat were measured, with a maximum retreat rate of up to one m/day.
- A reduction of permafrost area by about 35% occurred in the discontinuous permafrost zone east of Hudson Bay between 1957 and 2005, leading to the formation of hundreds of thermokarst lakes and shrubby hollows.
- Drilling, 3D thermal monitoring and resurveying of the lithalsa at the BGR site in Nunavik revealed that these landforms have an ice-rich core (≈ 65%) surrounded by an ice poor peripheral belt (≤ 10%). When the permafrost thaws this leaves a rimmed rampart around a thermokarst lake as the ground settles differentially. This hitherto unknown fact explains the size and morphology of the thousands of new ponds that are made in the forest tundra by permafrost thawing and that represent new aquatic ecosystems and greenhouse gas emitters, particularly methane (Figures 4 and 5).
- In the High Arctic (Bylot Island), faster snow melt recently generated increased overland flow which leads to the thermo-erosion of ice-wedges and major landscapes and ecosystem destruction. Such increased permafrost erosion will lead to increasing rates of sedimentation, organic matter and soil nutrients in catchment lakes.
- The knowledge of deglaciation history, post-glacial marine transgression and Holocene sea level fall was significantly increased east of Hudson Bay and west of Ungava Bay, thus providing basic context knowledge for the study of permafrost, land processes and ecosystem change as well as the necessary geotechnical information for development.
- Previously unknown landforms related to the opening of Hudson Bay 8.2 ka years ago and the sudden drainage of glacial lake Agassiz-Ojibway were mapped on the sea-floor of Hudson Bay. Sedimentary evidence of the rapid drainages of these glacial lakes was found in cores from Hudson Strait.
- As determined from analyses of lake cores, sediment yield in Arctic lakes reflects past and recent changes in erosion of permafrost terrain, particularly during the recent decades.
- Short-lived regional weather events leave a detectable imprint on the sedimentary structures in lakes. Monitoring of lake sedimentation and core studies are suitable integrating tools of monitoring climate-induced terrain changes in catchment. This also includes the study of variations in melt water flow from glaciers.
- ArcticNet researchers can rely for further appraisal of changing terrestrial and coastal conditions on a well-equipped and widespread network of automated meteorological stations, thermistor cables in permafrost, tide gauges, GBS base stations and other monitoring devices in lakes, plus a network of referenced observation sites to monitor climate changes and their impacts.

5.4.7 Discussion

Permafrost characterization and mapping:

A significant component of this project was the characterization of current permafrost conditions along both emergent and submergent coastlines. One key subproject consisted of collecting and mapping terrain, permafrost data and coastal features into a GIS to help characterize the sensitivity of coastal areas. Such mapping was completed for all of Banks Island and the Yukon coast of the Beaufort Sea. Mapping and analysis of erosional sections in permafrost was also completed in the Eureka Sound region. A data-mining exercise was also undertaken to recover 35 year old borehole data documenting the distribution of ice-bonded permafrost beneath a transgressive barrier-lagoon system on the Yukon coast.

In Nunavik in 2004, the project completed a 3D geological and permafrost model of the valley of Salluit, a community that faces particularly difficult challenges, seeing as it is built on highly sensitive permafrost. This project followed in the wake of a previous project undertaken for the community and funded by the provincial government and Natural Resources Canada (Inset 1: Allard et al. 2004). The running of a 3D heat transfer model (using the above geological model) was pursued to help forecast the impact of climate warming in the community. Elsewhere in Nunavik, geomorphological maps representing permafrost conditions were produced for twelve communities of Nunavik; these maps are now available to the regional government (KRG) and the municipalities to produce maps of suitability for construction on permafrost based on typical foundation designs (Inset 1: Allard et al. 2007b). Similarly, the soil conditions were characterized and the thermal regime of the permafrost was measured under all the airports of Nunavik (13) (with the exception of Kuujjuarapik where there is no permafrost) many of them being currently impacted by differential settlement due to permafrost degradation. One particular aspect of the problem of infrastructure maintenance that came out of the analysis was the damaging impact on the thermal regime of urban and transportation infrastructures produced by the combination of increased snowfall, wind drifting and snow management practices (Inset 1: Allard et al. 2007b). This is generally an underestimated factor in engineering designs.

Two studies characterizing tundra polygons were undertaken, one in the High Arctic and one in Nunavik. At Expedition Fiord and around Eureka Sound, aerial imagery and ground truth data were collected to help in quantifying and categorizing polygon geometry. The data were used in an analysis of ice wedge polygon patterns and their relationship to surficial geology and ice contents. An innovative, spatial point pattern statistical technique was used in the analysis and has revealed to be an effective method of quantifying ice contents and ice characteristics in polygonal terrains. On the east coast of Hudson Bay, halfway between Umiujaq and Inukjuak, a network of soil wedge polygons (likely overprinting a network of fossil ice wedges formed under colder climate conditions in the past) was surveyed and fossilized soil organic horizons under polygon sides were collected for pedological analyses and radiocarbon dating.

A scientific breakthrough was made in the understanding of how ice segregation accumulates in fine-grained soils ground when permafrost forms at the landscape scale. So far studies on this basic physical process were mostly on small, reconstituted samples in civil engineering laboratories and the process was simulated mathematically. Using an innovative drilling technique, high quality permafrost cores were recovered in Nunavik, brought back frozen to the laboratory and imaged by X-ray scanning (Calmels and Allard 2004). Run across an array of landforms such as peat plateaus, palsas and lithalsas, the image-based cryostructural analyses allowed an interpretation of the behaviour of ice forming ground water and a better understanding of how soil heaves and deforms. A direct and useful fallout of the approach is the exact measurement of ice volume in permafrost, which dictates the scale of the disturbances provoked by permafrost thawing, therefore improving the predictive capability of the impacts of climate warming on permafrost terrain.

A new methodological approach to mapping permafrost temperature was developed over the project duration. Daily near surface radiation temperatures (skin temperature) from the MODIS imagery were used to reconstruct annual temperature changes; thereafter mean annual surface temperature, freezing index and thawing index were derived and mapped with a spatial resolution of 1 km^2. The method was validated with field station data in Nunavik and Alaska, and helped in redrawing northern hemisphere permafrost maps and monitoring annual surface temperature in the following years (Figure 1). Predictions of surface temperature changes in permafrost regions of northeastern Canada from outputs of the Canadian Regional Climate Model were also published; increases of 4-5 °C are expected for the 2040-2070 period (Sushama et al. 2006).

Observations and measurements of coastal changes:

One key factor governing coastal recession and regression is relative sea level change. Long-term sea level fall or rise is usually determined through the construction of submergence or emergence curves. Rates are calculated by dating either submerged terrestrial material (e.g. soil turf in marine cores, submerged peat layers, etc.) for submergence curves and emerged marine material (e.g. sea shells in raised beaches) for emergence curves. The present day trends in relative sea level changes, albeit logically in continuity with past trends, need to be measured precisely in order to make a useful and relevant appraisal of actual conditions. In so doing, the isostatic (earth crust) and the eustatic (solely marine) components of relative sea level change must be determined.

During this project, long-term sea level changes were studied in the Resolute Bay region on a series of raised beaches. The research approach compared variations in beach morphology and sedimentology with a proxy record of sea ice intensity derived from driftwood and whalebone occurrences on emerged beaches. It was hypothesized that periods of reduced sea ice intensity and increased open water would expose shorelines to higher and more prolonged wave energy, leading to better developed beach berms. Preliminary results from three study sites on Lowther Island suggested a regional pattern in raised-beach sequence morphology. Sequences of massive and well-developed single-crested beaches were intercalated with numerous, closely spaced, often multi-crested beaches of smaller amplitude. Well-developed beaches were observed at elevations of 0-2 m, 5-7 m, and 9-11 m above mean sea level. Based on the relative sea-level curve for this area, these elevations correspond to the modern period of recent decades and to intervals of 1.25-1.75 ka BP and 2.25-2.50 ka BP, respectively. These ages do not necessarily correspond to periods of light sea-ice as interpreted from the distribution of driftwood and whalebone (Dyke et al. 1996; 1997).

Past changes in sea ice conditions and storm exposure were also reconstructed through detailed topographic (RTK-GPS) and sedimentological analyses of modern and raised beaches. Raised beaches and deltas were investigated and datable material was collected from Coral Harbour in order to construct an emergence curve for the region to show sea level trends.

On the eastern coast of Hudson Bay, new radiocarbon dates were added to the existing data base to construct an updated post-glacial emergence curve for this region which raised international interest for its fastest uplift rate in the world. Extending the uplift curve to the modern times indicated an actual emergence rate of 1.2 cm/year (Lavoie 2006).

Present-day vertical motion of the land and sea-level rise was monitored across the Arctic using continuous GPS and tide gauges. This project motivated the Québec Department of Transport and the Makivik Corporation to install new equipment and initiate such monitoring in other Nunavik communities given that this type of information is relevant for maintaining and operating docking facilities.

On submergent coasts, shoreline changes due to either erosion or sedimentation were measured on the decadal time scale by the use of collections of air photographs of various ages and satellite imagery. Notably, a 50-year reconstruction of coastal retreat and permafrost degradation was produced in the Herschel island area of the Yukon coast. Similarly, the costal erosional features and processes were mapped around Banks Island. In order to capture the interrelated components of the dynamic coastal system, the following were carried along the Yukon coast: bathymetric surveys for inputs to a wave energy model, sampling of massive ice to assess age, origin, and paleoenvironments during ice formation, sampling and analysis of carbon isotopes in nearshore sediments to determine source via C/N ratios and C-13 determinations, and continuing surveys of shoreline features, including block failures and thermo-erosional niches.

Many parts of the coast bordering the Arctic Ocean are slowly submerging with rising relative sea level. In these situations, formerly exposed frozen ground is flooded or eroded in the process of marine transgression. This leads to changes in thermal regime with important implications for the preservation or decay of ice-bonding and massive ground ice. A network of boreholes drilled in the Babbage Delta area of the Yukon coast provided information on the distribution of permafrost and ground ice beneath a barrier-lagoon and estuarine delta system undergoing slow transgression. The boreholes showed ice-bonded sediments beneath the subaerial delta plain, tidal flats, and spit and beneath the lagoon in shallow areas where winter ice was bottomfast. Thaw taliks were present under channels and deeper parts of the lagoon. Deposits under the spit were ice-bound to nine metres at one site (11 m at another), below which there was a four metre thick talik of unfrozen silt. The unbounded layer at depth beneath the spit and thicker units of unbounded sediments beneath deeper parts of the lagoon suggested downward refreezing of shallow estuarine sediments as the spit migrates landward. A borehole near the delta front penetrated frozen organic-rich sediments over 2.5 m of massive ice, underlain by ice-bound gravel to 23 m, where saltwater was encountered under pressure (Figures 2 and 3). These results confirmed the partial preservation of massive ice and ice bonding below formerly subaerial transgressed seabed, with downward thaw of seabed sediments in the nearshore as the spit migrated landward.

The approach to understand processes in their full context was also based on seamless mapping across the shoreline, combining high-resolution satellite and airborne mapping tools on land with multibeam bathymetric surveys. In collaboration with NASA, airborne laser altimetry (LiDAR) surveys were acquired in the Resolute Bay area for the purpose of building a high-resolution digital elevation model (DEM). As the survey was flown on an opportunity basis in late spring, the research component involved the discrimination of surfaces with negligible to thin snow cover to eliminate positively-biased elevations in snow-filled depressions and drifts. Measurements of snow depth and RTK-GPS topographic data collected in snow-free conditions were used to validate the DEM. These investigations were assisted by mapping of the seabed in the Resolute Bay and Oliver Sound areas using the *CCGS Amundsen* and the Heron launch.

Research on basic processes of thermokarst formation:

It is well known through observations and calculations (e.g. applications of the Stefan equation that relates summer temperatures and rates of soil thaw) that climate warming results in a deeper active layer. During this process, ice-rich near surface permafrost thaws and results in ground destabilization, differential settlement, and slope movements. Wet hollows and ponds are created, superficial slides (active layer failures) occur and longer term regressive thaw slides are activated. Observations and descriptions of such processes were reported by team members from the High Arctic, for instance in Eureka Sound and on Axel Heiberg Island. The measurement of the deepening of the active layer through ground temperature measurements in communities and under transportation infrastructures in Nunavik was provided to authorities in public reports to support decision making and initiate mitigation measures.

The dramatic changes in the discontinuous, ice-rich, permafrost zone of Nunavik imply more than atmosphere/soil heat transfers. Indeed, the whole system is changing through a complex chain of interactions with feedbacks loops involving ground settlement, changes in snow cover distribution, winter protection of shrubs, increased vegetation growth in warmer summers, and modification of local drainage networks. The impacts on landscapes and ecosystems are substantial; comparisons between old aerial photographs and satellite imagery showed that the permafrost has degraded by more than 35 % in the recent decades while thermokarst lakes and shrubs expanded by more than 40% (Figure 4) (Marchildon 2007).

In collaboration with Germany's Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), a monitoring site is operated near Umiujaq in a lithalsa (ice rich permafrost mound). Results from repeated measurements of the internal temperature and topographic changes of the actually collapsing mound led to the understanding that ground water flow around the permafrost body at depth brings convective heat to the permafrost core of the mound and that the deeper snow cover in the depressing surface of the mound isolates the permafrost and prevents the underground heat from escaping. Measurements were undertaken to test the hypothesis that large tracts of discontinuous permafrost are no longer in equilibrium with the climate and are in fact just slowly melting under the latent heat of fusion effect. This widespread aspect of permafrost degradation is not actually simulated in coupled climate-ground models.

Drilling, 3D thermal monitoring, and resurveying of the lithalsa at the BGR site in Nunavik revealed that these landforms have an ice-rich core (≈ 65%) surrounded by an ice poor peripheral belt (≤ 10%). When the permafrost thaws, this leaves a rimmed rampart around thermokarst lakes as the ground settles differentially. This hitherto unknown fact explains the size and morphology of the thousands of new ponds that are made in the forest tundra by permafrost thawing and that are new aquatic ecosystems and greenhouse gas emitters, particularly methane (Figure 5) (Calmels et al. 2008).

Another study in Sirmilik National Park, on Bylot Island documented in detail the rate of thermo-erosion of networks of ice wedges, with an appraisal of the amount of convective heat brought to the permafrost terrain by surface water (snowmelt and rain) (Fortier et al. 2006). The measurements of rates of thermo-erosion were made by way of annual resurveying from a network of benchmarks and stakes. The ecological impact of terrain destruction, particularly the loss of foraging wetlands for large bird populations, is dramatic.

Assessing mass transfer processes and rates of change through marine and lacustrine sedimentary records:

The physical and historical context of sediment and carbon transfer between land and ocean is determined locally by the Quaternary geology and geomorphology, both in terrestrial and the marine environments. This is necessary to identify sources (where erosion takes place), pathways and sedimentary environments.

Surperficial geology mapping and C-14 dating of landforms and Quaternary deposits were thus carried out at Coral Harbour and Resolute Bay. The same was done in Nunavik in the region of Lac Guillaume-Delisle where both marine geology (bathymetry and sea-floor sediments) and surrounding terrestrial geology and morphology were mapped, providing a first comprehensive appraisal of the history of deglaciation, Holocene river erosion and incision, and marine sedimentation (Duhamel 2005; Lavoie 2006). Surficial geology and radiocarbon dating of deglaciation events were also achieved over a region (1:50000 topographic map near Biscarat River) on the eastern Hudson Bay coast. In the macro-tidal Holocene and actual environment of Ungava Bay, mapping, analyses of the Holocene sedimentary record, and radiocarbon dating were also carried out along Rivière Bérard within the community lands of Tasiujaq, where tides are amongst the largest in the world.

Geological marine surveys using chirp sonars, multibeam echosounders and coring were also carried out in Hudson Bay and Hudson Strait in 2005 where detailed descriptions and analyses were carried out on 20 cores. This included grain size analysis, AMS 14C dating of shell fragments, CT-scans (image and CT-numbers), and measurements using a multi-sensor core logger (density, porosity and magnetic susceptibility) and a spectrophotometer (RGB values). Multibeam sonar and sub-bottom profiler data of Hudson Bay and Hudson Strait were integrated into a GIS and a DEM was produced. This fully geo-referenced geophysical data were combined with the sedimental database. Additional gravity and box cores of recent sediments were collected during the CCGS Radisson cruise from Cape Dorset to Kuujjuarapik. A detailed marine mapping survey was done off Umiujaq in the summer of 2007 from small boats with the participation of community members, again using a chirp sonar and obtaining grab samples and shallow cores. The surveyed area in the Nastapoka Sound was off the mouth of Sheldrake River where thermokarst studies and monitoring took place (notably the BGR site; see above). The results of this survey provided a basis for the assessment of carbon and fine sediment deposition and of the existing information on erosion and permafrost degradation in the river catchment.

Lakes in the coastal region are sedimentary environments and storage basins in the drainage network where eroded superficial soil material and carbon are transferred and deposited. At Cape Bounty, two lacustrine sedimentary records from paired watersheds were used to evaluate long-term sediment delivery processes and characteristics, and to infer past hydroclimate and aquatic ecology. Sediment deposition suggested that century-scale sediment yield from the watersheds varied and was inferred to be indicative of differential permafrost disturbance. One watershed appears to have been stable since 1600 AD but was preceded by a century of higher erosion. The adjacent lake showed steady sedimentation during the 16th century, but a sharp increase in erosion rates after c. 1970 AD. Integrated watershed research at Cape Bounty since 2004 focused on snowpack controls over runoff and nutrient fluxes and include detailed year to year snow surveys, the establishment of new transects with a higher spatial density, monitoring of water, total organic carbon and nitrogen fluxes, installation of snow fences and instrumentation for recording soil temperature and moisture, and sampling for organic carbon. These studies demonstrated the sensitivity of erosion and nutrient transfer to the amount of late winter snowpack. Exceptional warmth in the summer of 2007 resulted in widespread active-layer detachments in one catchment. Hence, future watershed studies will benefit from an exceptional baseline period (2003-2007) before these large active layer detachments.

Sediment coring for glacial runoff studies was carried out on Devon Island and preliminary analyses revealed laminae that hold the promise for highly detailed climate reconstructions from this region and quantitative indications of the links between glacier activity and coastal sediment delivery. Indeed, detailed analyses were conducted on the subannual structures in these cores, demonstrating for the first time a close association between short-lived regional weather conditions and sedimentary structures.

Similarly, analyses on cores from northern Ellesmere Island examined sediment delivery properties and linkages to climate over the past c. 1000 years. The approach through lacustrine sedimentology provided highly detailed climate reconstructions in the Arctic and quantitative indications of the links between glacier activity, meltwater generation and sediment delivery in the coastal zone. Collaborative work (with project presented in section 5.2) focused on the fossil and biomarker composition of the accompanying sediment to link watershed and lake aquatic processes. Results showed that organic carbon deposition has substantially increased during the 20th century, consistent with warming climate and the collapse of the adjacent ice shelves.

Improving the monitoring infrastructure:

This project made considerable use of data acquired by automatic weather stations, thermistor cables, automatic cameras, and transmissivity meters and sediment traps in lakes. Repeated samplings were conducted on a yearly basis at key sites. The project was tied to the CEN SILA network that has instrumentation across Nunavik (over 80 sites, representing nearly all communities), to stations operated by Theme 3 on Hudson Bay in collaboration with several Nunavik communities, and arrays of instrumentation sets at the McGill Arctic Research Station on Axel Heiberg Island. An additional station was installed at King Point on the Beaufort Sea shore. The project made use of Environment Canada's station and of tide gauges and GPS base stations of the Federal Government.

Human impacts and adaptation to changing environmental conditions in coastal settings:

Project members visited and were active in practically all the communities of Nunavik and those of the Baffin in Nunavut, plus localities of the Central and Western Arctic. Formal presentations, with discussion of results, were done in a total of 21 communities.

A large part of this project was oriented to cope directly with the concerns of northerners at both community and regional governance levels. For instance, in Salluit continuous high quality data from meteorological stations near Salluit were analyzed to extract information on extreme climatic events that are relevant to the community in terms oftraditional activities such as travel on snow and ice or by boat, and modern events of life (e.g. floods linked to fast spring thaw, wind gusts causing damage, airport closures, impacts on medivacs, damage to buildings and electrical distribution equipment). These data, in combination with the Canadian Regional Climate Model, will be used to forecast the frequency of future events. Two field monitoring sites were instrumented in support of a project to assess the increasing risk of active layer detachment slides over permafrost triggered by warming. Two field monitoring sites on sensitive slopes were instrumented to assess the increasing risk of active layer detachment slides over permafrost triggered by warming. The landslides in 1998 had dramatic consequences, forcing the moving of 22 houses.

Based in Kangiqsualujjuaq, a study of Inuit perceptions on the land-water interface and communication of information within families was completed. Part of the investigation examined how climate-related hazards in the coastal zone impact community members in the eastern Arctic, particularly those involved in the resource harvesting sector.

A workshop cosponsored by Natural Resources Canada and the Government of Nunavut in Iqaluit in December 2006 allowed project members to inform community representatives from all over Nunavut about ArcticNet research and the implications of climate change for communities including coastal hazards, reduced sea ice, degradation of permafrost and ground-ice, challenges involving water supply, and other issues. Representatives from several communities identified specific issues of concern and expressed a desire for research and adaptation to address these issues. Further community consultation was undertaken in Clyde River in March 2007 to involve the community research committee, the hamlet council, and the HTA in the planning of further work along the Baffin coast. A multidisciplinary research program was initiated in collaboration with the community in July-August 2007. Work was also initiated in Hall Beach in August 2007 at the request of the community and the Government of Nunavut (with significant in-kind support from both). The primary issue of concern was coastal erosion threatening a number of homes along the shore. A complete seabed and coastal survey was carried out along the hamlet waterfront to address this issue and the research team met with the hamlet council to discuss adaptation options.

5.4.8 Conclusions

In summary, knowledge of the factors and processes that govern the dynamic of transitional coastal permafrost has significantly progressed through the completion of this project. As well, rates of retreat in permafrost along permafrost coasts, rates of permafrost thawing in the discontinuous zone of the forest tundra, and rates of thermo-erosion and resulting sedimentation in lakes were assessed. Basic Quaternary geological knowledge with some reconstructions of Holocene changes was produced in various part of the Arctic. The main interaction level of project members was at the community level.

Future work will concentrate on the integrated geomorphological and ecological impacts of permafrost thawing and on the support of planning for the safe land use of Arctic terrain. Through the use of mapping thermal conditions of permafrost by remote sensing coupled with Arctic-wide field data acquisition, a more comprehensive vision of the upcoming impacts is a research goal. The predictive capability will be based on the outputs of regional climate models.

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5.4.10 References

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5.5 Cultural Self-Determination, Endogenous Development and Environmental Changes (Project 2.5)

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5.5.1 Abstract

Work was conducted at the interface between natural and social sciences to better understand some of the links between climate change, use of natural resources, and social-ecological systems in northern communities. The main findings were that the past and current ability of Inuit and other Northern Aboriginal communities to respond and cope with climate change may not be a reliable indication of their ability to adapt in the future, and that the effectiveness of local adaptive strategies is uneven across the Arctic. It has been found that traditional ecological knowledge and scientific knowledge more efficiently complement each other when they originate from observations performed at different spatial or temporal scales. This is important given the current emphasis on integrating these two knowledge systems. In addition, a large searchable database (available on the web) on northern ecological impact studies was built, based on literature and public record of Environmental Impact Assessment processes. This linguistic corpus database should become an invaluable tool to help articulate Aboriginal and scientific perspectives on change, and in situating the very of idea of change within specific historical and cultural frameworks. A final finding was that integrating natural and social sciences into an ArcticNet project is full of challenges because approaches, methods, and traditions differ between disciplines. Ironically, integrating knowledge across cultures but within a discipline (e.g. integrating western and Inuit ecological knowledge) seemed significantly easier than integrating knowledge across scientific disciplines. This should be taken seriously given ArcticNet's central objective of implementing Integrated Regional Impact Studies of the Canadian Arctic.

5.5.2 Key Messages

- The ability of Inuit communities to respond and cope with climate change, mainly by adjusting subsistence activities may not be a reliable indication of their ability to adapt in the future. Further research is needed on understanding how much change can be accommodated by the existing ways of life of indigenous peoples.
- The effectiveness of local adaptive strategies is uneven across the Arctic and there are large gaps in knowledge about why some Arctic communities do remarkably well, while others are more vulnerable and exposed to drivers of change, even when they share similar resources and ecological settings.
- The integration of traditional ecological knowledge and scientific knowledge gives a broader understanding of social-ecological systems than the use of a single type of knowledge. This is especially true when observations forming the basis of each type of knowledge have been performed at different spatial or temporal scales.
- Inuit and scientific perspectives on change were articulated in a new way by collecting literature on northern ecological impact studies and developing a searchable linguistic corpus database, with over seven million words in the corpus to date (the Northern Voice Project).

5.5.3 Objectives

The main objectives pursued in this project were the following:

- To better understand the ability of Inuit communities to respond and cope with climate change.
- To compare the effectiveness of local adaptive strategies across Arctic communities.
- To gather traditional ecological knowledge pertaining to wildlife and develop ways to integrate this knowledge to scientific knowledge.
- To develop a searchable linguistic database from literature on Northern Environmental Impact Studies.

5.5.4 Introduction

Arctic communities are faced with various challenges related to the effects of climate change and the increase in exploitation of natural resources. The overall objective of this project was to enhance understanding of the extent of the environmental issues and challenges faced by indigenous peoples in a rapidly changing milieu. The sections below present the main specific objectives of the project.

Social responses to change in Nunavut:

This part of the project aimed to understand local experiences of and responses to current and predicted climate change on community, wildlife and the environment in Nunavut. Existing data on the impacts of climate change on the livelihoods of the indigenous peoples in the Arctic is limited. Furthermore, very few studies have paid attention to understanding the impacts of climate change on social relations in indigenous communities. The ways of how changes in the environment and in the ability of Inuit to access food resources have a corresponding impact for the social fabric of communities were investigated. The project has determined to what extent climate impacts on subsistence activities threaten local abilities to sustain an appropriate human/food resource relationship in Inuit communities.

Comparative study of northern societal responses to change:

The project focused on identifying similarities and differences between societies in the circumpolar north in their responses to accelerated change. Although they face similar kinds of changes, communities across the Arctic are affected by environmental change in different ways and responses to change may not be universal. The goal was to understand how communities differ in their experiences, and what common perspectives they may share in order to understand strategies for mitigating negative changes and examine the effectiveness of adaptive capacity in different settings.

Public participation in Environmental Impact Assessments (EIA):

Despite the importance of public participation in EIA, this participation has received little attention from researchers. No consistent effort has been made to understand the dynamics of Aboriginal involvement in the process or to understand what effects participation creates, how public discourse is conveyed, or how it has changed over time. This is surprising since this is one of the few avenues that any citizen faced with a large scale development project may use to articulate their ideas. Discourses of change encountered in EIA hearings encapsulate a broader discourse of change which northerners have experienced and through which they may project responses to future changes from anthropogenic and natural sources. A systematic assessment of public participation serves to track changing social, ecological and economic conditions broadly. The specific objective was to identify, collect, digitize and make available through the web public statements made in environmental assessment scoping and hearing sessions on large projects in the North.

Traditional ecological knowledge (TEK):

TEK has contributed to environmental research and management, through improvement of baseline data on species and ecological processes (e.g. Mallory et al. 2003), by providing insights to develop alternative resources management systems (Berkes and Folke 1998), or by renewing conservation ethics (Berkes 1999). There are now structures that encourage or require the co-application of TEK and science in natural resources management. Yet the articulation of traditional and scientific knowledge is still not easy, and how much of what has been suggested by theoreticians applies to the real world is unclear (Gilchrist et al. 2005). There are several axes on which TEK and science can best complement each other. Given that scientists and members of local communities usually observe the natural world with different motives, equipment, and time

Figure 1. *Exchange of information between Elders, hunters, youth, and scientists in the Mittimatalik (Pond Inlet) and Sanikiluaq (Belcher Islands) regions, Nunavut. A- Interview time at the Goose Camp on Bylot Island. From left to right: Lucy Quasa (interpreter) and Elisapee Ootoova (Elder); B- Enjoying the sun while performing an interview at Cornelius Nutarak's home. From left to right: Elisha Pewatoalook (interpreter), Cornelius Nutarak (Elder) and Catherine-A. Gagnon (interviewer); C- Discussion between adult and youth at the Elder-youth camp on Bylot Island. From left to right: Rachel Ootoova (interpreter) and Moses Amarualik (young man); D- Storytelling by Gamaillie Kilukishak during the Elder-youth camp held on Bylot Island; E- Informal discussion between hunters and scientist during the Elder-youth camp on Bylot Island. From left to right: Mathias Qaunaq (hunter), Elijah Panipakoochoo (hunter) and D. Berteaux (scientist). F- Two hunters exchange information about winter hunting techniques and changes in abundance of common eiders in the Belcher Islands.*

constraints, the scale at which field observations is performed is one of the most promising directions offering potential for complementarities (Huntington et al. 2004). The links between traditional ecological knowledge and scientific knowledge were explored in order to build a broader view of northern social-ecological systems.

5.5.5 Activities

All activities in this section are summarized hereafter. More details are provided for one of them (integration of TEK and scientific knowledge) to demonstrate one example of ArcticNet research located at the interface between two disciplines, the natural and social sciences.

The work on social responses to change in Nunavut and the comparative study of northern societal responses to change have built on Nuttall's work as Lead Author for the Arctic Council's Arctic Climate impact (ACIA 2004) on climate change impacts on the livelihoods of indigenous peoples. Through an analysis of texts, documents, archives and other materials in the public domain, interviews with key stakeholders and participation in workshops (in Iqaluit, Inuvik, Yellowknife, Tuktoyaktuk and Holman, as well as in Ottawa), the institutional and legal barriers to adaptation to climate change in Nunavut and the western NWT were investigated. Management practices imposed on Inuit wildlife harvesting were analyzed at the international, federal and territorial levels, to determine whether they allow for the sustainability of local livelihoods or increasingly restrict hunting and fishing and reduce adaptive capacity. Conceptual work was needed to integrate sometimes widely separate ideas or pieces of information.

The work on public participation in Environmental Impact Assessments (EIA) has first involved identification of northern EIAs. All large projects that came under the terms of the scoping and/or comprehensive review processes were targeted

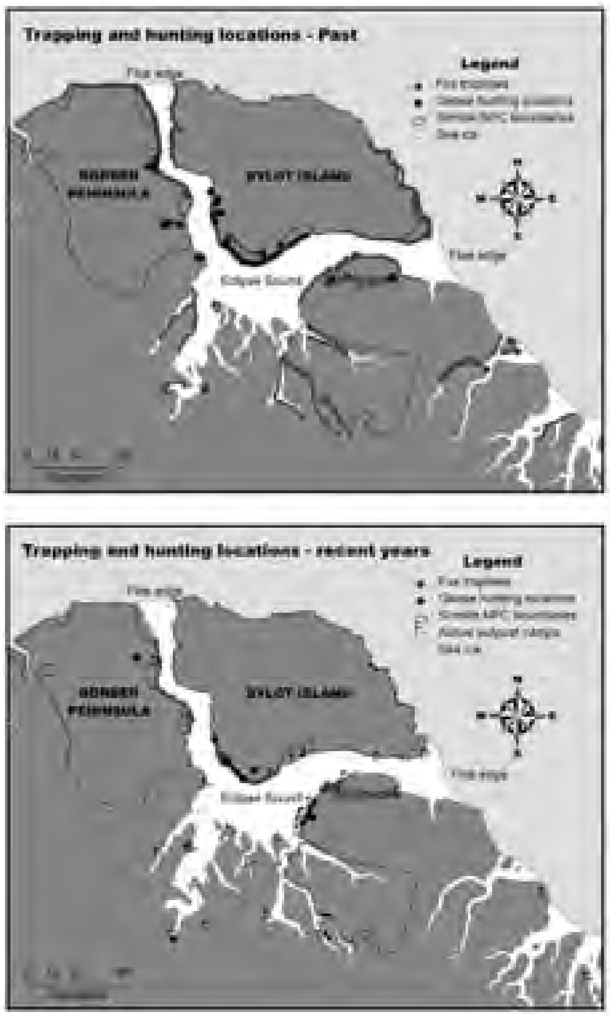

Figure 2. *Past (up to the late 1970s) and recent (1980s and after) areas used for fox trapping and goose hunting by the local experts from Mittimatalik (Nunavut, Canada) interviewed in this project (from Gagnon 2007). Flags represent the locations of the currently most active outpost camps. Comparing the two maps shows that the area used for fox trapping has considerably reduced, yet current use of the land is still performed on the same geographical scale.*

for inclusion in the database. The transcripts were located, digitized, and coded according to a series of several hundred themes determined through a consultative process. A searchable user interface (XML) that is located on the Text Analysis Portal for Research (TAPoR, University of Alberta) web site was then built. The TAPoR lab provided considerable computing, digitizing and analytical resources specifically designed for use in large text based projects. Two phases were envisioned: The first began with the current Federal legislative regime (CEAA) in 1992 and extended to the present. The second phase began with the former legislative regime (EARP) in 1985 to 1992. For the purposes of this study the North included all three Territories, territory under the James Bay and Northern Quebec Agreement, and Labrador.

For the TEK component we worked through three case studies. The first case study aimed at integrating local and scientific knowledge on Arctic fox ecology in the North Baffin area, where Sirmilik National Park of Canada must be managed using both TEK and scientific knowledge. The second case study aimed at integrating knowledge on the rapid spread of new diseases to Arctic wildlife populations. The focus was put on avian cholera, which has been detected among some bird populations (e.g. sea ducks, gulls, and geese) in the eastern Canadian Arctic with devastating effects. The third case study aimed at integrating local and scientific knowledge on wildlife population dynamics, using the Nunavik caribou herd as focus. Only the methodology used for the first case study (Gagnon 2007) is detailed hereafter. The second one (Henri 2007) shares a similar approach, while the third one was at a too early stage to allow reporting.

Study area and people: Project members worked with Inuit elders and hunters from Mittimatalik (Pond Inlet) (Figure 1). Modern Inuit and their ancestors have lived in the Mittimatalik area for 4,000 years (Mary-Rousselière 1984-1985). Prior to contact with Europeans (mid 19th century), the region was inhabited by nomadic hunters. In the mid 19th century, the arrival of whaling crews modified Inuit land use. This was exacerbated by the arrival of fur traders at the beginning of the 20th century. The trade of Arctic fox furs then became the main economical staple of Inuit, until the collapse of the fur trade market in the 1980s. The area originally used by Inuit for fox trapping is still heavily used for other outdoor activities, as shown by the location of currently active outpost camps (Figure 2). This ensures that local ecological knowledge derived from past practices is still linked with contemporary experiences. From 1990 to 2002, the breeding activities of Arctic and red fox have been surveyed scientifically on Bylot Island (adjacent to Pond Inlet). In 2002, the fox studies expanded to include surveys of fox breeding activities over 600 km^2 of Bylot Island and several aspects of the ecology of Arctic fox. This provided an ideal setting to investigate how TEK and scientific knowledge could best be integrated. Gagnon and Berteaux (2006) give many more details about the context of this study.

Collection of TEK: In February-March 2005, project members held two consultation meetings to present the project and invite the community to express ideas, concerns and advices. From February 2005-July 2006, TEK was collected using several qualitative research approaches such as workshops, semi-directive interviews, focus groups and participatory observations. These were spread over four visits to Mittimatalik. Upon approval from the community, the first phase of TEK collection began using semi-directive interviews (Huntington 1998), a methodology that allows unanticipated information to emerge. Between May and September 2005, 21 local experts were interviewed. Informants were selected based on the number of times their names had been recommended by elders, members of the Mittimatalik Hunters and Trappers Organization (hereafter HTO), and community members working for Parks Canada, the Hamlet Office, and the Nunavut Wildlife Management Board. Using multiple recommendations decreased biases in the selection of informants. Each interview lasted between one and a half and four hours, for a total of 38 hours recorded. Interviews started with questions about the informants' birth location and most known hunting and travelling areas, providing a temporal and spatial context for the information later collected. Information collected then covered topics regarding the ecology of foxes. Throughout interviews, 1:250,000 topographic maps were used to stimulate conversation and record geographical information (Huntington 1998). With the assistance of a professional interpreter, the interviews were conducted in both English and Inuktitut. Upon consent, an assistant from Mittimatalik audio and video recorded all interviews. Materials collected and produced during the research, including the video tapes and maps, remain the property of the community and are archived and made accessible by Parks Canada. When possible, interviews were conducted in places where local experts felt at ease. These included the local Parks Canada office and visitor centre (where elders have weekly gatherings), houses of informants as well as traditional campsites (Figure 1). Conducting interviews on the land was very effective in stimulating thought and old memories, but was logistically constrained.

Management, analysis, and verification of data: Segments of the transcripts were codified according to the topic(s) they covered, using both deductive (predefined) and inductive (defined a posteriori) coding. All the spatial information were digitized and georeferenced to produce comprehensive maps. From May-July 2006, the validation phase of the project was conducted. The interviewees were contacted, more interviews were conducted, and elders were consulted. Four verification workshops were organized, each with 4 selected experts, to confirm and discuss our findings. From 11-17 June 2006, project members also participated in an elder-youth camp organized in collaboration with the local elders' committee. While the main purpose of the camp was to create an opportunity for transfer of knowledge among generations, it also provided with the opportunity to see in situ demonstrations of the knowledge shared by local experts during interviews, and to have numerous informal discussions. Focus groups and informal discussions allowed to compare the congruence of information gathered using different approaches.

5.5.6 Results

Hereafter are listed a subset of research findings to support the main messages generated by this project.

Social responses to change in Nunavut and comparative study of northern societal responses to change:

The successful long-term inhabitation of the Canadian Arctic by Inuit societies has been possible, in part, because of their adaptive capacity (in social, economic and cultural practices) to adjust to climate variations and changes. The focus was put on how such flexibility and versatility is difficult within conditions of modernity. One of the hallmarks of successful adaptation strategies in Arctic indigenous resource use systems has been flexibility in technology and social organization, and the knowledge and ability to cope with climate change and circumvent some of its negative impacts. Today, much of this flexibility has been reduced and even lost as a result of rapid social, cultural and economic change. The Arctic's indigenous peoples live within different institutional settings than a generation or two ago. Adaptive capacity has further been altered and transformed by a number of other forces that threaten to restrict traditional resource use activities and reduce access to traditional local foods (fish and meat from marine mammals or caribou and birds, as well as berries and edible plants). Small Arctic communities, however remote, are tightly tied politically, economically and socially to the national mainstream, as well as being linked to and affected by the global economy. Today, trade barriers, wildlife management regimes, political, legal and conservation interests and globalization all affect, constrain or reduce the abilities of indigenous peoples to adapt and be flexible in meeting the challenges posed by climate variability and change. Inuit communities cannot adapt, relocate or change resource use activities as easily, because most now live in permanent communities, live in greatly circumscribed social and economic situations and their customary hunting and fishing activities are determined to a large extent by resource management regimes, resource ownership regulations and local and global markets.

Public participation in Environmental Impact Assessments (EIA):

Considerable progress was made on the Northern Voices project. A beta version of the database was established on the TAPOR website (http://ra.tapor.ualberta.ca/Fletcher/). Approximately eight million words are in the database and coding has been completed on the corpus. No one had ever attempted to produce a linguistic corpus of the scope and topical orientation that this project does.

Traditional ecological knowledge (TEK):

The results give several examples of TEK broadening current scales of scientific knowledge. In the North Baffin area and at the spatial scale, TEK about areas where various color phases of the red fox were observed, and to a lesser extent fox denning locations, all covered areas that expanded beyond the scientifically investigated south plain of Bylot Island (Figure 3). At the temporal and spatio-temporal scales, TEK about the increase in the red fox population (several decades) and the winter and spring ecology of Arctic fox (several seasons) also enlarged the realm of regional scientific data (several years, summer only). While scientific data collected locally on foxes tended to be very specific and detailed (the "zoom in" approach), Inuit TEK provided a broader picture (a "zoom out") of the system (details in Gagnon 2007).

In the Hudson Bay area, avian cholera had rarely been detected prior to 2004. Since it was first detected by the Canadian Wildlife Service on East Bay Island in 2004, there have been increasingly large outbreaks in Common eiders each year. As just one example, over 3,500 eiders died (>30% of nesting females) between late June and early August 2006 at a colony near Southampton Island. Most birds had lesions

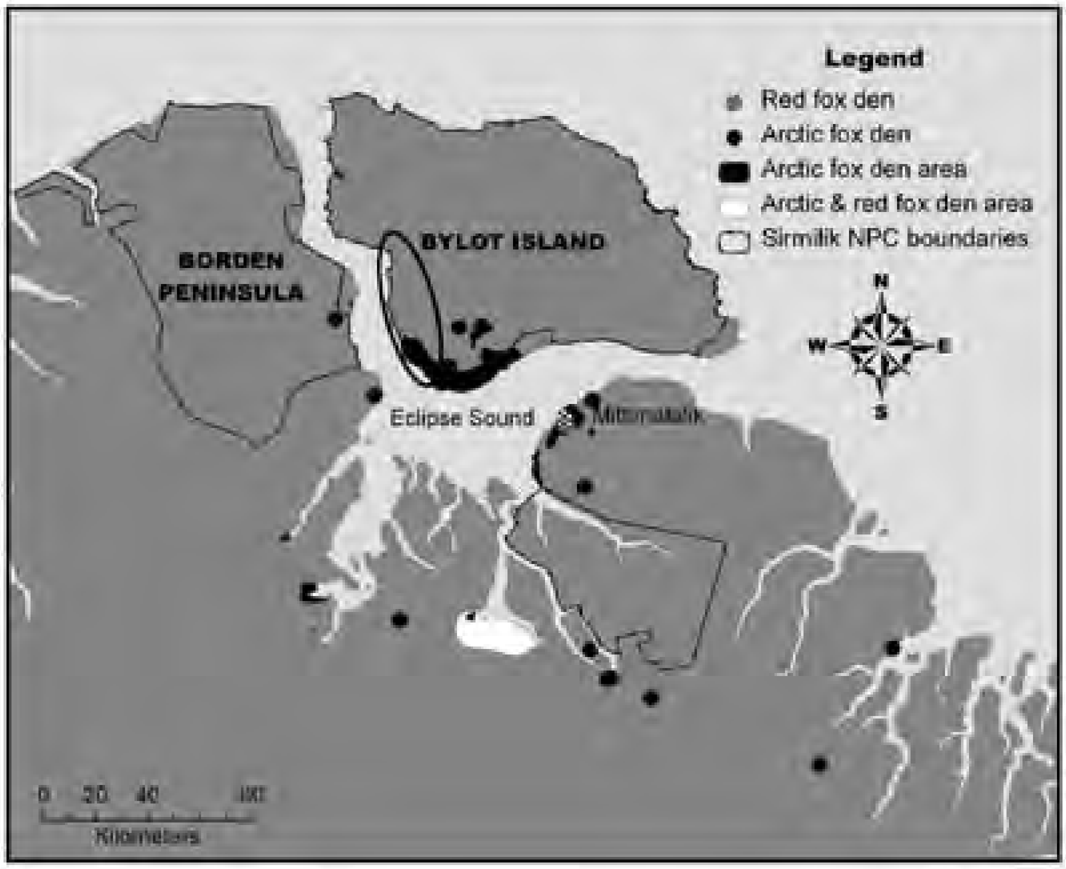

Figure 3. *Locations of arctic and red fox dens and denning areas, as reported by local experts from Mittimatalik (Nunavut, Canada) interviewed in this project (from Gagnon 2007). The ellipse on Bylot Island shows the area where intensive and detailed scientific investigations on fox ecology have been performed in the last decade. Note the large difference in spatial scale between the area studied by scientists and the area used by local experts.*

suggestive of septicemia, with positive isolation of *P. multocida*. Serotype 1 was the main cause of mortality in 2005, and serotyping of 2006 isolates is currently underway. The TEK study considerably expanded scientific knowledge. The 30 interviews held with experienced Inuit hunters and elders from Kimmirut, Cape Dorset, and Coral Harbour addressed the question of whether mass die-offs have occurred historically in the South Baffin Island and Southampton Island regions. The results show that avian cholera has only recently migrated into the west Hudson Strait and north James Bay area, rather than being a cyclical phenomenon in that region. TEK thus complemented scientific knowledge in that it expanded both the temporal and spatial scales of available information. Again, TEK provided a "zoom out" of the system whereas science provided a "zoom in" (details in Henri 2007).

5.5.7 Discussion and Conclusions

Social responses to change in Nunavut and comparative study of northern societal responses to change:

Inuit hunters and fishers have always lived with and adapted to shifts and changes in the size, distribution, range and availability of animal populations (Nuttall 2005). They have dealt with flux and change by developing significant flexibility in resource procurement techniques and in social organization. Yet the ecological and social relations between hunters, fishers and animal species are not just affected by climate-induced disruption, changing habitats and migration routes, or new technology. The livelihoods of Canadian Inuit are subject both to the influences of the market economy and to the implementation of management policies that either contribute to a redefinition of hunting and fishing, or threaten to subvert subsistence lifestyles and indigenous ideologies of human-animal relationships. It is argued that commercial, political, economic, and conservation interests have reduced the abilities of Inuit communities to adapt and be flexible in coping with climatic variability. Modernization and globalization places hunters and fishers in very inflexible situations. Faced with climate change they are not necessarily in a position to move or diversify. In a climate changed Arctic, how local communities are in a position to take advantage of the opportunities that may arise, as well as being able to change their mode of production, is a critical research need.

The political, cultural and economic diversity of the Arctic means that indigenous communities are affected by, and respond to, environmental change in different ways. Such diversity also means that local experiences of climate impacts and responses to climate variability and change may not be universal. Yet little is known about how communities differ in the way that risk is perceived, or how they differ in the ways they utilize harvesting strategies for mitigating negative change. Furthermore, the effectiveness of local adaptive strategies is uneven across the Arctic and there are large gaps in knowledge about why some Arctic communities do remarkably well, while others are more vulnerable and exposed to drivers of change, even when they share similar resources and ecological settings. Social and ecological resilience is a crucial aspect of the sustainability of local livelihoods and resource utilization and further research is needed in the Arctic because little is known about building adaptive capacity in the face of climate change. An understanding of adaptation can only derive from an understanding of social and economic vulnerability. Greater uncertainty and threats to food security resulting from increased climate variability stresses the need for resilient and flexible resource procurement activities. Yet, resilience and adaptability depends not only on ecosystem diversity, but on the institutional rules which govern social and economic systems.

The general conclusions were that, while aiming, in principle, to protect and conserve wildlife, wildlife management imposes restrictions of access to resources and in doing so, reduces, restricts and even prevents adaptive capacity in response to environmental change. Combined with the Arctic's natural vulnerability, this magnifies the potential effects of global climate change on indigenous peoples. It was also investigated whether climate change poses a threat to the implementation of the Nunavut Land Claims Agreement – work on this aspect was analyzed to produce an article on human rights and climate change.

Public participation in Environmental Impact Assessments (EIA):

This project was envisioned as open ended and cumulative. Agreements and funding were sought to keep new data entering into the database as future hearings take place. ArcticNet has shown considerable openness to exploring and supporting new ways of articulating Inuit and scientific perspectives on change generally and this project exemplified this.

Traditional ecological knowledge (TEK):

The question of scales in ecological studies has been a recurring source of discussion over the last decades (Levin 1992; 2000; Wiens 1989), as ecologists realized that patterns and processes observable at one scale could not always be generalized to other scales (Wiens 1989). In the Arctic, the scale of observations is often imposed on researchers by logistical constraints such as lack of infrastructures for transportation, extreme weather seasonality, or high costs of field work. Because they are year-round Arctic residents with considerable cultural and economic interest in natural resources, local experts have sometimes built an ecological knowledge over spatial and temporal scales not well covered scientifically (Gagnon 2007; Henri 2007).

Interestingly, many studies that have integrated TEK and scientific knowledge found that while TEK operated on long time series, it generally provided information at a smaller spatial scale than that provided by science. On the contrary, the study of Ferguson and Messier (1997) and this study, both performed with Inuit experts, found that TEK generally provided a broader spatial context than scientific data. Inuit from North Baffin Island and Hudson Bay have traditionally lived in camps spread out over vast territories (Brody 1976; Mary-Rousselière 1984; 1985; Treude 1977). Since settlement, they have modified their land use patterns, but have nevertheless continued to hunt over large areas (Riewe 1992). The use and knowledge of such vast areas (e.g. the people of Mittimatalik hunted over ca. 96,200 km2 in 1991 (Riewe 1991)) has been encouraged by a number of factors including the large spatial extent over which exploited animal populations were located (Brody 1976), the presence of sea ice which facilitates travel by dog teams or snowmobiles, and the usual absence of nearby villages.

While scientific data collected locally tended to be very specific and focused (the "zoom in" approach), TEK provided a broader picture (a "zoom out") of the ecological system, allowing local experts to identify regional patterns (e.g. regional distribution of fox dens, geographical history of avian cholera outbreaks) that could have gone unnoticed at the smaller observational scale used by scientists. The "zoom out" provided by TEK can now be used by scientists to test new hypotheses using a "zoom-in" approach. This complementarily between different approaches used at different scales echoes the "Strategic Cyclical Scaling" described by Root and Schneider (1995) in another context.

Collecting TEK by consciously focusing on information complementary to scientific observations helped identifying several areas of convergence between TEK and science (Riedlinger and Berkes 2001). First, it provided a historical perspective (e.g. on red fox abundance or past avian cholera outbreaks) that scientific observations simply lacked. Second, it provided several new insights for current and future ecological understanding and research.

Conclusion and significance of this work:

This project attempted to integrate natural and social sciences to gain a new understanding of some social-ecological systems in the Canadian Arctic. This project brought a better understanding of some relevant facets of these complex systems, which are now under pressure from global warming and modernization. However, the main significance of this work may lie somewhere else. One central objective of ArcticNet is to conduct an Integrated Impact Assessment of the Canadian Arctic. There are several challenges in doing so. First, "there is a tension between disciplinary traditions and standards and the interdisciplinary synthesis and needs of integrated assessment" (Yarnal 1998). Project members have experienced firsthand the delights and intricacies of attempting to bridge disciplines (social vs. natural sciences) through a common project. The delights have involved being confronted with and enriched by new ways of practicing science. The intricacies have been a large turnover of ideas, NIs, and leaders in this project. One lesson was that integration is costly in energy and time because it is unusual to most researchers. But it was also rewarding because it alone can grasp the essence of global phenomena such as the warming and modernization of the Arctic. A second challenge to conducting an Integrated Regional Impact Study (IRIS) is a problem of scales (Yarnal 1998). Specifically, integrated assessment models tend to address large geographical areas and aggregated socioeconomic factors, but without having the spatial resolution necessary to deal with regionally specific impacts of climate change or mitigation measures. This project proved that involving different types of knowledge (e.g. local knowledge and scientific knowledge) could provide one efficient way to deal with this problem of scales.

The future work will attempt to further merge scientific and local knowledge in an effort to build a multi-scale, integrated assessment of social-ecological systems in the Canadian Arctic. For several reasons, the focus will continue to be on issues related to wildlife. First, there are locally and in the scientific community two rich but still largely disjoint bodies of knowledge in this sector of enquiry. Second, decision makers at the federal, provincial, territorial, and community levels need to integrate these two forms of knowledge but often lack accepted methodologies to do so. Third, such research is well in line with the priorities of ArcticNet, Northern communities, and important players of the resource management sector such the Makivik Corporation, the Nunavut Wildlife Management Board, Parks Canada, the Canadian Wildlife Service, and the Committee on the Situation of Endangered Wildlife in Canada (COSEWIC). Finally, this was a highly successful area of investigation in this project.

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5.6 Warming the Tundra: Health, Biodiversity, and Greenhouse Gas Implications (Project 2.6)

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5.6.1 Abstract

Tundra ecosystems cover ca. 10-15 % of the Northern Hemisphere and have acted as important sinks for carbon over the past 10,000 years. In Canada, tundra covers nearly 30% of the country and contains ca. 20% of the soil carbon of the country. Tundra ecosystems provide essential biological resources and services to northern communities. They play important roles in regional and global climate systems as sinks for heat and carbon. They are also important as storage areas for atmospheric pollutants that could affect the health of northerners. The central objective of this project was to determine the effects of environmental variability and change on terrestrial ecosystems of the eastern Canadian coastal Arctic along the South-North transect from southern Hudson Bay to northern Ellesmere Island. Four general aspects of the tundra environment were examined: A) Responses of tundra systems to climate variability and change. Results from long-term warming experiments and repeated measurements at research sites showed that tundra plants respond strongly to even relatively small increases in temperature, with earlier flowering, increased rates of growth and greater production of seeds. Warming increases the cover of woody species, which will affect wildlife species and could enhance regional warming. The climate of the eastern Canadian High Arctic has warmed by as much as 1°C per decade over the past 30 years, and this has resulted in significant increases in plant growth in Arctic wetlands. B) Reconstruction of historical climate using dendrochronology methods and potential for treeline movement. The reconstructions of summer climate in the High Arctic from annual growth in a dwarf shrub (*Cassiope tetragona*) showed the climate has generally been warming since the end of the 1800s, with warming accelerated since 1980. Investigations of seed production in black spruce at the southern limit of the Arctic showed that warming will greatly increase the potential for increased density of trees. This will very likely result in enhanced warming through changes in the surface energy balance at local, regional, and global scales. C) Carbon dynamics in thermokarst ponds. These ponds are important components of the tundra landscape and vary strongly in their characteristics at local scales. This study was one of the first investigations on the carbon dynamics of these pond systems in Canada (together with Macrae et al. 2004 in the Churchill region). The ponds were found to be significant sources of carbon to the atmosphere. D) Dynamics and fate of mercury in northern terrestrial environments. Mercury is deposited on snow during late spring and can be transformed to methylmercury by bacteria in the snow and soils, which is a form that can be toxic to organisms. The importance of this flux in terms of health risks for northerners is still poorly known, but fluxes and methylation activity in the coastal environments were found to be relatively small. The investigation of Hg in tundra can serve as a model for other gaseous pollutants that may affect the health of the Arctic system, especially northern residents and communities.

5.6.2 Key messages

- Tundra ecosystems cover ca. 10-15 % of the Northern Hemisphere and have acted as important sinks for carbon over the past 10,000 years. In Canada, tundra covers nearly 30% of the country and contains 20% of the soil carbon of the country. Warming in these systems could change these systems from sinks to sources of carbon for the atmosphere.
- Coastal communities are dependent on services from tundra ecosystems for clean water, wildlife and other local food supplies. Temperatures have been rising since the end of the little Ice Age (ca. 1880) in the Canadian Arctic, and especially rapidly in the past 30-50 years. The quality of the ecosystem services will change with further increases in temperature over the next 50 years. For example, warming experiments and monitoring showed that there will be an increase in woody shrub species in most tundra areas and increased potential for northward movement of treeline. This will change the structure of the systems and will ultimately affect the wildlife and other resources used by northerners.
- Warming will result in improved reproduction of trees near the southern limit of the Arctic, and increase the potential for increased density of trees in the forest-tundra and the northward movement of treeline. Increased density of trees and shrubs in the forest-tundra will alter the regional energy balance and could result in warming of the same order as a doubling of atmospheric CO_2 concentrations.
- Tundra ponds are significant components of the landscape throughout the Arctic. These ponds play important roles in the carbon dynamics of the tundra landscapes, with carbon movement from the land to the water. Measurements of carbon fluxes from these ponds showed that they can be important sources of CO_2 and CH_4 to the atmosphere, and they must be included in regional carbon balance of tundra systems.
- Mercury and other persistent pollutants can be found throughout the Arctic and have potential health risks for northern residents. Fluxes of mercury from the atmosphere to the surface occur over wide areas of the Arctic during the late winter and early spring (mercury depletion events). These events can deposit important amounts of Hg in the snow where it may be methylated into bio-available forms. The importance of these fluxes of Hg in northern environments is still poorly known, although they were found to be relatively small.

5.6.3 Objectives

The central objective of this project was to determine the effects of environmental variability and change on terrestrial ecosystems of the eastern Canadian coastal Arctic along the South-North transect from southern Hudson Bay to northern Ellesmere Island. An improved understanding of responses in these ecosystems is necessary as they provide essential biological resources and services to northern residents and play important roles in transfers of carbon and pollutants to aquatic and atmospheric systems. Specific objectives were to:

- Measure responses in tundra ecosystems to climate variability and change along the latitudinal transect of the Eastern Canadian Arctic using a combination of long-term monitoring and experimental manipulations;
- Reconstruct historical climate patterns using dendrochronological techniques on both tree rings and stem growth patterns of the circumpolar dwarf shrub, *Cassiope tetragona*, and examine the reproductive potential of trees at the southern edge of the Arctic;
- Determine the carbon dynamics in a range of tundra pond systems;
- Measure the dynamics of mercury in terrestrial environments of the eastern Arctic.

5.6.4 Introduction

The total land area beyond treeline in the circumpolar Arctic region is approximately 7,567,000 km^2, with 33% in Canada (ACIA 2004). Tundra ecosystems cover nearly 30% of the landmass of Canada and contain between 30 and 40% of the soil carbon of the country, or approximately 10 % of the soil carbon on the planet (Tarnocai 1999). Terrestrial ecosystems in the Arctic play important roles in the global climate system as heat sinks (through permafrost, snow, and ice) and as carbon stores (ACIA 2004; Chapin et al. 2005). They provide living resources for communities throughout the North, and they are also stores of airborne pollutants; hence, they play important roles in human health and culture. Tundra and taiga ecosystems are expected to respond strongly to the predicted climate warming, although there will be regional differences. In various regions of the circumpolar Arctic there have been noticeable changes in: permafrost temperature leading to increased melting of ice-rich permafrost (ACIA 2004); species composition and abundance of tundra vegetation (Chapin et al. 1995; Sturm et al. 2001; ACIA 2004; Hill and Henry 2007); and in carbon

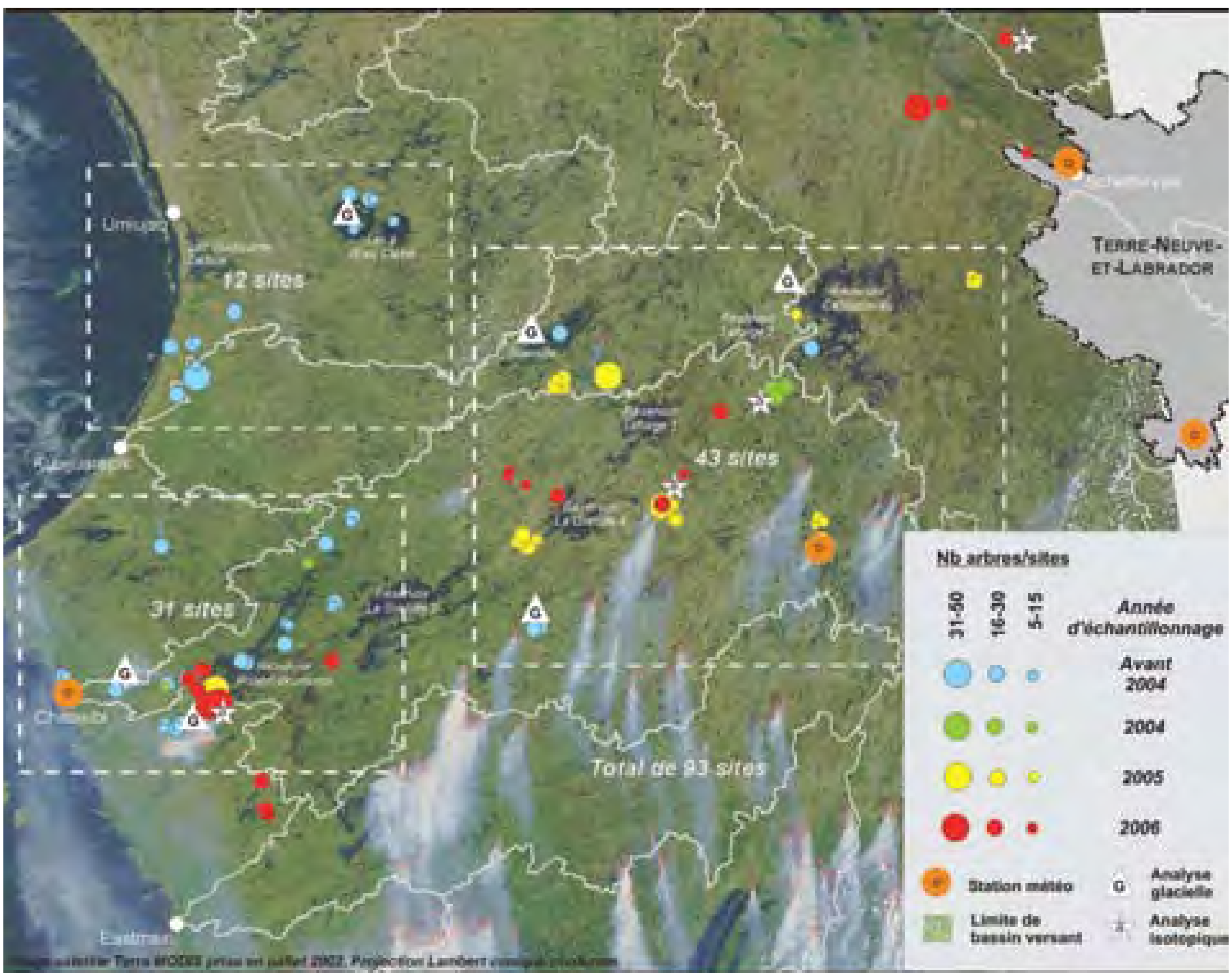

Figure 1. *Sampling area that for climate reconstruction using diverse tree-ring analyses.*

fluxes (Welker et al. 2004; Oberbauer et al. 2007; ACIA 2004). These changes will affect feedbacks between the tundra ecosystems and the climate and human systems. Improved understanding of the role of high-latitude ecosystems in the climate system requires a concerted research effort focused on geographical variation in processes controlling land-atmosphere and land-water exchanges, species composition, and ecosystem structure. This project was designed to examine some of these aspects in coastal tundra ecosystems along the broad latitudinal transect from southern Hudson Bay to northern Ellesmere Island.

5.6.5 Activities

A) Responses of tundra systems to climate variability and change:

The long-term experimental warming studies established at a coastal lowland site at Alexandra Fiord, Ellesmere Island were used as the main site for the studies of vegetation change in response to increased temperatures. The experiments were started in 1992, with open-top greenhouses established in seven different plant communities along moisture and exposure gradients. These studies are part of the International Tundra Experiment (ITEX). The greenhouses increase growing season temperature by 1-3 °C (Klady 2006). Routine measurements were made of the temperature and moisture conditions, and the phenology and growth of the major vascular plant species in each of the experimental plots. Vegetation change in response to warming and differing snow regimes (addition and removal) in a heath community were studied. Measurements of species composition and abundance were made using standardized methods developed for ITEX and have been combined with measurements made in previous years. A study on the reproductive responses of tundra plants to the warming experiments with measurements made of seed production and quality of the major species was completed. Collected seeds were germinated under field and laboratory conditions. The effect of warming on the composition of the soil seed bank was also determined by germinating seeds in shallow soil samples taken from the experimental plots. In addition, the study included the first measurements of seedling survival in High Arctic tundra in the experimental plots.

Studies were also made of the responses of tundra plants and systems to ambient changes in climate over the past decades. In 2005, net primary production of wet sedge tundra at Alexandra Fiord was measured in the same sites and by the same methods used in a study conducted from 1980-1984. Changes in climate over the same time period were determined from analysis of climate data from the site and from the High Arctic Weather Stations at Eureka and Resolute. A study on the analysis of phenology and growth data of the common tundra plant *Dryas integrifolia* monitored at a Low Arctic site (Baker Lake) and a High Arctic site (Tanquary Fiord) since 1994 was completed. Another successfully study completed involved the measurement of vegetation development and the role of biological soil crust on the recruitment of vascular plants in recently deglaciated terrain at a High Arctic site on Ellesmere Island. The glacier at this site has been retreating rapidly in the past 30 years as evidenced from direct measurements made in the early 1990s and from examination of historical air photos. In 2007, villages in Nunavik were visited to begin a study on vegetation change using TEK and permanent plots. These visits formed the basis of an IPY project to measure production of important plants (e.g. berries) and the changes in shrub cover.

B) Reconstruction of historical climate from dendrochronology methods and potential for treeline movement:

Variation in seed maturation is one of the most important mechanisms by which northern forests will respond to anticipated climate change. Cones of black spruce (*Picea mariana*) were collected to examine the potential for sexual reproduction

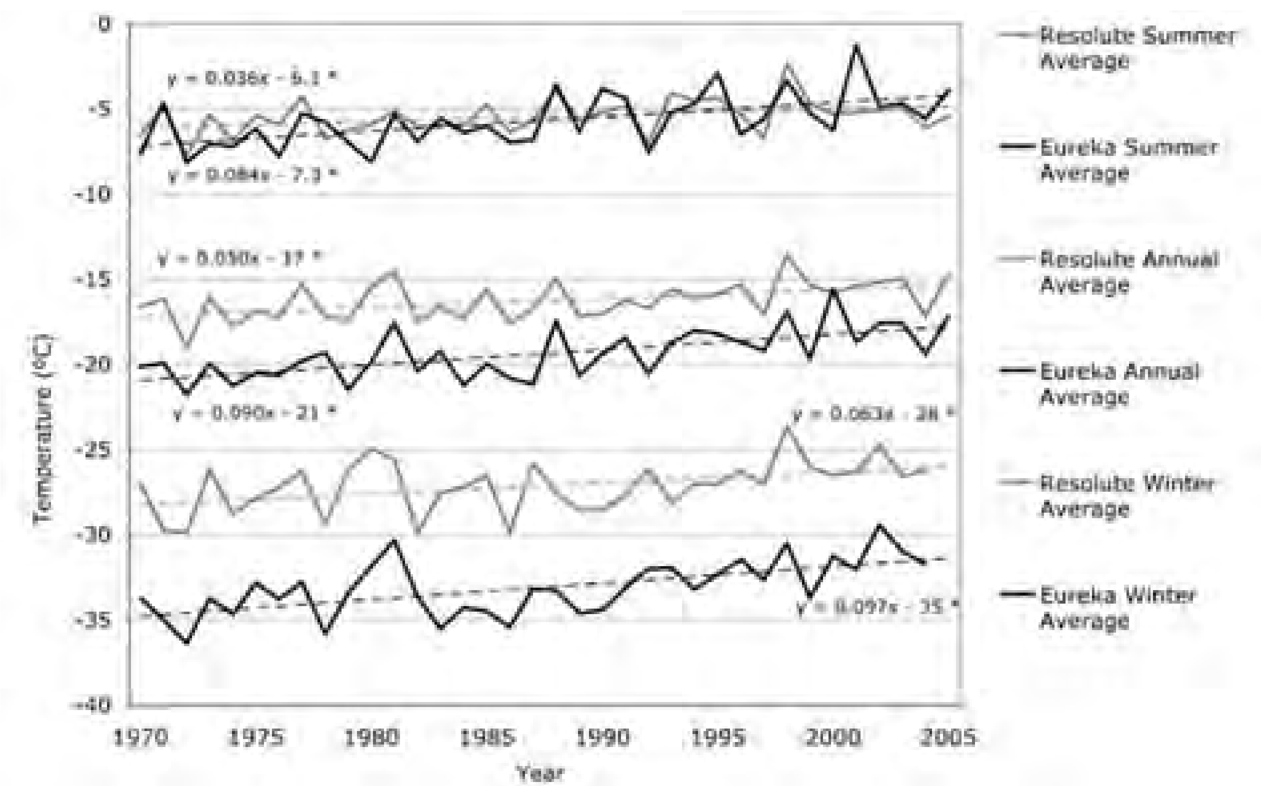

Figure 2. *Average summer, annual and winter temperatures since 1970 at Resolute and Eureka. Linear regression equations are shown. * = p<0.05 (from Hill and Henry 2007).*

throughout its range in Canada and along gradients in northern Quebec. Meunier et al. (2007) showed the relationship between climate (growing degree days) and seed maturation in black spruce at the continental, regional and local scales in Boreal and SubArctic Canada. In addition, tree-ring samples were taken at more than 100 sites in the eastern James Bay-Hudson Bay region from field studies in each of the four years, with comparative measurements of tree growth rates using automated dendrometers to calibrate the records. This sampling encompassed the vast La Grande watershed, and covered an area of 320,000 km^2. Dendrochronological analyses were completed on these samples and the data were used in statistical models to reconstruct the past 1000 years in terms of spring water supply, temperature, snow depths and flood peaks (Figure 1).

Samples of the circumpolar dwarf shrub *Cassiope tetragona* (Arctic white heather) were collected throughout the Eastern Canadian Arctic in 2004 and 2005 to augment samples collected between 1998 and 2002. The annual growth increment of the stems and annual flower production were accurately measured and the measurements were used in standard statistical analyses for dendrochronology to relate the growth patterns to climate. Stable isotopes of oxygen and carbon were used to determine the relative usage of snow melt or rain water by the plant as well as to infer precipitation changes. Statistical models were developed to reconstruct temperature and precipitation patterns over the past 100 years in the High Arctic.

C) Carbon dynamics in thermokarst ponds:

In 2004, a preliminary study at three sites in Nunavik was completed (sites close to Whapmagoostui-Kuujjuarapik,

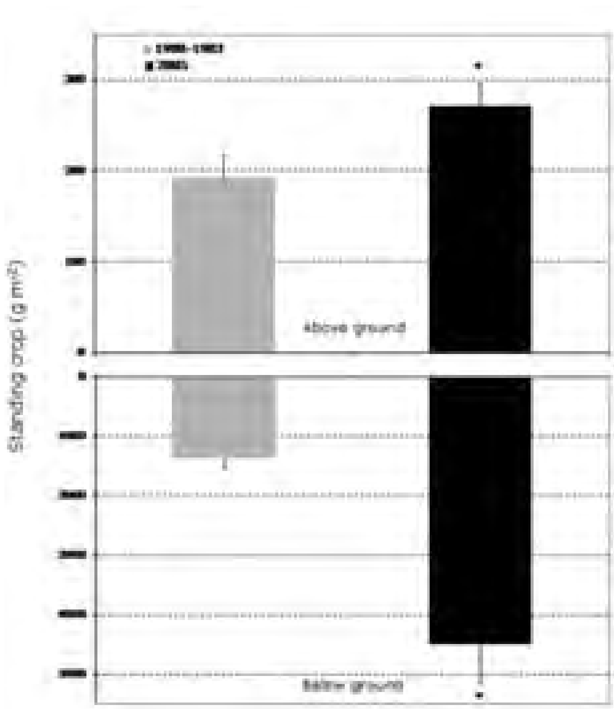

Figure 3. *Above and belowground biomass of wet sedge tundra sampled at the same site at Alexandra Fiord, Ellesmere Island, 1980-84 and in 2005. Significant differences ($p<0.05$) between sampling periods indicated by * (from Hill and Henry 2007).*

Umiujaq and Boniface River), where 28 ponds were sampled for basic limnological characteristics. In 2005, five ponds were selected to perform experiments on the transformation of dissolved organic carbon by microbial and photochemical processes. In addition, a site on Bylot Island was sampled to characterise limnological properties of thermokarst ponds located in the continuous permafrost region (18 ponds). Satellite image (Quickbird, multispectral) of a site located close to the village of Kuujjuarapik was also obtained to develop tools to estimate the dissolved organic carbon pool from remote sensing. In 2007, ponds located close to Kuujjuarapik (15) and on Bylot Island (18) were sampled for the planktonic and benthic microbial diversity and carbon cycling using stable isotopes and standard measurements of primary and bacterial production. During 2007, two additional instruments were used to measure gas fluxes at the water interface: a floating chamber connected to an EGM4 (PP-Systems) and an automated system for dissolved CO_2 measurements (Ray Hesslein prototype assembled by Hydro-Québec).

The limnological properties sampled include physicochemical profiling, dissolved concentration of CO_2 and CH_4 (discrete method, headspace injected in gas chromatograph), absorption and fluorescent properties of dissolved organic matter, total suspended solids, major cations and anions, chlorophyll a and other pigments (HPLC), planktonic microbes (bacteria, small phytoplankton cells) and bacterial production rates. Rotifers were also investigated to study diversity and dispersion of these small planktonic organisms. In 2007, primary production was measured using a ^{14}C method in addition to other measurements. DNA analyses of planktonic and benthic microbes (DGGE and cloning) and stable isotope analyses were performed.

D) Dynamics and fate of mercury in northern terrestrial environments:

A sampling campaign was completed at Kuujjuarapik during early spring 2004 in collaboration with many collaborators from University of York (UK) and University of Ottawa. Air-snow mercury cycling was investigated as well as halogen production during mercury depletion events (MDEs).

In spring 2005, sampling was conducted at Kuujjuarapik to detect and isolate psychrophilic microorganisms generating methylated mercury (MeHg) in northern ecosystems. Some bacteria strains (sulphate reducing bacteria and others) were isolated from snow and the waters of Rivière de la Grande Baleine. Mercury resistance was then tested for these bacteria and Hg mass balance was measured during growth. Microbial population stability was evaluated with spatial and temporal studies using polymerization chain reaction associated with denaturing gradient gel electrophoresis (PCR-DGGE). In

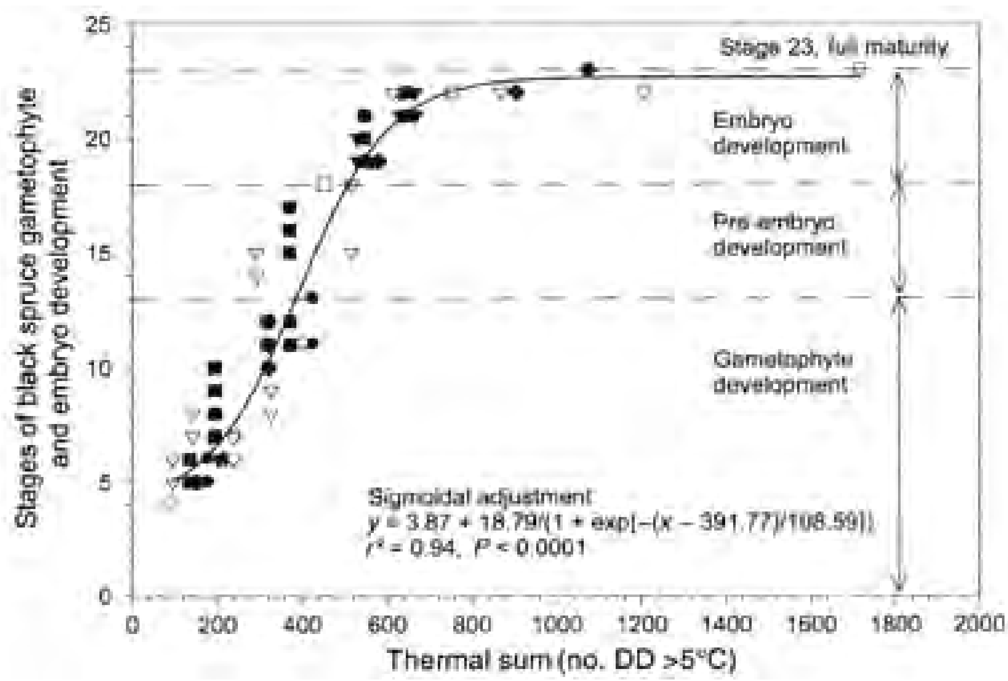

Figure 4. *Development of black spruce female gametophytes and embryos as a function of total degree days during the 2001 growing season at 11 sites within the Canadian boreal forest. Stages of development follow Sirois et al. (1999). The 11 sites were: (○) Gambo, (●) Fredericton, (▼) Boniface River (2 sites), (▽) Radisson (3 sites), (▪) Churchill (2 sites), (□) Zama, and (☐) Yellowknife (from Meunier et al. 2007).*

addition, research was initiated to investigate MeHg production from isolated Hg resistant bacteria strains and to evaluate their possible impact on biogeochemical cycling of Hg in northern ecosystems.

Also in 2005, another study was conducted in the Hudson Bay region onboard the *CCGS Amundsen* icebreaker. The specific objectives were: to measure and survey total gaseous mercury (TGM) along the cruise track in the Arctic; to measure mercury speciation during the cruise (atmospheric mercury chemistry); to measure the mercury gradient (deposition/evasion); to quantify mercury in sediments and water at various locations in the Arctic; and to apportion potential sources of mercury in the whole Arctic.

Field research continued at Kuujjuarapik during summer 2006, with a field experiment conducted to study the fate of mercury in tundra. A multi-faceted intensive field campaign on mercury was conducted. Mercury fluxes as well as mercury concentrations in many samples of air, water, and vegetation were collected.

In 2007, continuous measurements of TGM and ozone were made in Kuujjuarapik during spring and summer. Data analyses on the TGM and ozone time series (seven years) were completed. Two other projects started regarding Hg in sediments and GHG surveys in the vicinity of Kuujjuarapik.

Field research on Hg dynamics was also completed. During the 2004 and 2005 seasons, soil cores were sampled from wetland areas around Churchill for measurements of the distribution of Hg and other elements and sulphur reducing bacteria, which are believed to be responsible for methylation of Hg. The analyses of these cores were completed. In 2005, a continuous

Table 1.

	RE	RS		
SPECIES	REPRODUCTIVE BIOMASS	CUMULATIVE GERMINATION	PEAK GERMINATION	GERMINATION RATE
Combined response	S +* F +	+*	n/a	+ –
Shrubs				
Dryas integrifolia	S+* F -*	+*	+*	+*
Salix arctica	F-S+** F-F +			
M-F 0	+*	+*	+*	
Forbs				
Papaver radicatum	S +*	+	+	+
Oxyria digyna	S +	–	–	–
Draba spp.	n/a	+	+	+
Graminoids				
Festuca brachyphylla	S 0 F +*	+*	0	+*
Eriophorum angustifolium	S + * F +	+*	+*	+
Luzula spp.	S +* F +*	+ –	0	+ –
Carex misandra	S – F +	0	0	0

Table 1. *Increases (+) or decreases (–) in reproductive effort (RE) and reproductive success (RS) of fresh seeds (collected in 2004) in response to experimental warming at Alexandra Fiord, Ellesmere Island. '0' indicates no effect, 'n/a' not available. 'S' seed biomass, 'F' flower biomass, 'F-' female, 'M-' male. * $p \leq 0.05$.*

mercury sampler was established at the Churchill Northern Studies Centre to follow changes in atmospheric Hg through the year. In 2006, a study was initiated focusing on the delivery of carbon and mercury to Hudson Bay from the surrounding Lowlands in the Churchill region. Water sampling was carried out in selected water bodies and waterways in the lower region of the Churchill River watershed. Samples were collected at locations where hydrometric stations had been established. Samples were collected over a range of water level and flow conditions over the course of the summer. Water samples were analyzed for a wide variety of constituents: dissolved organic carbon, Coloured Dissolved Organic Matter by spectrophotometer, cations (Na^+, K^+, NH_4^+, Mg^{+2}, Ca^{+2}), anions (Fl^-, Cl^-, Br^-, NO_2^-, NO_3^-, SO_4^{-2}, PO_4^{-2}), trace metals, total mercury, and methyl mercury. Suspended sediment samples were analyzed for total suspended solids, organic carbon, total nitrogen, ^{137}Cs and ^{210}Pb. Flow data at the time of sampling was used to determine the loading of water constituents. At the time of sampling, in-situ measurements were taken of water temperature, pH, dissolved oxygen, oxidation reduction potential, electrical conductivity, and total dissolved solids.

5.6.6 Results

A) Responses of tundra systems to climate variability and change:

The research at the experimental sites at Alexandra Fiord showed that even relatively small increases in temperature can have a positive effect on seed production and quality in most of the important tundra plant species (Table 1) (Klady 2006). Most species across the sites showed increased biomass of flowers and seeds (reproductive effort) in the warmed plots. Seeds from

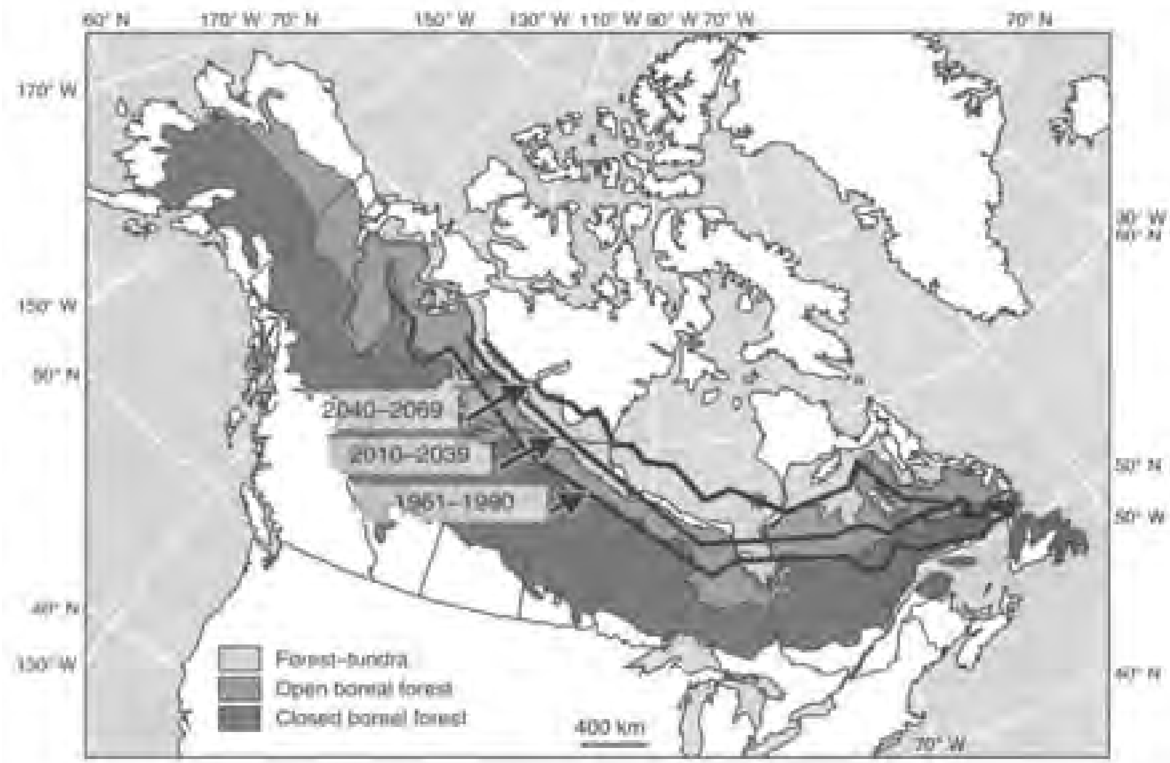

Figure 5. *Mean position of the 800 Degree Day isoline for the 1961-1990 reference period along with estimated positions for the periods of 2010-2039 and 2040-2069 calculated using base data obtained from GCM models (from Meunier et al. 2007).*

warmed plants had greater rates of germination than those in unwarmed plots. However, there were important differences between sites, with plants in mesic sites showing the greatest responses. In addition, warming continued to cause earlier flowering (5-12 days) and increased growth in plants that were followed throughout the experimental period. Initial analysis of the germinable seed bank also show a positive effect of warming on overall germination rates, with differences between the composition of the seed bank and the extant vegetation.

Analysis of climate data from Alexandra Fiord and the permanent weather stations at Eureka and Resolute, showed that over the past 35+ years this region of the High Arctic has warmed by ca. 0.7°C per decade in annual average temperature (Figure 2) (Hill and Henry 2007). There has been greater warming in the winter, with temperatures increasing by ca. 1°C per decade. Overall, both aboveground and belowground biomass had increased significantly over the 25 year period (Figure 3) (Hill 2007). The increase was considered as a response to the warming since ca. 1980, as annual variation in net primary production was found to be insignificant over the period from 1980-1984, despite large differences in annual climate. Responsive genera included *Carex*, *Eriophorum*, *Dryas* and *Polygonum (Bistorta).*

There were also large variations in annual thawing degree-days and precipitation at both Baker Lake (low Arctic) and Tanquary Fiord (High Arctic). In addition, the seasonal and annual mean surface temperatures were generally well above the 1971-2000 normals. *Dryas integrifolia* showed a strong

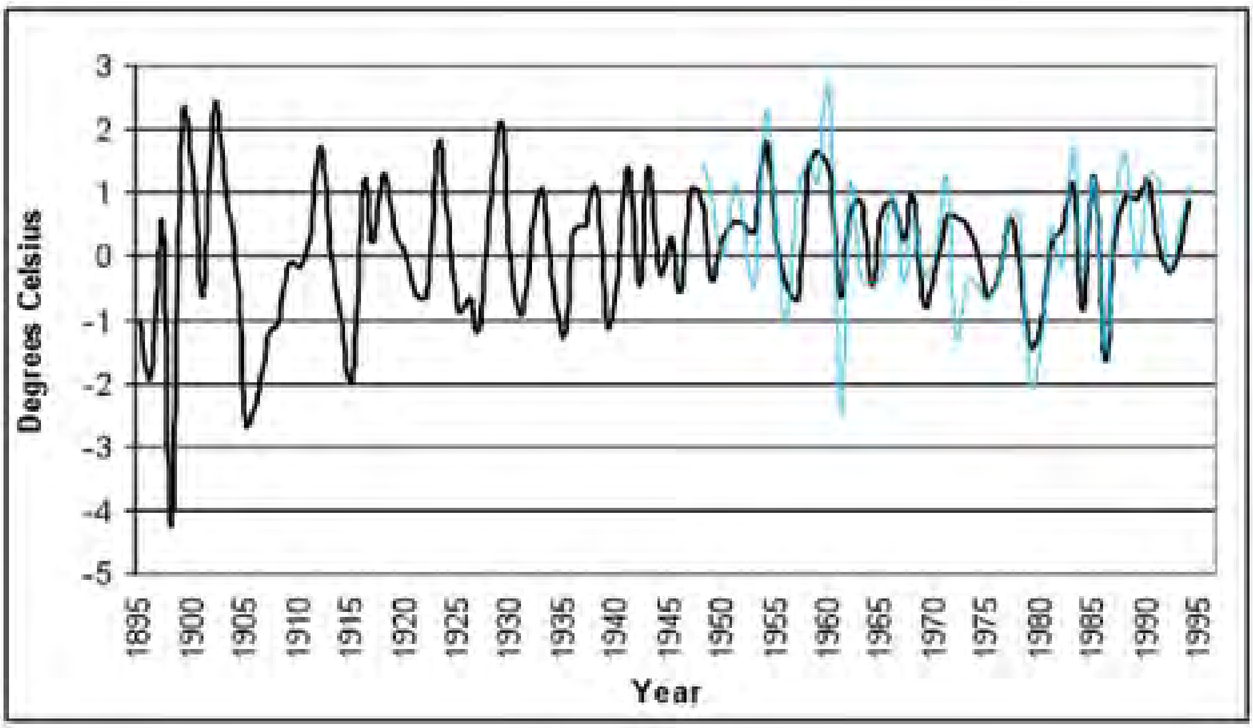

Figure 6. *Observed (blue line) and reconstructed (black line) July-September average air temperature for Alexandra Fiord, Ellesmere Island. Reconstruction covers the period of 1895-1994 (from Rayback and Henry 2006).*

phenological response to climate variability. Onset of budding varied by nearly 20 days among the years at both sites. The date of first bloom at Tanquary has advanced by more than 10 days since 1994, but has not changed significantly at Baker Lake. The thawing degree days (TDD) between the flower bud and fruiting stage was relatively constant among years at both sites. While the onset of flowering was triggered by snowmelt at Baker Lake, accumulated heat in June was the main control at Tanquary. Inter-annual variations of reproductive effort of Dryas were important and governed by different climatic factors at the two sites. Inter-annual variations of reproductive effort were synchronous among plants of a site and to some extent, between populations of the two sites separated by 17 degrees of latitude.

The study of vegetation development at the glacial foreland on Ellesmere Island showed that the biological crusts were associated with rapid colonisation by vascular plants within 36 m of the glacier (<20 years following glacier retreat) (Breen and Lévesque 2006; Breen 2006). Plant densities in the crusts were more than three times those of the surrounding areas. Crusts did not increase seed retention or germination compared to bare soil; however, they significantly improved the nutrient status of the substrate. Species dominant in later successional stages (e.g. the shrubs *Salix arctica* and *Dryas integrifolia*) had a higher density in crust, suggesting that their successful recruitment and/or maintenance is associated with the presence of crust (Breen and Lévesque 2007). The heterocysts (N-fixing cells of cyanobacteria) and chlorophyll a (estimate of biomass of photosynthetic organisms) in crust samples from the glacier chronosequence were also quantified to test plant performance in relation to microbial activity.

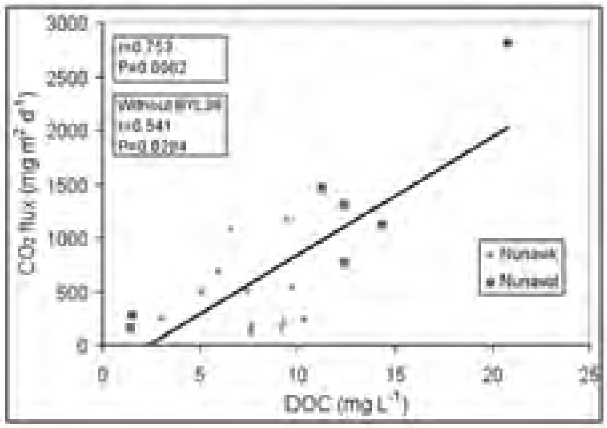

Figure 7. *Preliminary correlation between CO_2 fluxes (floating chambers) and DOC concentration, implying that DOC is having either a direct effect on fluxes (carbon source for respiring microbes and photolysis) or an indirect effect on light availability and oxygen profiles (from Dupont et al. unpublished data).*

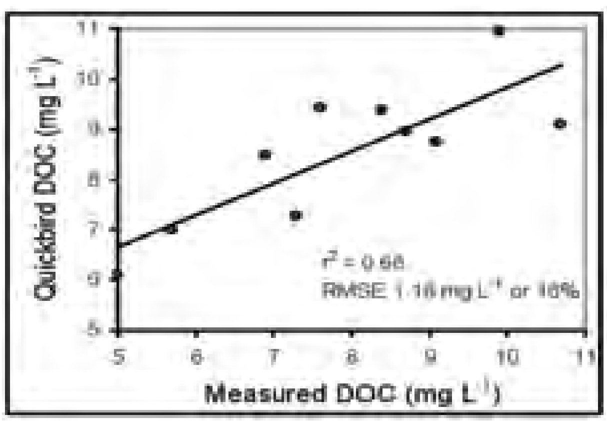

Figure 8. *Relationship between DOC estimated from satellite imagery (n=10) and in situ measurements using the multivariate model (n=25) (from Laurion et al. unpublished data).*

B) Reconstruction of historical climate from dendrochronological methods and potential for treeline movement:

The results confirm the 800-940 growing degree days (>5 °C) (GDD) thermal sum threshold necessary for the complete maturation of black spruce embryos at several populations distributed across the total range of the species. Along the regional South-North climatic gradient, the percentage of germination can be predicted by a sigmoid function of the accumulated growth degree days that reach a plateau at around 800-940 GDD (Figure 4). At the local scale, once the 800-940 GDD threshold is attained, variations in the percentage of seed germination are associated with inter-tree differences and local site factors (thickness of organic matter, density, tree height, tree age, fetch). During spring, cold enclaves are created by the presence of the hydroelectric reservoir. The seed germination percentage in these enclaves varied from 0.6 ± 0.7 to 14.9 ± 19.1, compared to 22.7 ± 15.1 for a site not exposed to the reservoir, which is the equivalent to the germination percentages for sites located 1-3 degrees of latitude northwards. These data suggest that the potential for black spruce regeneration increases strongly beyond the 800 GDD isotherm evoking the possibility that Arctic forest density may increase with the anticipated climate warming (Figure 5).

Two growth and two reproduction chronologies, ranging from 80 to 118 years long, were developed from each of two populations of *Cassiope tetragona* sampled from Alexandra Fiord, Ellesmere Island (Figure 6). Multiple regression models were used to develop a 100-year-long (1895–1994) reconstruction of July–September average air temperature that explained 45% of the climatic variance in the instrumental record (Rayback and Henry 2005; 2006). The reconstruction revealed an increase in summer temperature from; 1905 to the early 1960s, a cooling trend from the mid-1960 to the 1970s, and an increase in temperature after 1980.

C) Carbon dynamics in thermokarst ponds:

There was a large variation in optical and limnological conditions in thermokarst ponds: e.g. Kd, the attenuation coefficient for visible radiation, ranged from 1 to 7 m^{-1} in 2007. They are often stratified and hypoxic at the bottom (especially in Nunavik), and have an active microbial food web (in 2006 in

Nunavik, bacterial abundance ranged from 1 to 111 × 106 mL^{-1}; bacterial activity ranged from 204 to 840 pmol leu L^{-1} h^{-1}) (Breton 2007). Almost all ponds were over-saturated in CO_2 and CH_4 (at the surface of ponds in 2005, CO_2 ranged from 86 to 10381 ppm; CH_4 ranged from 1 to 64), indicating that these systems act as a source of carbon to the atmosphere (Figure 7). Dissolved gas concentrations were significantly lower in Arctic ponds (Bylot Island) compared to subArctic ones (average of 875 ppm of CO_2 compared to 1932 ppm, respectively in 2005). However in 2007, dissolved CO_2 concentrations in Arctic ponds appear much lower, possibly linked to a drier summer. In these ponds, fluxes ranged from -856 (uptake of CO_2) to 2802 mg CO_2 m^{-2} d^{-1} (average of 73 mg m^{-2} d^{-1}). Hence, these systems were not always a carbon source to the atmosphere, but a sink of carbon, at least at time of sampling (July). Discrete gas measurements including CH_4 and other pond characteristics were also analyzed and validated.

Satellite imagery was used to estimate the concentration of dissolved organic carbon (DOC) and total suspended solids (TSS) in ponds from Nunavik sites (2006). The multivariate statistical model (canonical correlation analysis) gave reasonably good accuracy in the estimation of DOC (Figure 8).

D) Dynamics and fate of mercury in northern terrestrial environments:

Total mercury (THg) concentrations in snow samples increased after MDEs. THg levels ranged from 1.18 - 2.41 pg L^{-1} prior MDEs (January to February) to 1.99 - 12.09 pg L^{-1} in March and April when episodic MDEs occurred (Figure 9) (Poissant and Pilote 2003; Constant et al. 2007). No significant correlation was observed between THg and MeHg snow concentrations. In early spring (March), when air temperature was below the freezing point, MeHg snow concentrations correlated significantly with sulphates (SO_4^{2-}) and chlorides (Cl^-) levels, suggesting an atmospheric source. Hence, MeHg, SO_4^{2-} and Cl^- snow peaks were observed when the air masses arriving at the sampling site originated from northern Hudson Bay. Interestingly, snow MeHg concentrations also followed a significant diurnal cycle, with weaker concentrations observed early in the morning. However, in late spring (April-May), when the air temperature became warmer, the snow MeHg concentrations were best predicted with bacterial total heterotrophic counts and filterable solid material. In these warm conditions, insignificant correlations were obtained between snow MeHg and SO_4^{2-} or Cl^-.

An intensive field campaign to measure the Hg flux at the air-surface interface of different substrates including air-water, air-moss, air-rock and air-sand was conducted using a dynamic flux chamber (DFC) method and micrometeorological techniques. The air-moss Hg flux was measured by both methods and showed that the moss acts as an Hg sink (Banik et al. 2006). A diurnal pattern in Hg flux was observed with the lowest deposition during the afternoon hours.

These results indicated that marine boundary layer was not very active in regard to mercury chemistry during the cruise period in 2005. Hg speciation measurements indicated very little reactive mercury production in the whole Canadian Arctic survey. Total gaseous mercury gradient measurements suggested active air-to-water gas exchange trends. Mercury concentration in sediments and water were between 0.015-0.087 ng/mg and 0.25-0.62 ng/L, respectively and the largest concentration were observed at estuary locations (Mackenzie and Nelson Rivers).

5.6.7 Discussion and conclusions

A) Responses of tundra systems to climate variability and change:

Results from warming experiments showed that tundra plants and ecosystems respond strongly to even small increases in temperature. The increases in rates of phenology and growth

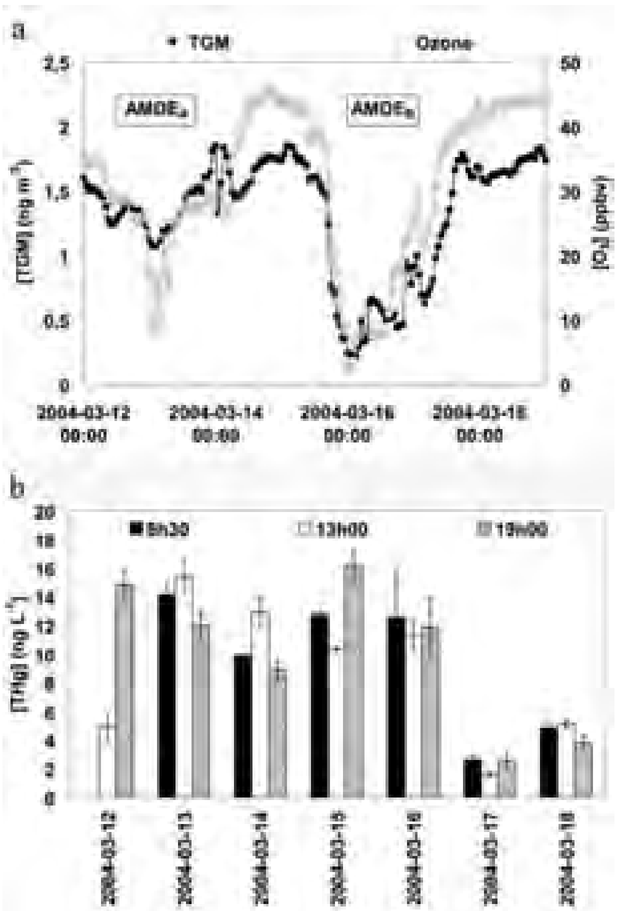

Figure 9. *Mercury depletion events in Kuujjuarapik (a) and mercury concentration in snow samples (b) measured during winter 2004 (from Constant et al. 2007).*

have been found in similar experimental studies across the tundra biome (Arft et al. 1999), and confirm the results of advances in phenology for *Dryas integrifolia* in the High Arctic. The increased reproductive effort and success of nearly all species measured in the warmed plots indicates that there is strong potential for increased density and extent of vegetation through recruitment by seed. This is especially important in the High Arctic, where there is room for expansion of vegetation in the bare areas in polar deserts and semi-deserts (ACIA 2004; Klady 2006; Breen and Lévesque 2006).

Changes in the composition and abundance of species in the warming experiments indicated that tundra ecosystems will likely become dominated by woody species as the climate warms. Greater shrub cover has been noted in some areas of the Low Arctic, notably Alaska (Sturm et al. 2001) and the changes in shrub cover across the Canadian Arctic still need to be examined. Changes from an herbaceous to woody-dominated tundra will have implications for wildlife species, with changes in forage for herbivores, and for the carbon and energy balances. Greater shrub cover will decrease the reflectivity of the surface (albedo) and increase absorption of solar radiation, which will contribute to warming. Calculations by Chapin et al. (2005) showed that a conversion from herbaceous to shrub tundra result in warming that is in the same range as doubling the CO_2 concentrations in the atmosphere.

The climate of the Arctic has warmed considerably over the past 50-100 years (ACIA 2004; Hill and Henry 2007). Responses to the warming have been noted in many systems (ACIA 2004) and we have measured some of the first responses in terrestrial systems of the Canadian High Arctic. Advances in flowering date of *Dryas integrifolia* and the significant increases in net primary production of wet sedge meadows (Hill and Henry 2007) are clearly attributable to the general warming over the past 30 years. The warming increases the length of the growing season, with earlier snow melt and later freezing noted in many Arctic areas (Hinzman et al. 2005). While increases in net primary production in tundra systems can be expected, the effects on the carbon balance will not be straightforward. Changes in species composition and abundance, especially increases in abundance of woody species, could lead to greater absorption of CO_2. However, warmer soil temperatures and greater thaw depths are likely to lead to greater soil respiration rates and losses of CO_2 from tundra systems (ACIA 2004; Mack et al. 2004; Welker et al. 2004; Oberbauer et al. 2007). In addition, changes in soil moisture with melting permafrost will strongly affect the vegetation development and carbon balance of these systems.

B) Reconstruction of historical climate from dendrochronology methods and potential for treeline movement:

Warming along the southern edge of the Arctic will increase the potential for recruitment of tree species, such as black spruce. Results showed that the isotherms for development of mature seeds are likely to move northward by as much as 1° of latitude with each 1° C in average annual temperature. This will result in an increase in density of trees in the northern boreal forests and especially in the forest-tundra. The change from tundra to forest has important implications for other components of the ecosystems, and for feedbacks to climate. Wildlife species dependent on or endemic to tundra regions (e.g. muskoxen, certain migratory birds, etc.) will lose habitats as the treeline moves northwards. As with conversion of herbaceous tundra to woody tundra, the change from forest-tundra to forest cover will result in enhanced warming through decreases in albedo and increases in absorption of solar radiation (Chapin et al. 2005).

The reconstruction of summer temperatures over the past century in the High Arctic from retrospective analysis of *Cassiope tetragona* showed similar patterns to those found using other proxy indicators, such as diatoms and pollen in lake cores and analyses of ice cores (Gajewski and Atkinson 2003). The most recent warming period appears to be a combination of warming and shifts in the Arctic Oscillation (Welker et al. 2005). The plants show an increase in the use of rain water over snow melt water, matching a general increase in rainfall over the past couple of decades (ACIA 2004, Welker et al. 2005). Further analysis of *Cassiope* samples throughout the Canadian and circumpolar Arctic will allow examining the regional patterns in climate changes since the end of the Little Ice Age (Rayback and Henry 2005).

C) Carbon dynamics in thermokarst ponds:

Thermokarst ponds are important features of circumpolar tundra landscapes. In areas of ice-rich permafrost it is expected that more ponds will develop as rates of melting increase over the coming decades. This research provided some of the first measurements of the carbon dynamics of these systems and clearly showed these ponds are important components of the carbon balance of tundra landscapes. While some ponds in the High Arctic acted as sinks for carbon during parts of July, most systems were supersaturated and losing CO_2 and CH_4 to the atmosphere. There was a good correlation between the level of dissolved organic carbon in the ponds and the flux of CO_2 from the ponds. Better correlations for variables that are more directly coupled to gas production are expected. A particularly interesting result was that newly formed ponds had high DOC concentrations and higher fluxes as compared to older ponds colonized with dense microbial mats and lower DOC. These mats likely photosynthesize efficiently enough to reverse the CO_2 flux, turning the ponds into carbon sinks. Further research is necessary to verify these observations from a few ponds.

The strong correlation between direct measurements of DOC in ponds and proxy measurements from satellite imagery provided a very useful avenue for research on the regional carbon status and balance of tundra pond systems. This area of research was expanded as part of an IPY project.

D) Dynamics and fate of mercury in northern terrestrial environments:

The flux of Hg to the snow surface during MDEs was confirmed by the measurements done; however, the importance of this flux and the methylation of Hg (MeHg) in snow, soils and sediments of northern terrestrial systems are still poorly understood. Results suggested that MeHg in subArctic snow could be (1) transported from marine areas and (2) produced in situ by biotic and/or abiotic processes. Sulphate reducing bacteria are responsible in soils and sediments for Hg methylation. These bacteria use this mechanism to remove Hg^{2+} from their environment, while non-specific enzymatic reactions are implicated for some strains (e.g. *Desulfovibrio desulfuricans* LS). Measurements of MeHg in water and sediments along the cruise track in 2005 indicated very low concentrations and fluxes of Hg throughout the coastal waters. Investigations into the dynamics of Hg in northern systems were pursued to evaluate the health risk posed by Hg in these regions.

5.6.8 Acknowledgements

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5.7 Climate Impacts on the Sentinel Species Arctic Char (*Salvelinus alpinus*) in Northern Canada (Project 2.7)

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5.7.1 Abstract

Arctic char (*Salvelinus alpinus*) have been an important food resource for the Inuit for centuries, providing critical vitamins and other essential nutrients required for healthy living. The combination of ubiquity, ease of capture during migration and nutrient value has made the Arctic char an indispensable part of the Inuit lifestyle. In more recent times, abundance has supported limited commercial fisheries that have enhanced economic opportunities for northerners. The prevalence of Arctic char in all aspects of Inuit life, therefore, makes conserving and sustaining existing populations of the utmost importance. Recently, the Arctic Climate Impact Assessment (2004) noted considerable gaps in scientific and traditional understanding of Arctic char population biology including the capacity of populations to respond to changing climate and the necessary background information to adequately manage populations in the face of changing northern circumstances. Coupled with concerns about the sustainability of Arctic char stocks, are concerns about the potential for increasing Hg contamination resulting from temperature-driven changes in critical lake habitats. Put simply, Inuit communities wanted to know: 1) will char populations continue to exist with abundance levels suitable for local exploitation, particularly as climate change begins to affect the Arctic, 2) can existing populations be enhanced and 3) will the fish be safe to eat? The paucity of long-term or repeated site studies on Arctic char populations, however, hampers the ability to predict and validate answers to these questions, thereby complicating the important task of anticipatory community-based management. In light of the above, this project set out four interlinked research components, nested within the overall ArcticNet Integrated Regional Impact Studies (IRIS) framework of climate change in the Canadian Arctic. Research components sought to redress information deficiencies by drawing on existing traditional ecological and scientific knowledge to construct an information fish database pertinent to Arctic char management, experimenting with population enhancement methods, validating scientific understanding of climate change effects through the study of Arctic char thermal ecology, exploring the connections between food web and habitat use and mercury contamination and by developing methods for analyzing existing fishery Arctic char fishery data for evidence of climate change impacts.

5.7.2 Key Messages

- This project has helped meet the need for accurate, community-based information on key fish species through development of a GIS database for use in local management of Arctic char in Nunavik. The project also used community gathered information from Paulatuk, NWT, to demonstrate how climate-related variations (temperature and precipitation) were related to locally observed variations in size and weight of Arctic char. Studies of mercury (Hg) in Arctic char completed by this project were the largest to date in the Arctic or subArctic in terms of numbers of lakes sampled.
- Study results showed that what the fish eat (diet) controls Hg levels in fish, but that the geology and water chemistry of the lake basin in which the fish live also plays an important part in determining Hg levels.
- This project also developed new techniques for studying how climate affects fish by perfecting techniques allowing researchers to accurately determine the actual water temperatures fish lived in on the basis of a chemical analysis of the earstone (otolith). Connections found between thermal effects and growth suggested strong links to climate and increased growth rates as lakes warm.

5.7.3 Objectives

- **Component 1** addressed practical issues of Arctic char management of specific interest to Inuit participants as they pertain to management database construction and the collation of information for management purposes.
- **Component 2** utilized monitoring data collected from Arctic char management projects, including Component 1, to improve and validate scientific understanding of the potential consequences for Arctic char biology of Inuit introduction of char to new rivers and climate change impacts along north-south latitudinal and east-west longitudinal gradients.
- **Component 3** examined linkages between possible climate change and the contaminant loadings of Arctic char that may require mitigation of current management and use strategies for Arctic char resources.
- **Component 4** addressed issues related to temporal change in the biological characteristics of a western Arctic char fishery related to climate variability, thereby enhancing scientific understanding of trends and the rates of change occurring in the biology of Arctic char.

5.7.4 Introduction

This research project was proposed as a means of linking pro-active Inuit led initiatives in Arctic char management and enhancement with scientific research on the large-scale impacts of climate change on existing Arctic char populations. The combination of interests has facilitated addressing both regional (i.e. population-specific) and national (i.e. effects of climate and mercury contamination) questions and has produced significant information. The research, therefore, included Inuit-driven research questions (e.g. effects of climate on specific stocks) and cutting-edge scientific analysis (e.g. otolith thermometry, mercury analysis). The general aim of the project was to help Inuit organizations better collect and understand data pertinent to the management of the Arctic char stocks upon which Inuit communities heavily rely. Overall, the research conducted significantly improved the data and information base available to local community managers and helped facilitate the construction of local impact models.

5.7.5 Activities

Arctic char research work began in 2005/06 as a pilot project funded by the project on Water Quality, Supply and Indicators of Change (presented in section 5.2). Analysis of existing data for Paulatuk and Nunavik indicated good potential for Conceptual Work. This was a preliminary to a larger scale project that took place in Nunavik, Nunatsiavut, Nunavut and the Inuvialuit region on the life history characteristics, phenology and biological characteristics of char populations in relation to climate variability. In 2006, this collaborative project was funded, and it consisted of four inter-linked components.

Component 1 focused on practical issues of Arctic char management of specific interest to Inuit participants and has concentrated on the design and implementation of a GIS database for enhanced char management in Nunavik. In 2006 a GIS database of char streams was created in Arcview by local high school students with the assistance of technical experts in the Nunavik Research Centre. The creation of the database was a specific objective of the proposal. Work continued in 2007 to include graphical images (photos and drawings) relevant to the status of Arctic char streams within the database. The data acquisition portal, available from any Internet linked computer, was used to update the information in the database. As a pilot information project, digital images of Nunavik char from multiple sites were recorded for uploading into the database. This aspect of the work was twinned with an IPY project examining char biodiversity (Reist, Power, Dempson et al. "Climate Variability and Change (CVC) Effects on Char in the Arctic"). In conjunction with the GIS database construction, continued proof-of-concept work management work carried out on a single enhancement project on the Nepihjee River (2006-2007), northeast of Kuujjuaq. Specifically, an aerial photo survey of the Nepihjee River complex was completed (2006) and the removal of a large boulder obstructing the water course in the fish ladder. Work on monitoring Arctic char migrations in the river and establishing standardized monitoring protocols was inhibited by abnormally high flows in 2006, but was completed successfully in 2007. Finally, the completion of a before-and-after Arctic char introduction study of the food web of the lakes in the Nepihjee system was completed with a complete faunal survey of an over-wintering lake in the Nepihjee system. The

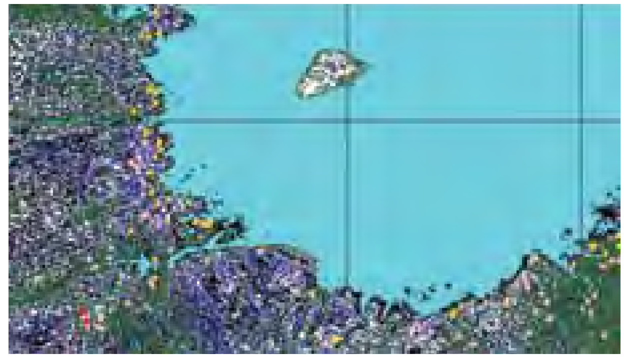

Figure 1. *GIS plot of stream potential.*

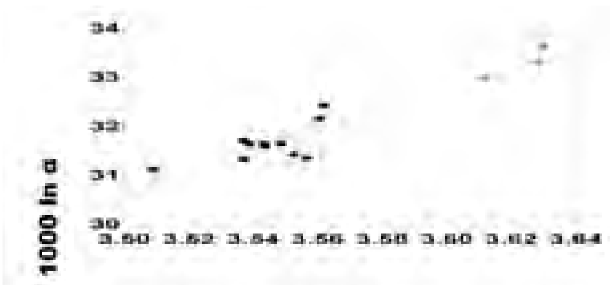

Figure 2. *Estimated fractionation equation showing relationship between mean 1000lnα (fractionation) and a water temperature scale used to estimate the fractionation equation for Arctic and Brook char. Mean values of the samples obtained from each study site on a single sampling date are plotted as black (Brook char) or gray (Arctic char) circles. Standard errors are plotted as vertical bars.* $r^2=0.90$.

surveys was completed by local Inuit, and fish tissue samples matching those of archival samples obtained under the auspices of 1999 sampling program conducted before Arctic char were introduced were provided to the University of Waterloo for isotope analysis. Stable isotope analyses of the 2007 field samples were completed.

Component 2 aimed at utilization of monitoring data collected from Arctic char management projects, including Component 1, to improve and validate scientific understanding of the potential consequences for Arctic char biology of Inuit introduction of char to new rivers and climate change impacts along north-south latitudinal and east-west longitudinal gradients. Three initiatives were carried out under component 2. The first entailed the assembly of data for an analysis of variations in size-at-age along a latitudinal gradient in the eastern Arctic. Work was completed and all necessary data sets (both fish and environmental) have been assembled for analysis. Consistent with the initial objectives of project application and the IRIS regional framework, the data sets have been divided into regional subsets (western and central Arctic, eastern Arctic and Quebec/Labrador) for latitudinal and longitudinal gradient analysis. Results of the analysis are given below. A complementary longitudinal analysis using the western and central and eastern Arctic subsets of data has been undertaken. This analysis twinned with IPY conducted research also examining spatial differences among populations of Arctic char. A detailed regional analysis of differences in age-at-maturity as it relates to environmental variation, which has implications for reproductive potential and the impacts of climate change on population abundance was completed. A detailed temporal variability study was also completed using the Nain data set. This study was a complement to the initially proposed spatial variability studies, but enhanced abilities to comment directly on likely climate change impacts and greatly improved abilities to address issues of direct concern for policy makers and communities.

A 3rd initiative under Component 2 was the study of thermal adaptation in Arctic char as evidenced in the past. Samples for this study were assembled and stable isotope analysis of thermal habitat requirements along a latitudinal gradient have been completed. Data sets initiated were extended in the summer of 2007 in connection with an IPY funded project (Reist, Power, Dempson et al. "Climate Variability and Change (CVC) Effects on Char in the Arctic") and were used to spatially expand the analysis (e.g. inclusion of Baffin Island, improved sample resolution in Labrador, further High Arctic samples).

To further improve abilities to correlate the biological responses of Arctic char to environmental variation, a dedicated micro-mill was employed for sub-sampling from the annual otolith growth rings. This laboratory equipment was used to enhance the understanding of inter-annual variation within selected Arctic char populations (e.g. Nain) where detailed biological data sets exist. Canadian data obtained and analysed have permitted the development of collaborative linkages with Norwegian labs examining similar questions of spatial and temporal differences in thermal habitat use. This collaboration allowed comparing methods and exchanging

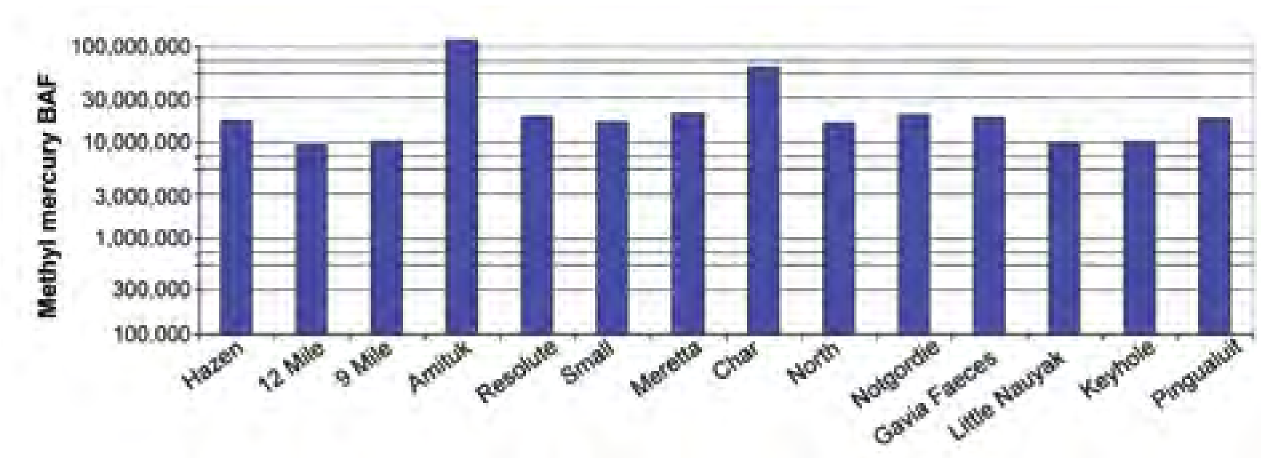

Figure 3. *Bioaccumulation factor for methyl mercury (concentration in char muscle divided by concentration in water) in Arctic char from 14 lakes based on collections in 2006 (2007 for Pingualuit).*

data. This equipment has also considerably improved the abilities to collaborate with project Component 3. Overall progress on Component 2 has been excellent, with more scientific results than expected having been achieved.

Component 3 aimed at establishing linkages between climate change and the contaminant loadings of Arctic char that may require mitigation of current management and use strategies. Fieldwork related to his project on mercury was conducted in landlocked Arctic char, their food webs including juvenile char, and surface Arctic char that may require mitigation of current management and use strategies. In 2006 fieldwork related to mercury in landlocked Arctic char was conducted, their food webs including juvenile char, and surface waters and sediments, for six weeks at three separate locations, Kent Peninsula/ Cambridge Bay area, Resolute Bay and Lake Hazen. Samples have been analysed for total mercury and stable isotope ratios. Determination of total mercury and 30 other elements in adult char for lakes Resolute, Amituk and Hazen (N=40) were completed as part of the Northern Contaminants Program (NCP) and other Hg analyses were paid for by the Northern Ecosystem Initiative (NEI) and by Environment Canada internal funding. In 2007, detailed food web sampling of Lake Hazen and surrounding lakes was completed with the data used to extend the ArcticNet initiated study. Repeat sampling of 10 Resolute area lakes was completed (aided by Debbie and Philipoosie Iqaluk of Resolute Bay). Partnerships with NCP and IPY projects have provided valuable leverage to the ArcticNet funds and have facilitated the completion of a comprehensive Hg study twinned with initiatives completed under Component 3. Progress was excellent and results obtained have been reported to local communities.

Table 1.

YEAR	CHAR COUNTED
1999	230
2000	no fence
2001	250
2002	no fence
2003	500
2004	600
2005	1050
2006	no fence
2007	400

Table 1. Number of char ascending the fish-way since 1999.

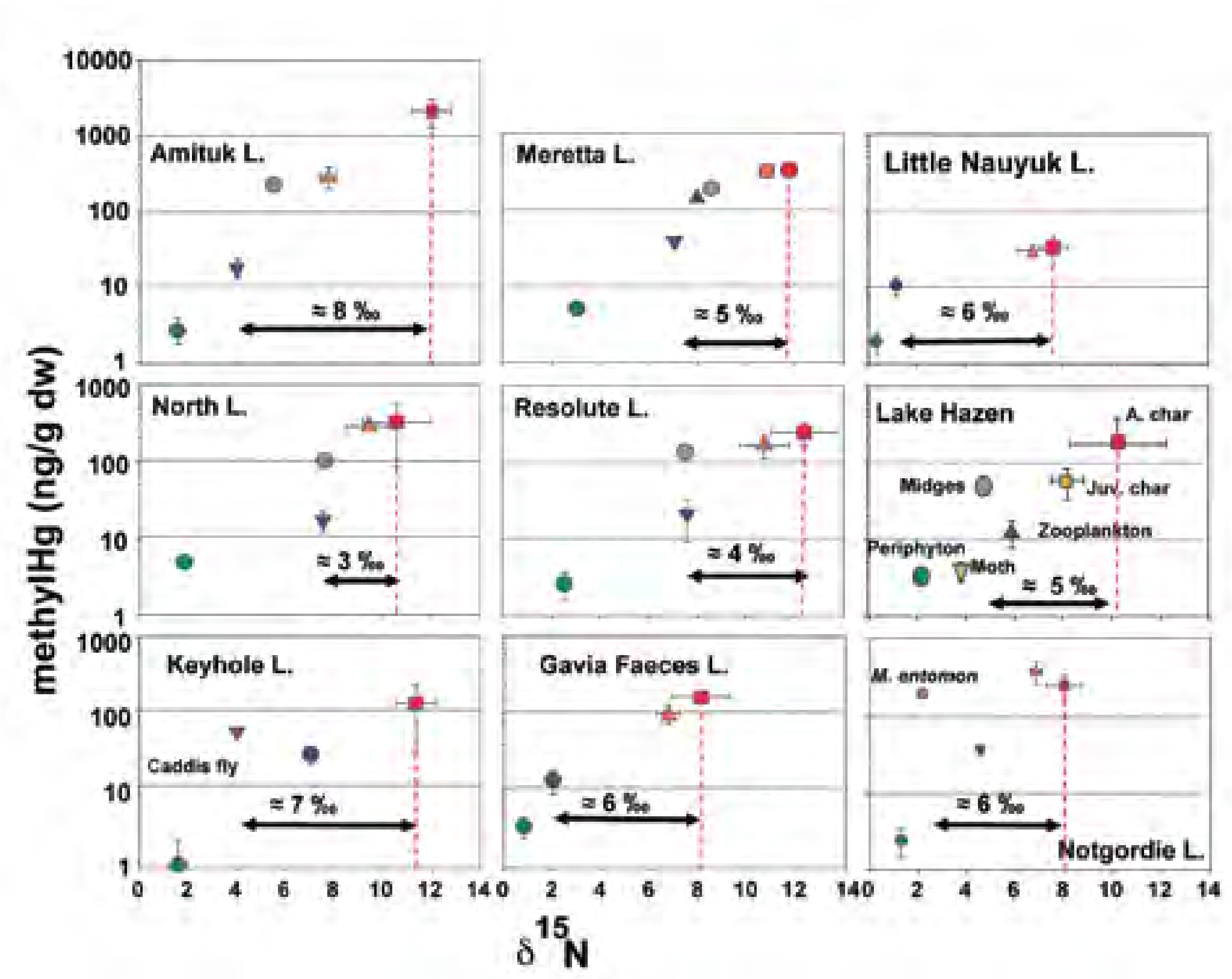

Figure 4. *Average [methylHg] (± SD) of food web components collected from 9 lakes is related to trophic level as indicated by $\delta^{15}N$ signatures. The length of the food web (from zooplankton to Arctic char) in each lake is shown with the horizontal arrows.*

Component 4 was to address issues related to temporal change in the biological characteristics of a western Arctic char fishery as it related to climate variability. A study aimed at under-standing the causes of temporal variation in the biological characteristics of Arctic char from the Hornaday River was initiated in collaboration with FJMC and DFO. Sufficient data were available from DFO and local Paulatuk fishers to complete a detailed analysis of the Hornaday River fishery. This component was completed in 2006.

5.7.6 Results and Discussion

Component 1:

In Nunavik more than 200 streams provide the Inuit with Arctic char. Increasing demands for country food have put pressures on the available supply and created the need for pro-active management to increase the supply of char. In 1999, a fish-way was constructed on the Nepihjee River near the river's mouth to allow Arctic char to pass around the falls that blocked

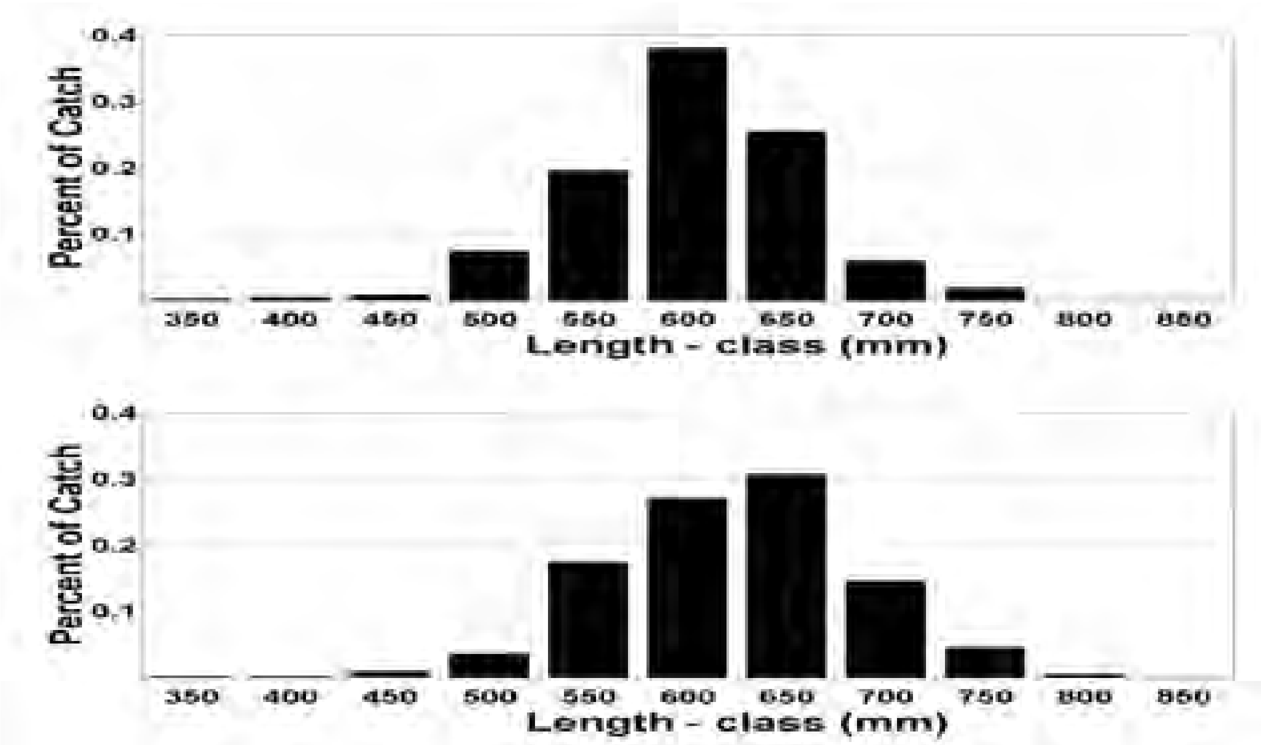

Figure 5. *Comparative length-frequency distributions of captured age 6 to 8 Arctic char from the Hornaday River from cold (top panel: 1979, 1981) and warm (bottom panel: 2000-03) years showing the effect of increased temperature on the size composition of the population. Distribution of means and variances differs significantly (P<0.05).*

upstream migration, thereby opening a productive river system to Arctic char colonization. Supported by a local hatchery and rearing programme, the number of char ascending the fish-way has been counted in some years since 1999 (Table 1) and shows a rising number of individuals in the populations. In addition to monitoring numbers, a sub-sample of all fish was measured to determine the length-frequency distribution. Water temperature and water levels were also monitored (Table 1). Counts of Arctic char were made at the counting fence at fish-way on Nepihjee River, 1999-2007.

An Arctic char data-base including the Nepihjee and other suitable Arctic char rivers in Nunavik has been developed as a management tool to better assess the status of Arctic char populations and to provide necessary biological information on Arctic char in a system-specific manner. The system rates all streams for char potential, noting whether obstructions to migration exist and there is potential for the introduction of char to the stream. The system combines both TEK (hunter) and scientific information. In 2007, data-base entries including all existing historical and available scientific information were updated. GIS plots of Nunavik can be created (Figure 1) that rate potential into categories denoting streams with potential for Arctic char introductions (orange), key areas of concern (red) and migration obstructions (gray). Community-based access through the Internet allows real time use and update. In 2007 a pilot project using digital photos of Arctic char harvested at Lake Duquet was initiated, with photos being incorporated into the database. Photos from other systems were and continue to be added to build a documented library of morphological variation in Nunavik Arctic char. The photos formed the basis of a morphological biodiversity study.

Component 2:

As a key to understanding possible linkages between climate and Arctic char population responses to climate variation oxygen stable isotope studies were undertaken. A key step in the study involved the development of a fractionation equation that facilitates translation of oxygen isotope measures into temperature, with temperature allowing inferences to be made about how variations in temperature may affect growth. A field-based fractionation equation for the *genus Salvelinus* was developed using a mixture of Arctic char and Brook char (*Salvelinus fontinalis*) otoliths obtained from sampling of young-of the-year fish. (Figure 2).

Studies demonstrated that species-specific fractionation equations useful for climate impacts prediction could be successfully estimated from field data. The combination of field collected otoliths and monitored water temperatures from sites across the range of the distribution of Arctic char and Brook char were used to estimate a statistically significant *Salvelinus* fractionation equation explaining 90% of the variation in the data. The equation permits the translation of otolith oxygen isotope values into temperature measures reflective of the environment inhabited by the fish. When compared to literature reported equations for other fish species the developed fractionation equation had a statistically similar slope but dissimilar intercept. Statistical similarities among fractionation equation slope estimates suggest a common otolith $\delta^{18}O$ incorporation response among fish species that may be interpreted as widespread equilibrium otolith $\delta^{18}O$ deposition. Statistical dissimilarities among intercept estimates question broad applicability of any single fractionation equation to all fish species and were interpreted as having biological meaning as a result of known differences in standard metabolic rates among species. Attempts to statistically cross-validate fractionation equations by predicting the water temperatures used in other fractionation studies indicated significant biases in the range of –7.9 to 6.7°C that preclude the broad use of any single fractionation equation for accurate thermal reconstructions for other than the species for which the equation was developed. Differences in equation intercepts and the prevalence of predictive biases do not support the conclusion of previous studies concerning the wide applicability and/or general accuracy of fractionation equations and suggest fractionation equations are best developed at the species- or taxon-specific (e.g., genus) level. Accordingly, accurate prediction of the impacts of climate change on Arctic char required special purpose equations as developed during this project.

However, when gathering samples to estimate a fractionation equation work has also shown the use of preserved otoliths would bias thermal history inferences in unknown ways, with the nature of inferential errors depending on the combination of preservative and species (Storm-Suke et al. 2007). The inclusion of ethanol or formalin preserved otoliths in the development of fractionation equations also bias results in ways that were not immediately evident unless the specifics of species life-histories (e.g., growth rate, relative ration) and otolith chemical composition were known. Accordingly, pilot-studies should be completed to determine the nature of possible preservation-related effects before museum specimens are used to reconstruct individual thermal histories, infer past climatic baselines or estimate fractionation equations (e.g. Høie et al. 2003).

Component 3:

Field work for this component was designed to develop baseline data with which to examine the question of whether climate warming is resulting in increased exposure of biota to mercury (Hg) in the Arctic. Increases in mercury concentrations in landlocked Arctic char are a concern from the point of view of contamination of the subsistence food supply in communities in the High Arctic and resulting consequences for human health. During 2005-07 landlocked char and food web samples were collected from lakes in the Kent Peninsula and Cambridge

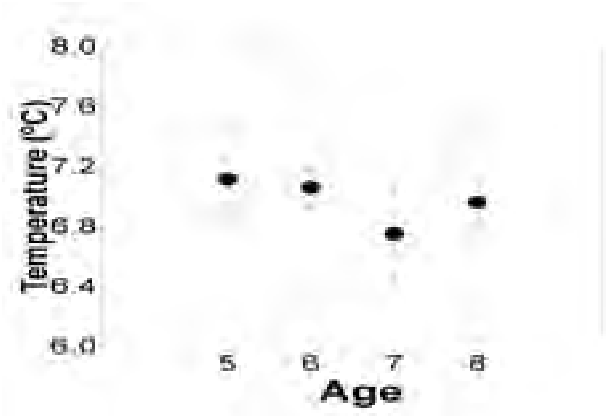

Figure 6. *Age-specific optimal temperatures for Hornaday River Arctic char as estimated from quadratic models relating length-at-age to mean summer temperature (°C). Mean estimated optima plotted as solid circles (●) plus or minus standard error. All pairwise comparison P-values from t-tests for significant differences between means were ≥ 0.40.*

Bay area, as well as on Cornwallis Island and in Lake Hazen in Quttinirpaaq National Park. Two Local Resolute Bay residents, Debbie and Pilipoosie Iqaluk, were hired for the month of July and part of August, each year for work on the collection and preparation of samples. Included were three lakes on the Kent Peninsula (Notgordie, Little Nauyuk, Gavia Faeces) as well as Keyhole Lake near Cambridge Bay, and 10 lakes on Cornwallis Island, Lake Hazen, and, in August 2007, lakes east of Lake Hazen. Also in May 2007, collection and analysis of char from the Pingualuit crater in Nunavik with the help of Inuit fishers were completed.

The estimated bioaccumulation factors of methyl Hg in char from lakes sampled in 2006 (Pingualuit in 2007) are shown in Figure 3. Very high bioaccumulation is evident (107-108) illustrating the extraordinary magnification of methyl mercury in these aquatic systems which have very low methyl mercury concentrations in water (0.01-0.02 ng/L). There were large lake to lake variations in the BAFs despite all lakes (with the exception of Meretta and Resolute Lakes) being isolated from any significant human activity. Lake and watershed area, or littoral zone area do not explain these differences. Factors such as warmer littoral zones and watershed soils/wetlands could result in greater methyl mercury inputs to the lakes.

Food chain length may also be a crucial factor affecting lake to lake variation of mercury and one that is also influenced by climate warming and this was investigated by determining methyl mercury concentrations food web organisms along with nitrogen stable isotope ratios. Average concentrations of methyl mercury in fish and food web organisms in 2006 are shown in Figure 4. The graphs show that food web length differs between lakes and these differences (up to ≈ 3‰) are near the δ15N enrichment factor for one trophic level of 3.4‰. Because methyl mercury biomagnifies in the food web, food web length affects mercury in the adult Arctic char. Shifts in abundance of zooplankton and chironomid midges due to greater open water, could therefore affect trends of mercury over time in the char.

This study of Hg in Arctic char and their food webs represented the largest study to date in the Arctic or SubArctic in terms of numbers of lakes and food webs sampled. Preliminary conclusions of this project component were: (1) $\delta^{15}N$ signature or fish size explain much of variability of [Hg] within populations, indicating that diet controls Hg delivery to adult char; (2) Available prey items may differ among lakes of different regions, resulting in variable [Hg], $\delta^{13}C$, and $\delta^{15}N$ signatures per region; (3) Zooplankton and phytoplankton do not fully explain isotopic signatures of adult char, indicating that other food sources are preferred by adult char; (4) Underlying geology and water chemistry of lakes may also play a significant role in influencing tropic status of the lakes and mercury bioaccumulation.

Component 4:

Mean length and weight characteristics of subsistence-fished Arctic char *Salvelinus alpinus*, available from 15 years of monitoring on the Hornaday River, NWT, were significantly influenced by among-year differences in local summer temperature and/or precipitation patterns. Environmental influences on mean length were age-specific, with temperature being the most important influence on younger (age-5) fish and precipitation being the most important influence on older (age-8) fish (Figure 5). Mean weight was positively influenced by precipitation only. Significant models of length-temperature relationships further indicated that larger mean sizes occurred in years when average summer temperatures ranged from 6.7-7.1°C (Figure 6). Increased precipitation positively affects nutrient export to the nearshore marine area, triggering age-dependent increases in both length and weight as a result of increased nearshore productivity. Correlations between inter-annual variations in weather-related environmental parameters and population biological characteristics (e.g. weight, length) suggest that the large-scale environmental changes expected of climate change will hold significant implications for Arctic char from the Hornaday River. Similar population-specific effects are likely to be exhibited in other northern Arctic char populations affected by climate-induced variations in year-to-year environmental conditions.

Work on the Hornaday and with fractionation studies (discussed above) has demonstrated the importance of the environment for Arctic char. Environmental influences on long-term phenological patterns in Arctic char (Berg 1995) and their biological characteristics (Power et al. 2000) have been reported previously. The findings here generally concurred with those of earlier studies in noting significant associations between stock mean length and weight characteristics and local environmental variation (e.g., temperature and precipitation). Age-specific differences in the importance of environmental influences on mean length were also found in the Hornaday study, suggesting that the importance of increasing length varied by life-period. Findings from studies on the Hornaday study, interpreted in the context of life-history strategies and requirements for the species, indicated clear environmental effects on the biological characteristics of Hornaday River Arctic char. Temperature and precipitation are the most important environmental influences on Arctic char as a result of their respective effects on fish metabolism and opportunity for acquiring surplus energy for growth. Climate change will affect both environmental variables. Changes in environmental variables will have varying impacts on different populations of Arctic char that depend on the magnitude and variety of trophic impacts that occur (ACIA 2004), and the specifics of population adaptation to existing environmental conditions. Arctic char, in particular, are known to be sensitive to minor changes in inhabited biotic and abiotic environments (Langeland 1995) and, therefore, are likely to show substantive variation in age-specific mean length and weight as a result of climate-induced environmental variation. To understand and maintain sustainable fisheries for Arctic char, appropriate management regimes must be developed to account for the effects of climate variation and change. Well-designed management regimes will rely on the availability of suitable long-term data. As this study has highlighted, there is value in long-term fisheries data and the extension of programmes in the Arctic to acquire matching fishery and environmental data to better understand the course of climate change effects on Arctic char and other key northern fishery resources are crucial.

5.7.7 Conclusions

Overall this study has demonstrated the need for accurate, community-based information on key fish species. Efforts being made by Nunavik communities to enhance and manage their local char stocks (e.g. Nepihjee River) form an important part of the strategy to ensure population sustainability. Integral to any successful management scheme is information. The developed GIS database will serve as a key tool for the active management of char systems in the face of both increased exploitation demand and perturbations likely to be caused by climate change. The community-based monitoring data from Paulatuk allowed a long-term study of climate-related impacts that yielded locally relevant results largely supportive of the conclusions of previous studies noting the impacts of temperature and precipitation on population-level characteristics. As these environmental variables are among the most likely to be significantly impacted by climate change, expected variations in local environmental conditions can now be used to make more accurate prediction of likely population level impacts on Arctic char. Use of otoliths collected from field studies in conjunction with this and other studies largely supported the results of previous laboratory work noting that when a relationship between otoliths and temperature is established for a species, analyses of otolith $\delta^{18}O$ provide a suitable proxy for the ambient temperatures experienced by fish (e.g. Campana 1999; Høie et al. 2003). Work here, however, has shown that differences in species physiology, however, imply the search for a common relationship describing oxygen isotope fractionation at all temperatures for all species is probably not realistic. Therefore, fractionation equations should be developed on a species or at least genus-specific basis where the specifics of life-history (e.g. temperature optima for growth) and physiology (e.g. metabolic rate) are known and may be accounted for. Broad use of fractionation equations not tuned to the physiology of the species of concern will result in substantive inferential error and their use in this situation should be avoided. This requires the use of purpose estimate fractionation equations for thermal reconstructions, which can now be performed with the use of the equation results reported above. With the use of an equation specific to Arctic char it is now possible to begin to accurately predict local climate change effects on Arctic char populations. Knowledge of the impacts of temperature and growth connect logically through improved understanding of lake mercury contamination dynamics. As work here has shown, size and diet control much of the variation seen within and among Arctic char populations. Connections between thermal effects and growth suggested strong links to increased growth rates and changing feeding habits as lakes warm. Although much progress has been made in understanding lake populations, information of sea-run Arctic char populations is still lacking. Future studies of Arctic char in the Arctic should expand to focus on this economically important food resource, using the mercury contaminant and otolith oxygen isotope analysis tools developed here for lake-dwelling populations, particularly as preliminary work with the sea-run Hornaday populations has indicated the likelihood of significant impacts.

5.7.8 Acknowledgements

We thank the numerous people who have contributed to the collection and archiving of the data over the years, particularly the fishers of Paulatuk for whom the effects of climate change on Arctic char are a critical concern, DFO field technicians (J. Babaluk, M. Shears, R. Wastle), and the Canada/Inuvialuit Fisheries Joint Management Committee.

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5.8 Climate Changes in Nunavik: Access to Territory and Resources (Project 2.8)

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5.8.1 Abstract

An ice monitoring program was developed in Nunavik to generate adaptation tools and strategies to support safe access to territories and resources and to enhance local adaptive capacity via participation in community-based monitoring activities. The Nunavik ice monitoring program brings together partners (northern communities, organizations and universities) having various perspectives and expertise on the issues of land, ice and resources in Nunavik. The ice monitoring program also brings together traditional knowledge and scientific knowledge linking data collected through semi-structured interviews, local ethno-cartographic interviews, ice monitoring activities and meteorological data gathered at weather stations. The partnership-based Nunavik ice monitoring program is an example of how communities and scientists can work together to understand the issues of climate change impacts in the North, and how local adaptive capacity can be developed through an integrated and cooperative research and monitoring process.

5.8.2 Key Messages

- A community based ice monitoring and research program was established in five Nunavik communities bringing together local experts and scientists to look at the impacts of climate change in trail access and use and human safety
- Current capacity to adapt with changing ice and climate conditions is supporting Inuit communities in being able to continue to access their territory and resources
- River mouths and new areas of open water were identified as key hazards for travel and hunting, and the near shore sea ice environment was mentioned as being potentially the most hazardous in the new climate conditions
- New quantitative indicators associated with environmental conditions and lake and sea ice formation were identified by bringing together Inuit knowledge and science

5.8.3 Objectives

The principal objective of this project was to help Nunavik communities to develop adaptation strategies based on traditional and scientific knowledge of the climate and environmental change and to provide tools which will help the communities face increasing challenges associated with accessing local territories and resources meanwhile ensuring human safety. The local land, freshwater and sea ice based trails are extremely important for the northern communities because they provide access to natural resources throughout the year. The specific objectives of the project were:

- to document the impacts of the climatic changes on the trails networks in Nunavik communities and the adaptations to allow the access to resources or human safety during displacements;
- to develop and lead a Community monitoring strategy for the trails safety; and
- to evaluate the potential impacts of the climatic changes on the access to the territory and the traditional resources by the means of climatic scenarios.

5.8.4 Introduction

It is projected that Arctic regions will be the most, and perhaps the first, affected by climate change (ACIA 2005). These changes will be experienced in terms of shorter winters and warmer summers (IPCC 2007). Such climate changes can affect the accessibility of local territories and resources for residents of Nunavik communities. For example, these new conditions will reduce, by several weeks, the freezing period during which it is safe to use winter trails, a situation which has already been noted by northern communities in the Northwest Territories, Nunavut and Alaska (Fox 2002). Several recent reports show that the impacts of climate change influence the access to the land and sea in Nunavik and Labrador as well where weather unpredictability and ice instability negatively affect the conditions and safety of travel and hunting activities (Tremblay et al. 2006). In addition to affecting human safety, these new conditions can change the timing at which certain areas are accessible during times of wildlife migration (Thorpe et al. 2002) and thus have impacts on socio-economic status, health through diet change, or culture and tradition via the potential abandonment of hunting and fishing activities. Consequently, these changes imply strong social and cultural impacts for Inuit living in the circumpolar North.

This project, developed in collaboration between the Kativik Regional Government and Trent University, was a research program carried out "in the North, for the North and by the North". This partnership based approach is essential to improve the adaptive capacity of northern communities. In this community based research and monitoring program, an active and qualified local researcher worked on the project in

Figure 1. *River mouth not frozen during the winter period, Salluit February 2007.*

Figure 2. *Ice monitoring station installed during the winter 2006-2007 near the Smith Island, Hudson Bay.*

each participating village (with the exception of Akulivik and Ivujivik where one local researcher was responsible for activities in both communities). The local researchers played a critical role in the project and maintained the link between the scientists on the team and the communities. They were true partners in the research process in the development of adaptation strategies and the collection of field and community data. Among other things, they were responsible for and led the organization and conduct of semi-structured interviews, leading local activities of the ice monitoring program and in providing information on the study to the local population. The principal goal in this approach was to ensure that the local researchers, and communities, adopted the project and took increasing levels of control and direction over the work in their own area as capacity was developed at the local level on these issues.

5.8.5 Activities

Since its inception, the Nunavik community based ice monitoring program has utilized semi-structured interviews, local ethno-cartographic interviews, ice monitoring activities and meteorological data gathered at weather stations. Semi-structured interviews and ethno-cartographic interviews were conducted by the local researchers in each of the participating Nunavik communities between the years of 2004-2006 of the study. This work was done to document local use of sea, freshwater and land based trails, how the trail conditions and use was changing, and the potential relationships to environmental change in the region. As well, increasingly dangerous areas along trails were identified. This work, via initial funding from the Climate Change Action Fund, Ouranos, and the Northern Ecosystem Initiative provided the foundation for the establishment of local ice monitoring programs in three of the five communities (Kangiqsualujjuaq, Umiujaq, and Kangiqsujuaq). Since funding from ArcticNet was received in 2006-7, this work has continued and expanded to standardize local ice monitoring measurements, include two other communities in the documentation of trails and trail use (Akulivik and Ivujivik), start monitoring in one additional community (Akulivik), gather and analyse meteorological data in these four monitored communities and continue the investigation of potential new indicators of ice safety for northern communities. Analysis has been done to investigate the relationship between local ice formation processes and key meteorological variables (in collaboration with analysts at Ouranos). This was strengthened via the purchase and installation of two mobile meteorological and sea ice measuring stations in cooperation with D. Barber's team. Local data collection in the three communities has continued each winter to measure and record sea ice conditions and to interview local experts to document qualitative perception of sea ice conditions and safety. This information was posted regularly for the community on a KRG website for the project which is becoming an information hub for Nunavik communities on this topic.

5.8.6 Results

Climate change impacts on the trail networks in northern communities:

The principal impacts of climate and environmental change on access to territories and resources observed and reported in Nunavik communities were associated with later winters and earlier spring which modify the duration of the frozen period and the ice dynamics. According to the experts interviewed in Nunavik communities, the most sensitive environment to the recent climate warming is the coastal zone, especially where the large rivers of Nunavik open into the ocean (Figure 1). These places can remain a significant hazard throughout the winter, but are particularly dangerous at the beginning of the winter and then once again in the spring. The lakes, which now freeze much later than before, do not appear to pose significant risks to human safety for Nunavik residents during winter. Once the ice is firmly formed at the beginning of the winter, it is generally safe until the spring period (with the exception of the areas at the mouths of rivers). The later accumulation of snow however, now more frequently documented in the region, can limit movement on the land significantly. Snow drifts and snow pack, sufficient for the use of a snowmobile, can arrive long after the freeze-up of lakes and delay individuals' access to the territory. Moreover, in spring time it is common that the snow on the trails disappears well before the break-up of lake ice.

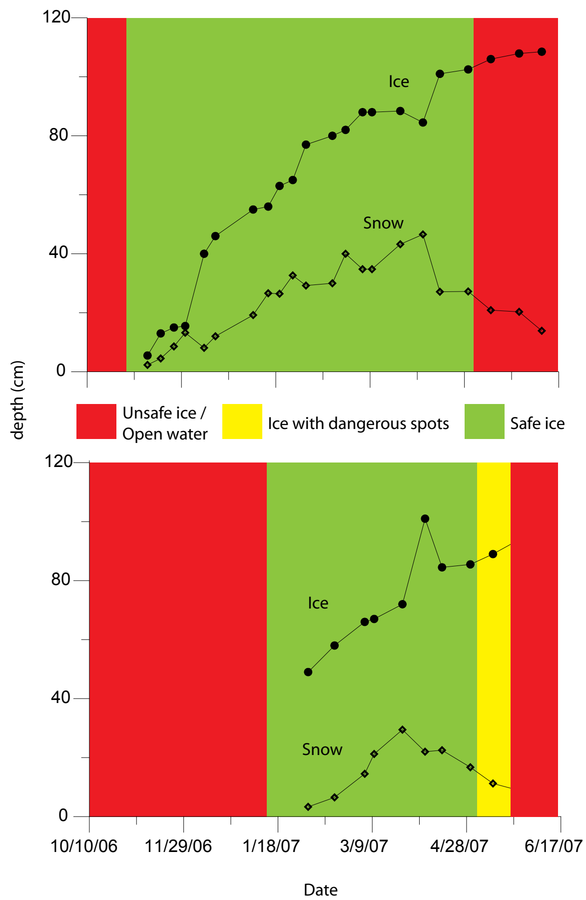

Figure 3. *Sea and lake ice monitoring in Kangiqsualujjuaq, winter 2006-2007.*

Inuit observations on the impacts of climate change

"Before, the snow and the land were solid enough to travel on safely. Because of global warming the situation has changed. They [harvesters] have to be more careful and the routes that are taken during the winter are sometimes not frozen, especially the rivers".
Quitsak Tarriasuk, Ivujivik

In spring time, however, lakes present more numerous risky areas. The higher snow accumulation on lake changes the ice dynamics. The melting of the snow cover increases the water accumulation. The mixture of water and snow is particularly a problem for the snowmobilers whose snowmobiles get stuck.

Development of a community-based monitoring strategy for ice trail safety and use in Nunavik communities:

The main objective of the ice monitoring program was to increase the community's capacity to collect, understand, deliver and use local information related to climate and environmental change. The ice monitoring program was active in four of the five communities involved in the project. The 2006-2007 season represented the third ice monitoring season for Umiujaq, Kangiqsujuaq and Kangiqsualujjuaq and the first season for Akulivik. The community-based monitoring strategy for ice safety gathered information from ice and snow measurement at strategic locations along the trail network of each community, local perception from interviews on the trail quality and weather data (data from the Centre d'études nordiques (CEN) at Laval University and the ice monitoring stations established in cooperation with the University of Manitoba, Figure 2). The weekly information on sea and lake ice environments was used to develop new, community driven climate indicators of ice development and ice break-up and to establish threshold levels in association with local perception information that supports the identification and understanding of whether or not the ice is safe for travel. The development of climate indicators relevant to ice formation was done in collaboration with the climate change consortium Ouranos and data from the 2006-2007 season were analysed. The results presented below come from the local research results in each community.

The 2006-2007 ice monitoring data from Kangiqsualujjuaq showed that the ice in lake environments appeared around the end of October (Figure 3). The local observations noted that ice was not formed in the center of lakes and that these environments were considered safe to travel on only in mid-November. The short interviews conducted during the end of the winter season with local experts allowed to document that the lakes were not safe for travel on as early as the beginning of May. The local observers noted that the lakes began to flood at this time. Moreover, at the same time, most of the inland trails were affected by melting snow making lakes inaccessible. The meteorological data analysed with Ouranos helped to determine the key variables and conditions that lead to safe or unsafe ice conditions in the lake environment.

The 2006-2007 sea ice monitoring in Kangiqsualujjuaq showed that the ice appeared around mid-January and was considered safe for travel within a few days after (Figure 3). The short interviews conducted throughout the winter allowed to document that the currents were sources of danger even before break-up of the ice. Some information from local observers noted open water in several areas at the beginning of May, mainly in areas near strong currents. Despite the presence of open water in several places, the coastal area was considered safe for snowmobile travel until the beginning of June. The meteorological variable analysis with Ouranos also allowed the determination of the key weather conditions and variables that lead to safe or unsafe sea ice conditions.

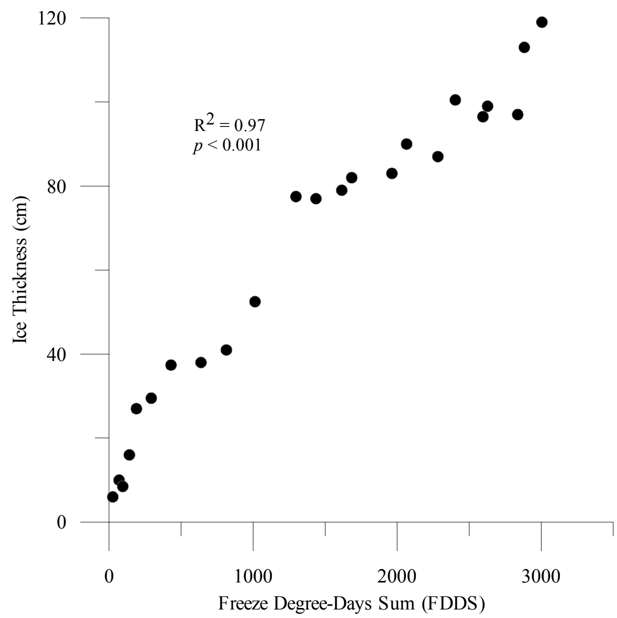

Figure 4. *Freeze Degree Sum. The 2004-2005 and 2005-2006 seasonal analyses demonstrated the reliability of the Freeze Degree Sum for the lake ice development.*

Previous analysis of local perceptions of trail conditions, ice and snow measurement and weather data for 2004-2005 and 2005-2006 identified a climate indicator that is significantly associated with ice development and safety. The sum of freezing degree days (the sum of the mean daily temperatures below zero) appears to be a strong indicator of ice development in lake environments. The results of this analysis showed a strong relationship between the sum of freezing degree days and ice thickness ($r^2 = 0.97$; Figure 4). This variable could be used to determine the threshold at which the ice may be considered safe for snowmobile travel. Analysis of the most recent monitoring season data (2006-2007) should allow more in depth investigation of this and other relationships for sea ice formation and safety.

Individual and community adaptations to climate changes and cooperatively develop strategies with communities to adapt to these and future changes:

The interviews conducted under the study have documented that the residents of these five Inuit communities (Akulivik, Ivujivik, Kangiqsualujjuaq, Kangiqsujuaq and Umiujaq) already use adaptation strategies in response to the environmental changes they have experienced. Alternate trails are used during the winter to avoid the riskier or inaccessible areas. The results of this research showed that alternate trails are often used to bypass thinner sea ice or open water areas (in all five Inuit communities) or because of a lack of snow cover on ice at the beginning of the winter season (Ivujivik and Akulivik). Although this adaptation provides access to the territory, trail users will spend more time to reach the intended harvesting location. Navigation and communication equipment are also more popular today than in the past according to local respondents. Global Positioning Systems (GPS) and satellite phones are now used by some hunters. Some information on trail quality is also more regularly communicated on the local radio to make this information more accessible to other travelers and hunters.

Several adaptation tools have been developed (or are in development) by this research team. The cartographic interviews have allowed the gathering of information on the main trails used in each community, the position of local 'risky areas', the alternative trails and others significant information. It is expected that this information is of particular interest and aid (based on community perspectives) to younger and less experienced hunters. These maps are now available for the communities and others on our web site (http://climate-change.krg.ca/) and on a CD.

The interviews with hunters and elders have allowed the documentation of Inuit knowledge and perceptions of ice dynamics for sea and lake environments during the freeze-up and break-up periods. The traditional knowledge on ice dynamics is a significant piece of the development of effective adaptation tools that can help hunters and travelers to learn more about their local environment and which cues to pay attention to when in these areas. The traditional knowledge supports or informs, among other things, the evaluation of ice conditions considering the weather/climate and environmental conditions.

The identification of future adaptive strategies in the communities remains to be conducted. Various climatic scenarios, developed in collaboration with Ouranos, were presented in the participating communities (winter 2007-2008) and methods for adaptation (if required) were discussed. The climatic scenarios (ranging from severe negative impacts to minimal change) should guide the identification and development of future adaptation strategies.

5.8.7 Discussion and Conclusions

The principal impacts of climate change and variability on access to territory and resources in Nunavik reported are associated with later onset of winter and earlier arrival of spring which modifies the duration of ice coverage and which also influences ice dynamics in the North. The most sensitive environment is the near coastal regions, especially where the large rivers of Nunavik empty into the ocean. These locations can remain a significant hazard throughout the winter, but are particularly dangerous at the beginning of the winter and throughout the

spring. Once the ice is firmly formed at the beginning of the winter, it is generally safe until late spring (with the exception of river mouths). The late arrival of snow-cover can however limit movement on the land. Snow drifts and pack, sufficient for the use of the snowmobile, can arrive long after freeze-up of the lakes and delay residents' access to hunting areas. The lakes may present also major problems for travel safety and hunting during the spring time. The higher snow accumulation on lakes during the winter changes the ice dynamic. The melting of the snow cover increases the water accumulation on the ice. The mixture of water and snow is particularly a problem for the snowmobilers who their snowmobiles can be stocked. As frequently, the snow covering winter trails disappears early in the spring before ice break-up, again limiting access to certain inland areas.

Access to local areas and resources is essential to maintain the economic, social and cultural health of Nunavimmiut. Several recommendations were presented to support safe access to resources and territory. The users of snowmobiles must be particularly alert at or near these areas identified as being increasingly 'risky' and must begin to learn their locations. Moreover, reinforcing the practice of hunting and traveling with at least one other companion using another machine, particularly for long trips, should be favoured to avoid the potential of mechanical problems creating safety issues in a changing ice environment. Experienced hunters in this study also mentioned that it should be advised to also bring navigation and communication equipment, such as a GPS and satellite telephone when possible. There is a need to continue to encourage residents to heck weather forecasts before going off on the land or sea in order to avoid bad weather conditions such as blizzards. Snowmobile drivers should try to use more frequently o often, terrestrial networks for travel to avoid, when possible, the hazards associated with the near shore ice environment. The use of snowmobiles in coastal areas, at least in the newly formed ice zones, should be done with extreme caution following examination of the thickness of the ice in several locations. Further, particular attention should be paid to travel near river mouths throughout the winter. Additionally, Inuit traditional knowledge is exceptionally rich and constitutes an important part of adaptive capacity for hunting and travel safety in the face of climate change and variability. The transmission of this knowledge should be supported in whatever way possible especially with future and young hunters. The inclusion of traditional knowledge in school curriculum could contribute to educate future hunters more prepared to face a changing environment as in the North.

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Spring Leads

Artworked by Stephen D. Petersen, an ArcticNet postdoctoral fellow.

PART IV: ArcticNet Publications

This section compiles the refereed ArcticNet scientific articles, book chapters, books and monographs, within all four themes, published 2004 to 2008. This list is updated on the ArcticNet website: www.arcticnet.ulaval.ca

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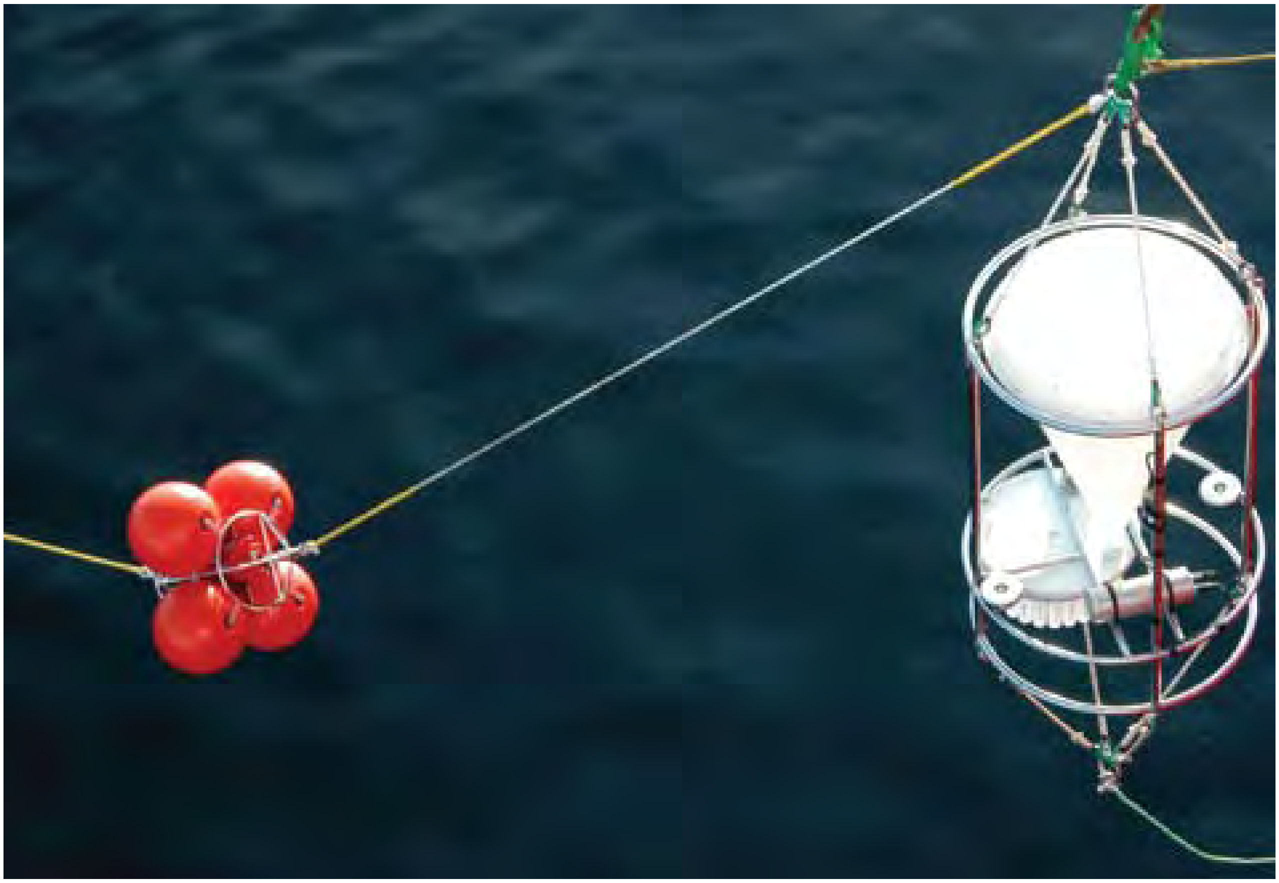

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