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FOREWORD

The Arctic is the region of the globe most severely impacted by the present warming of Earth's lower atmosphere. Many of the symptoms of a warming Arctic anticipated by climate models have already been verified by observations on land, at sea and from space. As summarized in the Arctic Climate Impact Assessment (ACIA 2005), the multiple environmental, socio-economic and geopolitical perturbations taking place in the Arctic are interacting to bring about an irreversible transformation of the North. ArcticNet is a 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 adaptation strategies and policies that will help northern societies and industries to prepare for the full impacts of environmental, economic and societal changes in the Canadian Arctic and Subarctic regions. 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. The ArcticNet IRIS (Integrated Regional Impact Study) structure provides an exciting opportunity to further develop linkages between natural science specialists, networks of expertise in northern health, and specialists in societal issues such as cultural change, adaptation and the recognition and respect of Inuit perspectives. We thank all of our network investigators, students, other researchers, colleagues and partners for helping ArcticNet achieve such early success, and the ArcticNet Eastern Subarctic editorial team for bringing this document through to completion.

Louis Fortier, Scientific Director of ArcticNet



Martin Fortier, Executive Director of ArcticNet



ArcticNet Eastern Subarctic Editorial Team

Michel Allard and Mickaël Lemay

Centre d'études nordiques (CEN: Centre for Northern Studies), Université Laval, Québec, QC, G1V 0A6.

ArcticNet is a Network of Centers of Excellence of Canada that brings together scientists and managers with northern expertise in the natural, human health and social sciences with their partners from Inuit organizations, northern communities, federal and provincial agencies and the private sector. The mission of the Network is to study the impacts of climate change and globalization in the Canadian Arctic and to produce new and applicable knowledge for the benefit of Canadians, in particular Northerners, and Inuit. One of ArcticNet's major objectives is to disseminate research results to communities, government departments and private organizations to help them face the increasing challenges and meet the opportunities resulting from changes in the natural and human environments. Some of the topics covered by ArcticNet are climate, thawing of permafrost, variations in vegetation, changes in animal populations, impacts of climate warming on lakes and rivers, human health issues related to shifts in diversity and quality of country food supply, as well as drinking water supply and quality. The culture of Canada's Inuit, their ways of understanding the environment and their economic expectations are central to the concerns of ArcticNet researchers in their effort to integrate scientific research and Inuit knowledge.

ArcticNet's research program spans the entire Canadian Arctic, both at sea and on land, which makes it challenging to address concerns applicable to all community and government levels in one comprehensible and succinct synthesis report. However, in the geographic expanses of Canada's North, the overall human challenges are similar because of a combination of characteristics such as physiography, hydrography, coastal settings,

climate, vegetation, animal populations, human history and system of governance. Based on these general similarities and to facilitate the organizational structure of this study, the North was divided into four broadly defined regions (Western and Central Arctic, Eastern Arctic, Hudson Bay and Eastern Subarctic, Figure 1) for each of which an Integrated Regional Impact Study (IRIS) will be produced. In this IRIS, research results are organized into topical chapters, and key findings from each chapter are highlighted in the Science to Policy Synthesis chapter. The IRIS framework was designed after a consultation process that involved the scientists themselves, ArcticNet's Research Management Committee and the Board of Directors of ArcticNet, the latter two entities having representatives from both national Inuit organizations and the Inuit governments of Canada (Nunatsiavut, Nunavik, Nunavut and Inuvialuit). The concept has been presented and discussed at several Annual Scientific Meetings and in the case of this volume, the framework was also presented to the two regional authorities of Nunavik and Nunatsiavut at the beginning of the writing process. This IRIS assessment constitutes a tangible deliverable of ArcticNet, however, the consultation and integration processes also yielded intangible but important outcomes; some policy decisions are already beginning to be implemented as a follow-up to information transferred during the consultation and writing process. Another unforeseen outcome was the exchange of information on land management and policies between administrative officers of Nunavik and Nunatsiavut during IRIS planning and writing meetings in both regions. Inter-governmental collaboration on some common issues, for example, the management of caribou herds, will likely expand in the future.

The development of the Eastern Subarctic IRIS has benefited from considerable support, expertise and knowledge from the *Centre d'études nordiques of Université Laval* (CEN) (Box 1). CEN has a long history of research and currently has more than 40 ongoing projects in the region of Nunavik. One of CEN's important partners is the Nunavik Research Centre, which has been

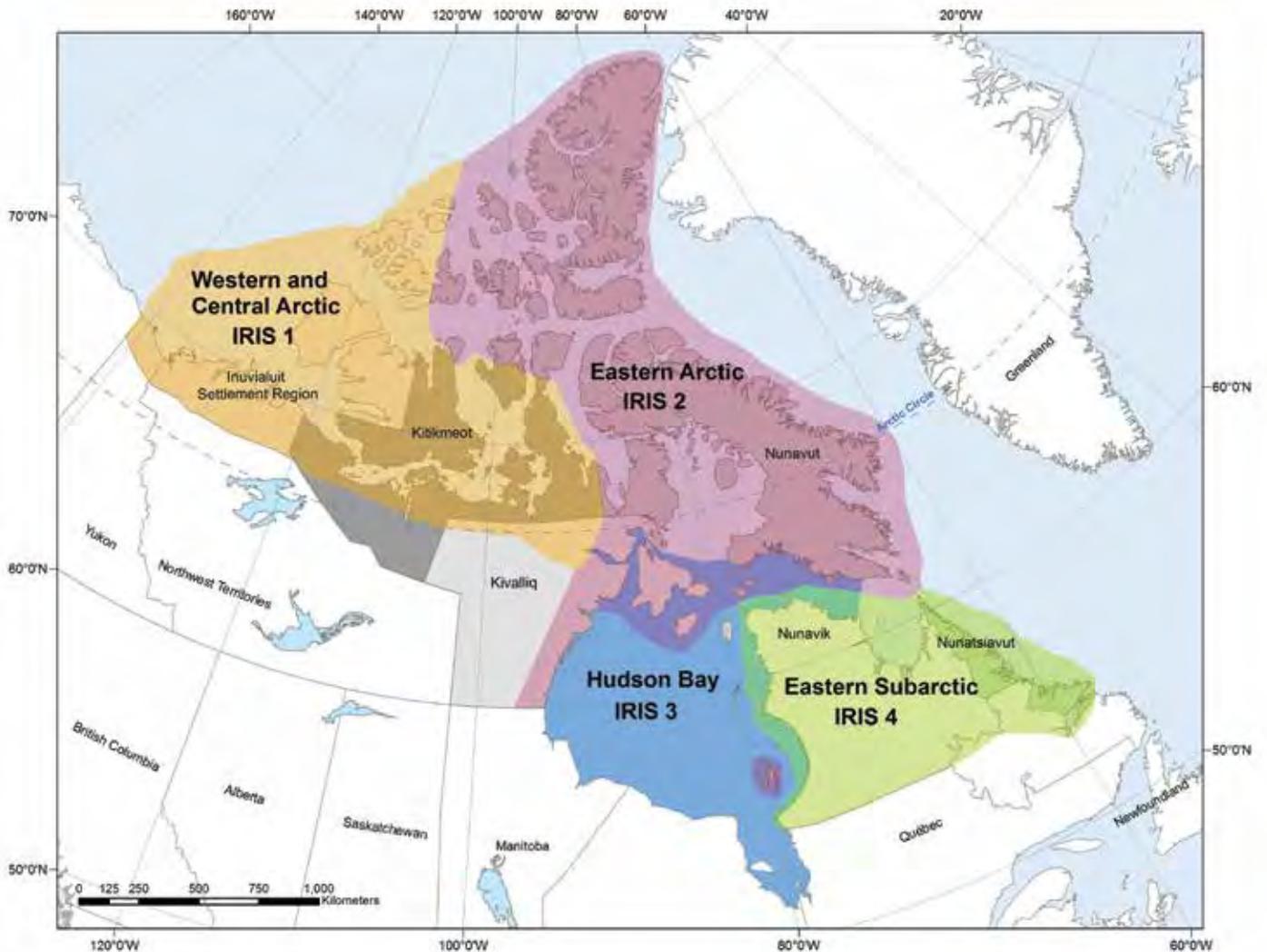


Figure 1. Map of the four ArcticNet IRIS regions covering the Canadian Arctic.

conducting research for over 30 years on issues related to the needs of Inuit. In Nunatsiavut, the IRIS benefited from knowledge inputs from the Labrador Institute, which leads several research projects in collaboration with Memorial University of Newfoundland. Ouranos, a Montreal-based research consortium on climate change and adaptation made a substantial contribution to this IRIS. Through the consultative committee of Ouranos' Northern Environment Program, many of the priority issues and knowledge gaps for the region were identified. Moreover, Ouranos played a key role in the IRIS by providing model data, gathering information

and producing a major part of Chapter 2 on climate. Chapter 3, which presents highly significant data results on human health, was lead by researchers of the *Centre Nasivvik pour la santé des Inuit et les changements environnementaux*.

As part of their mandate under the Network of Centres of Excellence Program, ArcticNet researchers are encouraged to formulate collaborative relationships with partners from Northern, public, private, and government sectors. A large proportion of the research results presented herein would not be available without



Box 1. The Centre d'études Nordiques (CEN)

The *Centre d'études nordiques*, (www.cen.ulaval.ca) is an interuniversity research centre whose focus is the evolution of northern environments in the context of climate warming and accelerated socio-economic changes. CEN's mission is twofold: 1- to contribute to the sustainable development of northern regions by way of an improved understanding of environmental change and, 2- to train highly qualified personnel in the analysis and management of cold region ecosystems and geosystems. CEN's research is multidisciplinary, bringing together over forty researchers including biologists, geographers, geologists, engineers, archaeologists, and land management specialists. The research takes place across a 4000 km North-South ecological gradient, from the boreal forest to the High Arctic, via the CEN Network composed of over 75 meteorological stations (the SILA network) and 8 field stations

(the Qaujisarvik network). The CEN Network was recently upgraded in collaboration with northern communities. The research results are utilized by many northern stakeholders including municipalities, policy makers, government departments, the private sector and other research partners in Canada and abroad. It is also part of the Circum-Arctic network of terrestrial field bases, SCANNET (www.scannet.nu) and thereby helps meet Canada's international responsibilities in monitoring the circumpolar Arctic. CEN also continues to play a leading role in the development of the ArcticNet-CCIN Polar Data Catalogue (www.polardata.ca) for Arctic data archiving, discovery and access.



the support of these partners; including the Inuit groups: Makivik Corporation, the Kativik Regional Government and the Government of Nunatsiavut; and government departments: Aboriginal Affairs and Northern Development Canada, Natural Resources Canada, Ministère des Transports du Québec and Ministère des Affaires municipales des régions et de l'occupation du

territoire du Québec. Many of ArcticNet's researchers are also grantees from research funding agencies such as the Natural Science and Engineering Research Council of Canada and Fonds québécois de recherche sur la nature et les technologies. A Regional Science Meeting/Workshop held in Kuujjuaq on 10-12 November 2009 reunited scientists, managers, and decision and policy



makers from both Nunatsiavut and Nunavik to design the structure and content of this IRIS report in order to address priority issues across the two regions (Figure 1).

This IRIS report begins with the Science to Policy Synthesis chapter that provides an overview of key research findings. The findings address four main issues: 1- human health, 2- safety and security, 3- vulnerability of infrastructures, and 4- resource exploitation and socio-economic development. The recommendations that stem from the report are included in this chapter, which is also published as a stand-alone document in English, French and Inuktitut. Chapter 1 provides an introductory description of the regional geography and briefly depicts the demographic and socio-economic context of Nunavik and Nunatsiavut. Chapter 2 provides a synthesis of the past and present climate in the IRIS regions as well as climate projections upon which experts based their assessments of expected impacts. The seven following chapters form the core of the report and present the supporting scientific evidence for the assessment. These chapters cover health issues, freshwater resources, food security, infrastructures on permafrost, arctic charr populations, vegetation

changes and berries as a food source and, finally, caribou herd dynamics.

Many individuals helped in the preparation of this IRIS report. We especially thank Martin Fortier, Louis Fortier, Katie Blasco, the Eastern Subarctic IRIS Steering Committee and all ArcticNet researchers and research partners for their contributions to this document.

SCIENCE TO POLICY SYNTHESIS OF THE NUNAVIK-NUNATSIAVUT IRIS ASSESSMENT



AUTHORS

*This Chapter was written by the Steering Committee of the Nunavik-Nunatsiavut Integrated Regional Impact Study (IRIS), whose members are **Michael Barrett** (Kativik Regional Government), **Tom Sheldon** (Nunatsiavut Government), **Ross Brown** (climatologist from Ouranos/Environment Canada), **Michel Allard** (ArcticNet IRIS Leader for the Nunavik-Nunatsiavut region) and **Mickaël Lemay** (ArcticNet IRIS coordinator). Acknowledgment also goes to **Selena Whiteley** from Kativik Regional Government for her contribution to this chapter.*

REPORTING PROCESS

Priority adaptation issues were identified and discussed during a workshop held in Kuujjuaq in November 2009. During this workshop, the IRIS assessment structure was defined and the IRIS Steering Committee designated. The IRIS chapters written by ArcticNet scientists and their co-authors were reviewed by the Steering Committee who then met in Nain in September 2011 to write the core of the Science to Policy Synthesis. The key findings of the scientific chapters were assessed, and a series of recommendations were then formulated and discussed with government officials from Nunavik and Nunatsiavut.

This IRIS assessment is principally based on research conducted through a series of scientific projects supported by ArcticNet. Since the funded projects do not cover all of the potential issues of concern for the regions, some major research gaps still exist and are highlighted both in the synthesis and in the IRIS chapters.

(Photo caption : Kuujjuaq Town Hall): Scientists from various disciplines, regional government representatives, community members and stakeholders met in Kuujjuaq (November 2009) for the first Nunavik-Nunatsiavut IRIS workshop.

INTRODUCTION

Globally, Inuit communities in Nunavik and Nunatsiavut are amongst the groups most affected by the impacts of climate change. Scientists and northern residents are witnessing increasing evidence of the direct impacts of the accelerated warming in this region, which is expected to continue well into the future. This warming, combined with changes in the natural and the socio-economic environment, is creating cascading effects on the ecosystem and society with significant impacts on human health and quality of life.

The Integrated Regional Impact Study (IRIS) framework was created to disseminate the results of ArcticNet's scientific research to the public. However, the goal is also to inform policy makers and to make policy-related recommendations. One of the main aims of the Canadian Eastern Subarctic IRIS region study (Figure 1) is to transfer knowledge and assessments of predicted changes

to communities, stakeholders and policy-makers to assist in the development of adaptation strategies. The underlying principle in developing policy-related recommendations is to maintain an environment capable of sustaining the health of Inuit and preserving the long-term productivity of ecosystems upon which they depend. This Science to Policy Synthesis summarizes the key findings and conclusions of the Nunavik and Nunatsiavut IRIS for the four priority issues that were identified in the region: **1- human health, 2- safety and security, 3- vulnerability of infrastructure and, 4- resource exploitation.**

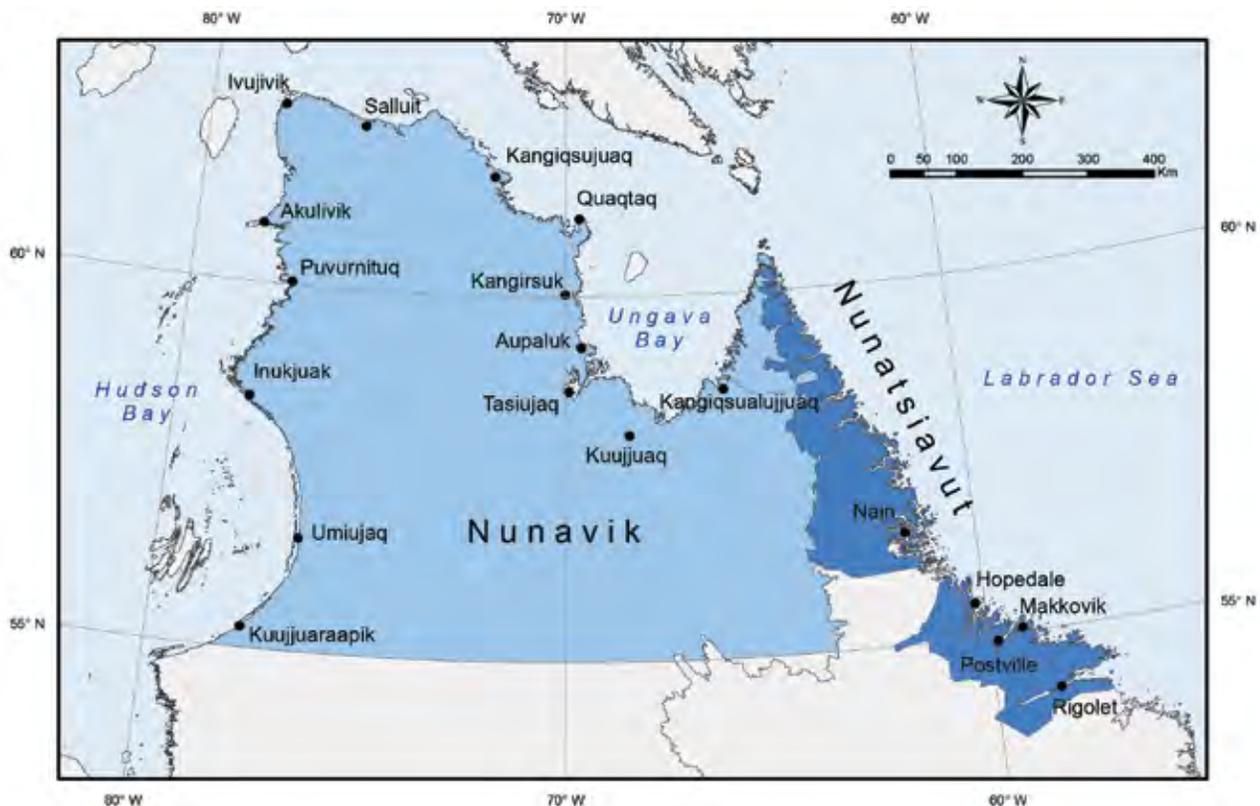


Figure 1. The Nunavik and Nunatsiavut IRIS region and the Inuit Communities

CLIMATE CHANGE AND MODERNIZATION

Climate warming has been highlighted many times in recent scientific literature and reported in the media as the main driver of change in the Arctic regions. However, the Arctic is also undergoing “modernization”, a general term that is not defined clearly and covers socio-economic processes.

A broad range of changes (other than climate) affecting people in Nunavik and Nunatsiavut can be linked to several factors that were either non-existent or of low significance only three to four decades ago. Firstly, the negotiation of self governance over territories and empowerment over educational and administrative matters has raised Inuit empowerment and level of political leadership. Secondly, significant improvements in infrastructure and transportation in the North (e.g. internet and air transportation) make it much easier to connect with other cultures and stay informed of current issues. Another aspect of change is rapid population growth due to very high birth rates over recent years. Thanks to improved schooling (despite the need for more improvements) the new generation is more likely to take on wage gaining employment, take charge of community and regional affairs, protect the environment and their cultural heritage, and participate in business. These cultural, educational, political and socio-economic changes are occurring against a backdrop of increasing pressure for exploitation of mineral and other natural resources that has the potential to bring increased wealth to the North but also carries the potential to threaten the resources essential to maintaining the Inuit way of life.

This modernization occurs simultaneously with climate warming which greatly modifies ecosystems, which the Inuit rely on as a food source. Permafrost, lake, river and sea ice, vegetation, and animal populations are all affected.

Changed eating habits, more difficult access to traditional food sources and the impact of new southern lifestyles are all contributing to major health problems across the Arctic. Of particular concern to Nunavik and Nunatsiavut are declining key animal populations such as caribou and Arctic charr and maintaining access to high quality drinking water.

An important issue resulting from population growth and climate warming is the availability in communities of land suitable for new housing. In Salluit for example, new housing cannot be constructed in the existing community because of ice-rich frozen soils that settle in response to warming. This problem has required the development of a community expansion plan at a nearby location where soils are less sensitive to warming.

Another issue of concern that requires further study is the coastal environment of Nunavik and Nunatsiavut. Inuit are a coastal people who travel on water in summer and on ice and snow in winter. Fish and marine resources are part of their long survival history and are still an important source of healthy food today. Islands, bays, estuaries and fjords constitute the cultural landscape. The scientific research carried out in the Nunatsiavut fjords presented in this volume is a good example of a strategy that needs to be pursued. Inuit groups consulted during the Nunavik-Nunatsiavut IRIS process repeatedly emphasized that effective land conservation planning was essential to protecting their territories and ecosystems in light of increasing local population and industrial development.

The following key findings raise major issues for human health, safety and security, vulnerability of infrastructures and for the impacts of resource exploitation. They are followed by recommendations to address these issues and improve quality of life, protect the environment and facilitate sustainable development.

NUNAVIK AND NUNATSIAVUT ARE EXPERIENCING RAPID WARMING

RECOMMENDATION

- *Improvements are needed in weather forecasting and environmental prediction at regional and local scales.*

The vulnerability of the region to climate change has been highlighted in recent years due to an abrupt and unprecedented warming that began around 1993. This warming has contributed to wide-reaching and rapid environmental changes. For example, snow and ice cover duration are currently decreasing at a rate of about 1.0 day/year, ground temperatures have warmed by over 2°C with significant increases in active layer depth over permafrost. Glaciers in the Torngat Mountains lost approximately 20% of their total area between 2005 and 2007. Inuit knowledge indicates that these recent changes are outside the range of previous community experience. Together with more unpredictable weather, these changes are having wide-ranging impacts on human health, safety, municipal infrastructure and access to territory and resources. Climate model projections for the 2041-2070 period indicate a continuation of the observed warming trend as well as increased precipitation over the region (Figure 2).

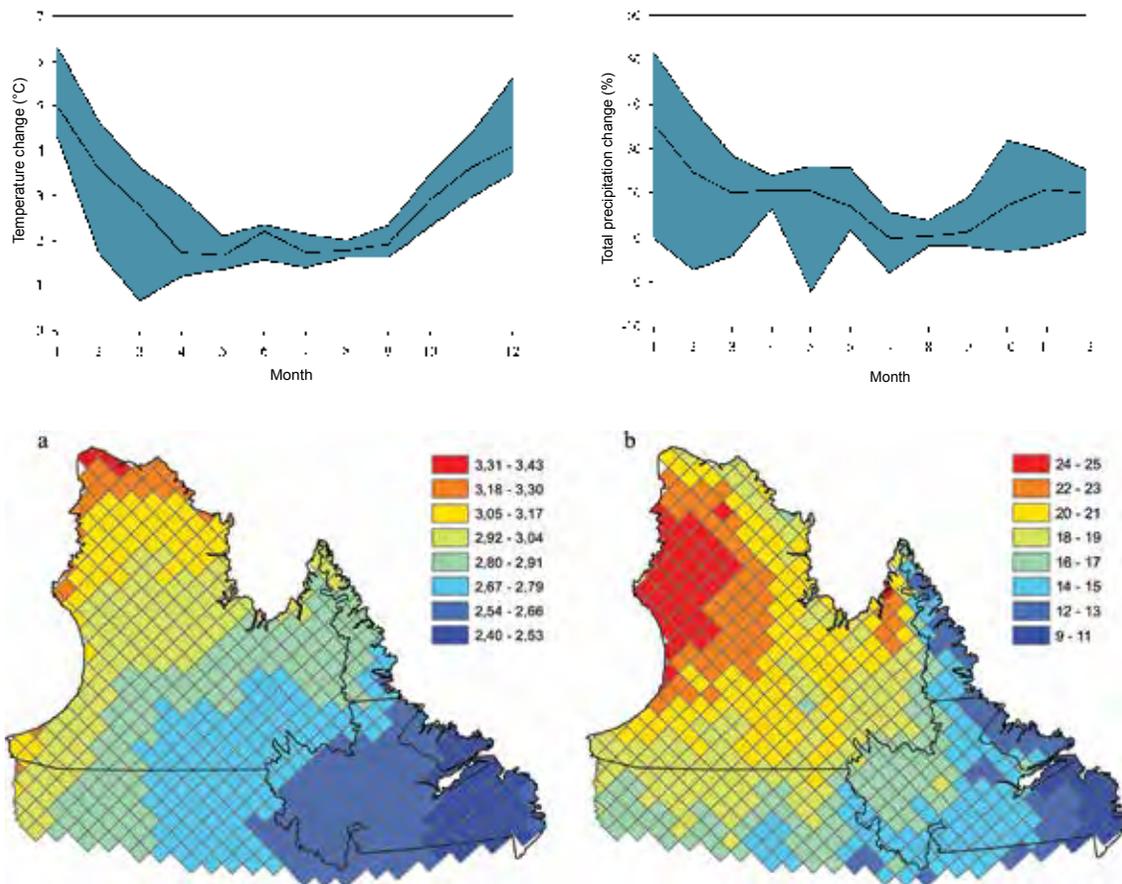


Figure 2. Top: Seasonal character of projected change in monthly mean temperature (left panel) and total precipitation (right panel) from six CRCM runs for 2050 period, averaged over all model grid cells in the study region. The outer lines represent the range in the six simulations. Bottom: Corresponding spatial pattern of projected change in (left) mean annual temperature (°C) and (right) mean annual total precipitation (%).

INUIT IN NUNAVIK AND NUNATSIAVUT HAVE A LIFE EXPECTANCY 10 YEARS SHORTER THAN MOST CANADIANS



RECOMMENDATIONS

- *Policies must be developed and adopted to address the current significant health inequality and lower life expectancy.*
- *Promotion of a healthy lifestyle must be encouraged; the negative impacts of drugs and alcohol cannot be ignored.*
- *Promotion of health and nutrition education in communities is also crucial.*
- *Research-driven interventions, such as those that were successful in the Inuit regions, must be pursued. For example: the study leading to the ban on trans-fats in Nunavik, the research that disclosed the substantial decline in persistent organic pollutants both in the environment and in people, and the research that revealed that marine fatty-acids provide protection against CVDs (Cardio-Vascular Diseases).*
- *An active lifestyle must be promoted to enhance quality of life.*

Nunavik and Nunatsiavut have the shortest life expectancy of the four Inuit regions and one that is substantially lower than the rest of Canada. Young males and older females are particularly vulnerable to premature death. Mortality profiles differ by sex with intentional and non-intentional injuries weighing most heavily for men and chronic diseases for women. Environmental changes together with changes in the socio-economic environment are contributing to this problem through negative impacts on human health and well-being. Recent health indicator data including food and nutrition, CVD (Cardio-Vascular Disease) risk factors, contaminants, infectious diseases from animals or drinking water, and injuries through travel, indicate that the people of Nunavik and Nunatsiavut are among the least healthy in the country with the situation apparently declining.

While significant declines in mean blood concentrations of mercury, lead and cadmium have been observed in Nunavik between 1992 and 2004, a significant proportion of individuals, particularly women of childbearing age, continue to have concentrations exceeding the acceptable level set by Health Canada. State-of-the-art research is identifying deleterious effects on the development of young Inuit with initial findings indicating long-lasting adverse effects of early contaminant exposure on cognitive functions. However, positive effects of fatty acids on sensory and memory function have been identified.

Obesity and cardiovascular disease levels are high and rising. However, for the same level of risk factors, Inuit are in better health than Caucasian populations. The consumption of marine fatty acids, the beneficial effects of which appear to be multiplying, is one of perhaps several protective factors that seem to be at play. However, these factors may be at risk due to dietary transition, environmental changes and the availability of quality country food.

A HIGH NUMBER OF INUIT FAMILIES WITH CHILDREN ARE FOOD INSECURE



RECOMMENDATIONS

- *Access to a sustainable supply of healthy country food is of paramount concern. Enhancing hunter support and community freezer programs, formalizing the support for country food sharing networks, and finding ways to increase the availability of country foods circulating in communities via commercial sale and distribution are recommended.*
- *Healthy store-bought foods need to be available and affordable.*
- *Initiatives such as ice monitoring, trail marking and access to survival equipment (such as spot tracking devices) must be encouraged.*
- *Search and rescue capacity at local and regional levels must continue to be improved and supported.*
- *Traditional and land skills knowledge transfer between generations must be encouraged.*

The transition away from the consumption of high amounts of country foods towards a more western diet as well as the rise in chronic diseases in the two regions is also associated with the status of food security. Food security exists when “all people at all times have access to sufficient, safe and nutritious foods to meet their dietary needs and food preferences for an active and healthy life” (FAO, 1999). Food security is influenced by food availability, accessibility and food quality. Depending on the way food security is classified, the rate ranges between 25% and 72% in Nunavik while in Nunatsiavut, 46% of households with children are reported to be food insecure, with about 16% reporting severe food insecurity. High food costs, availability of country foods, employment, low household income, the decrease in consumption of country foods, lifestyle choices and the lack of nutritious food options are factors affecting these high levels of food insecurity. People who are food insecure are at an increased risk of being overweight and having chronic health conditions, mental health challenges and a lower learning capacity.

Policy and program mechanisms for alleviating food insecurity in the two regions require greater attention as this public health problem grows. Enhancing hunter support or community freezer programs, formalizing the support for country food sharing networks, finding ways to increase the availability of country foods circulating in communities via commercial sale and distribution, and reorienting market food subsidies all show promise in addressing this issue. Promoting health and nutrition education in communities is also crucial for addressing this issue.

THE POPULATIONS OF THE LARGE CARIBOU HERDS ARE DECLINING



RECOMMENDATIONS

- *Caribou habitat, calving areas and migration routes must be conserved.*
- *Sport hunting, if it affects the health of the caribou herds or Inuit subsistence harvesting, should be curtailed or banned.*
- *An across-boundary partnership and coordination entity should be established for caribou management.*

The George River (GR) and Leaf River (LR) herds are two of the largest migratory caribou populations in the world. The available data indicate that the total number of caribou from both herds grew to in excess of 1 million animals during the 1990s but decreased dramatically to probably less than half this number by 2010.

The current decline in numbers is having negative social and economic implications, particularly for Inuit that rely extensively on caribou meat for subsistence. Changes in the distribution of caribou, for example a shift to Labrador for the GR herd (Sharma et al. 2009), as well as decreases in abundance, are expected in the near future and are unlikely to be offset by potential positive effects of an earlier and longer period of vegetation growth in a warmer climate.

Climate change will also bring additional stress to caribou for instance through prolonged exposure to insects. Communities, stakeholders and responsible entities should be prepared for a lower abundance of animals and perhaps a less predictable distribution affecting accessibility to the resource. Management efforts focusing on preserving high quality habitat, limiting anthropogenic landscape disturbances, and managing hunting in a sustainable manner, could alleviate stressors on migratory caribou of the Québec-Labrador peninsula.

ARCTIC CHARR IS AN IMPORTANT FOOD RESOURCE AT RISK



RECOMMENDATIONS

- *The sustainability of the Arctic charr harvest must continue to be assessed.*
- *Habitat enhancement and restocking for Arctic charr should be considered.*
- *Community-based monitoring of Arctic charr populations should be implemented.*

Arctic charr are considered vulnerable to the predicted impacts of climate change because of their preference for cold-water conditions. In a warming environment, lacustrine Arctic charr are the most likely to be impacted by predicted summer temperature increases, with effects being most acute at the southern edge of the distribution range where the warming will be greatest and competition from other salmonid fish species better able to cope with warmer temperatures will be most intense.

Arctic charr (migrating charr) may reduce their period of sea-residency as temperatures increase. Such changes will have profound impacts on Inuit who rely on Arctic charr as a significant source of healthy dietary protein and fatty-acids. To some extent, such impacts may be mitigated by pro-active environmental management as Inuit-led stream enhancement and population introductions have shown.

Key knowledge gaps concerning biology and population dynamics inhibit our abilities to accurately predict climate change impacts on Arctic charr and suggest there is considerable value in collecting long-term data sets specific to the species (e.g. through community based monitoring programs).

BERRY PRODUCTION IS PREDICTED TO DECLINE UNDER INCREASED SHRUB COVER



RECOMMENDATION

- *Important berry harvesting areas close to communities should be protected.*

Recent warming is promoting shrub growth as well as treeline expansion over Nunavik and Nunatsiavut, but not in a uniform way. Research has documented an increasing trend in dwarf birch and willow bush cover, as well as an altitudinal expansion of larch. With warmer and longer summers favouring increased viable seed production and seedling recruitment, trees are expected to gradually expand beyond current boundaries.

Changes in the distribution of shrubs are expected to alter snow distribution and its persistence on the land, affecting permafrost, feedbacks to the atmosphere and wildlife and human transportation routes. Warmer and longer growing seasons may not benefit the growth and productivity of all berry-producing plants. Berry species that have their highest productivity in full sun (especially partridgeberry/redberry and bog bilberry/blueberry) will most likely decline under an increased shrub cover, yet the patchy nature of arctic vegetation should enable other species more tolerant to partial shade such as black crowberry/blackberry/paurngaqutik and cloudberry/bakeapple/aqpik to take advantage of the changing conditions.

Community-based monitoring is an important tool to enable the collection of long-term data crucial to understanding current uncertainties about berry productivity and other ecosystem changes. Such long-term, sustained monitoring will enable Northerners to track environmental changes in their communities and to tailor appropriate adaptation strategies for their region such as the development of protected areas to ensure easy access to high quality sites for this culturally important activity.

MAINTAINING GOOD QUALITY DRINKING WATER IN COMMUNITIES IS A CHALLENGE



RECOMMENDATIONS

- *Monitoring of water quality for both primary and secondary sources of drinking water in communities should be improved.*
- *Important sources of drinking water close to communities should be protected.*

Nunavik and Nunatsiavut have a rich natural heritage of lakes, rivers and wetlands that require ongoing stewardship and protection. Permafrost thaw lakes (thermokarst ponds) are a major classification of northern freshwater ecosystems, and they appear to be increasing in abundance and total surface area in parts of the circumpolar North, including Nunavik, as the permafrost continues to warm and degrade. The avoidance and mitigation of chemical pollution of northern aquatic ecosystems from both long-range and local sources requires ongoing vigilance.

Secondary water sources near communities are commonly used and are culturally important sources of drinking water. A variety of drinking water problems related to both supply and quality have been identified throughout Nunavik and Nunatsiavut. The monitoring of water quality of both treated and untreated secondary sources of water is currently deficient.

THE THAWING OF PERMAFROST MODIFIES THE NATURAL ENVIRONMENT AND REQUIRES ADEQUATE INFRASTRUCTURE



RECOMMENDATION

- *Improved urban planning and appropriate engineering practices should be applied to take into account local environmental conditions including permafrost and climate change effects for construction projects.*

Permafrost degradation is seriously affecting the natural environment. Thawing of the permafrost in the discontinuous zone creates new ponds and provokes landslides and changes to drainage patterns. The infrastructure of villages in both regions is particularly affected due to inappropriate practices or design flaws combined with climate change. A well-documented case is the community of Salluit, which is built on ice-rich clays where the active layer increased by 30-40 cm in the past twenty years.

The effects of these changes can be seen in the roads as well as in movement of some of the buildings. In many Nunavik communities, permafrost thawing has begun to occur along the sides of some runway sections. In most Nunatsiavut communities, community infrastructure development, including water supply and sewage system placement as well as land-use plans have failed to accommodate Subarctic environmental conditions including permafrost, freezing of active layer and seasonal hydrological conditions.

Great care must be taken in the development of adequate infrastructure and housing. Adaptation strategies are being developed to support improved land-use planning, respond to construction issues, and lessen the impacts of permafrost thaw through better maintenance practices.

SEA ICE COVER IS DIMINISHING IN ITS EXTENT AND DURATION AND FJORD ECOSYSTEMS ARE CHANGING



RECOMMENDATION

- *A better understanding of Nunavik and Nunatsiavut river and coastal systems is crucial.*

An ongoing biological and physical study of the fjords of Nunatsiavut is providing new insights into these critical areas in the face of changing climate and modernization. There has been a significant reduction in sea ice cover across the fjords in northern Labrador over the past 50 years with extreme, recent record lows in coverage, accompanied by reduced salinity in the fjords over this same time period. Generally, Inuit in Nunavik and Nunatsiavut have also reported a decrease in sea ice cover and duration over recent years.

On a shorter timescale, over the past 10 years, there has also been an increase in marine productivity along a north to south gradient in Labrador. Although the biological significance of these changes will vary, it is expected that if these changes continue, a general increase in species abundance as well as new species in these fjords will occur, which could alter food web systems including the harvesting practices of Inuit. More importantly, it has been found that high-energy marine ecosystems along the coast of Labrador can demonstrate substantial resilience and recovery from anthropogenic disturbances if managed in a sustainable and progressive manner.

However, the legacies of local sources of contamination continue to have an impact on coastal marine systems, as indicated by elevated levels of contaminants (PCBs) in some ringed seals (approximately 10-15%) captured from the coast of Labrador. Ringed seals still remain a healthy source of nutrition, and contaminant levels in Inuit from Nunatsiavut are generally lower than the rest of the Arctic due to overall diet choices.

NUNATSIAVUT AND NUNAVIK HAVE BEGUN IMPLEMENTING LAND USE PLANS



RECOMMENDATION

- *Parks, protected areas and land sheltered from development should continue to be identified for the conservation of valued ecosystems.*

The Master Plan for Land Use in the Kativik region was approved in 1998 and includes land identification and classification of: areas that are essential for harvesting, areas of interest to Inuit, caribou calving grounds and reserves for parks. The Nunatsiavut Government has recently approved a land use plan for the Labrador Inuit Settlement Area (LISA) which includes the following land designations (total percentage of LISA in designation): National Park (14.4%), General Use (52.3%), Traditional Use without George River Caribou Calving Area (13.4%), Special Policy - George River Caribou Calving Area (19.5%) and Other (0.5%). In Nunatsiavut, the creation of the Torngat Mountains National Park in 2005 by Parks Canada also resulted in the protection of 9 700 km² of the region's 72 500 km² of land from industrial development. In partnership with the Kativik Regional Government and Makivik Corporation, the Government of Quebec created the Parc national des Pingualuit (1 149 km²) in 2004 and the Parc national Kuururjuq (4 461 km²) in 2009.

The proposed Parc national Tursujuq (26 000 km²) and the Parc national Ulittaniujalik (5 272 km²) should be created by 2013. No industrial activity is permitted in the parks of either region. There are four other areas in Nunavik, totalling 9 949 km² designated as park reserves. In Nunavik, community consultations are underway for 11 additional proposed protected areas. The objective is to protect at least 20% of Nunavik from Industrial development by 2020. The Government of Quebec has announced its objective to shelter 50% of the Plan Nord region, which includes Nunavik, from industrial development by 2035. Inuit harvesting areas overlap with some of the conservation areas and in other cases are within close proximity to the communities. All of these designated areas, in addition to their importance for conservation, will help cope with the impacts of climate change, while coexisting with areas of industrial development in both regions.



CONCLUSION

The key findings of this study indicate major issues in regard to human health, safety and security, vulnerability of infrastructure and the need to protect ecosystems from the impacts of resource exploitation. Numerous actions to improve quality of life, safeguard the environment and facilitate sustainable development need to be implemented. Many of these actions are presented here as recommendations.

SYNTHESIS OF FINDINGS AND RECOMMENDATIONS



NUNAVIK AND NUNATSIAVUT ARE EXPERIENCING RAPID WARMING

- Improvements are needed in weather forecasting and environmental prediction at regional and local scales.



INUIT IN NUNAVIK AND NUNATSIAVUT HAVE A LIFE EXPECTANCY 10 YEARS SHORTER THAN MOST CANADIANS

- Policies must be developed and adopted to address the current significant health inequality and lower life expectancy.
- Promotion of a healthy lifestyle must be encouraged; the negative impacts of drugs and alcohol cannot be ignored.
- Promotion of health and nutrition education in communities is also crucial.
- Research-driven interventions, such as those that were successful in the Inuit regions, must be pursued. For example: the study leading to the ban on *trans*-fats in Nunavik, the research that disclosed the substantial decline in persistent organic pollutants both in the environment and in people, and the research that revealed that marine fatty-acids provide protection against CVDs (Cardio-Vascular Diseases).
- An active lifestyle must be promoted to enhance quality of life.



A HIGH NUMBER OF INUIT FAMILIES WITH CHILDREN ARE FOOD INSECURE

- Access to a sustainable supply of healthy country food is of paramount concern. Enhancing hunter support and community freezer programs, formalizing the support for country food sharing networks, and finding ways to increase the availability of country foods circulating in communities via commercial sale and distribution are recommended.
- Healthy store-bought foods need to be available and affordable.
- Initiatives such as ice monitoring, trail marking and access to survival equipment (such as spot tracking devices) must be encouraged.
- Search and rescue capacity at a local regional level must continue to be improved and supported.
- Traditional and land skills knowledge transfer between generations must be encouraged.



THE POPULATIONS OF THE LARGE CARIBOU HERDS ARE DECLINING

- Caribou habitat, calving areas and migration routes must be conserved.
- Sport hunting, if it affects the health of the caribou herds or Inuit subsistence harvesting, should be curtailed or banned.
- An across-boundary partnership and coordination entity should be established for caribou management.



ARCTIC CHARR IS AN IMPORTANT FOOD RESOURCE AT RISK

- The sustainability of the Arctic charr harvest must continue to be assessed.
- Habitat enhancement and restocking for Arctic charr should be considered.
- Community-based monitoring of Arctic charr populations should be implemented.



BERRY PRODUCTION IS PREDICTED TO DECLINE UNDER INCREASED SHRUB COVER

- Important berry harvesting areas close to communities should be protected.



MAINTAINING GOOD QUALITY DRINKING WATER IN COMMUNITIES IS A CHALLENGE

- Monitoring of water quality for both primary and secondary sources of drinking water in communities should be improved.
- Important sources of drinking water close to communities should be protected.



THE THAWING OF PERMAFROST MODIFIES THE NATURAL ENVIRONMENT AND REQUIRES ADEQUATE INFRASTRUCTURE

- Improved urban planning and appropriate engineering practices should be applied to take into account local environmental conditions including permafrost and climate change effects for construction projects.



SEA ICE COVER IS DIMINISHING IN ITS EXTENT AND DURATION AND FJORD ECOSYSTEMS ARE CHANGING

- A better understanding of Nunavik and Nunatsiavut river and coastal systems is crucial.



NUNATSIAVUT AND NUNAVIK HAVE BEGUN IMPLEMENTING LAND USE PLANS

- Parks, protected areas and land sheltered from development should continue to be identified for the conservation of valued ecosystems.



Chapter 1. Nunavik and Nunatsiavut: an Inuit homeland peninsula

Lead authors

Michel Allard and Mickaël Lemay
ArcticNet, Centre d'étude nordiques (CEN), Université Laval

Contributing authors

M. Barrett, M. Bertol, F. Brassard, S. Cossette, G. Duhaime, N. Girard, F. Poisson, T. Sheldon and A. Simpson

Abstract

This chapter provides a geographic overview of the territory of this Integrated Regional Impact Study. Nunavik, in Québec, and Nunatsiavut, in Newfoundland and Labrador, are two Subarctic territories where Inuit make up the majority of the population. Both of them have Inuit-led regional governance regimes that resulted from major historic agreements. The James Bay and Northern Québec Agreement (1975) is the treaty that created Nunavik and its governing institutions, and the Labrador Inuit Land Claim Agreement (2005) is at the origin of the Nunatsiavut Government. The study region consists of the northern part of the “Québec-Labrador” peninsula which was divided by a court decision made in London, England in 1927, creating a border set along the height of lands of the Labrador watershed. All of the Inuit communities (14 in Nunavik, 5 in Nunatsiavut) are located along the coastline, many of them at the mouths of important rivers or in fjords. Currently, the population of Nunavik is increasing rapidly whereas the population of Nunatsiavut is more or less stable, although it has shown a recent increase in birth rate. The populations of both regions face economic difficulties as they are at a disadvantage in terms of rate of unemployment and level of income in comparison with the rest of Canada, including the other Inuit regions. Similarly, health conditions and food security are below the standards of most of Canada. The Québec-Labrador peninsula is acknowledged for its high mineral potential, which generates a dual adaptation challenge in the face of rapid climate and environmental changes and pressure for industrial development. Having taken responsibility for their homeland, Inuit of both territories have already produced land management plans which propose to exclude from development, areas necessary for living and ecosystems in need of protection, while still leaving the door open for economic development.



1.1 Introduction

Nunavik and Nunatsiavut, homeland of Inuit and part of the Inuit Nunangat, possess an exceptional natural, human and cultural richness. The Inuit of Nunavik and Nunatsiavut share many interests with Inuit from Nunavut, the Inuvialuit Settlement Region, Alaska and other circumpolar communities.

Globally, these populations are among the most affected by the impacts of climate warming. Both scientists and northern residents are reporting observations of direct impacts of the accelerated warming that is taking place in Nunavik and Nunatsiavut. The permafrost is warming up and thawing with the result that transportation infrastructures and communities are now being affected. Governments and communities are supporting ongoing research projects targeted at improved land planning and designing technical solutions for adaptation on sensitive terrain. Changes in the vegetation cover are reported both by Inuit and researchers. Shrub cover is expanding in the forest-tundra and the treeline is reported to be extending upwards on hillsides in the eastern Ungava Bay region. Expected impacts on key animal species such as large caribou herds and Arctic charr populations will likely be through a series of complex interactions between climate factors, food availability, vegetation dynamics, water temperature, ice cover duration and thickness on lakes and rivers, population dynamics, herbivory and predator-prey relationships. Hazardous ice conditions are limiting access to food resources and increasing the risk of injuries and even death for Northerners practicing traditional activities such as subsistence harvesting. Adaptation strategies for the people dependant on these resources will likely take multiple approaches over the varied geographical domain.

Impacts of climate change are being felt while northern populations are experiencing the development and diversification of their socio-economic activities, which are accompanied by a rapid demographic growth in Nunavik, and while both regional governments are evolving towards greater autonomy. Economic and cultural globalisation

constitutes an additional driver of change that contributes to modifying the way of life of Nunavimmiut and Nunatsiavummiut. Considering this transformative context driven by the current socio-economic and climate changes, the adaptation capacity of northern peoples is dependent on thorough knowledge of the ongoing and expected changes and the anticipated impacts on their natural environment.

This chapter provides a descriptive overview of the geography of the study region, summarizing its major biophysical traits and presenting a brief portrait of its prevailing socio-economic conditions. The key governance elements of Nunavik and Nunatsiavut are also introduced in this chapter. Existing land use plans already produced by these governments are presented and the role of industrial activities in the study region as a current and potential model of change is briefly touched upon.

1.2 The communities in their natural environment

The Nunavik and Nunatsiavut peninsula (Figure 1) is bounded by seas on three sides (Hudson Bay to the west, Hudson Strait and Ungava Bay to the north and the Labrador Sea to the east), a geographical setting that creates a continental-type climate with some coastal influences resulting in higher precipitation, particularly snow, along the Hudson Bay coast and in smaller thermal amplitudes along the Nunatsiavut coastline. The region lies entirely within the Canadian Shield with the highest elevations located in the Torngat Mountains along the boundary between Nunavik and Nunatsiavut. The Torngats host the only glaciers east of the Rockies in continental Canada. The transitions from forest to tundra and from discontinuous to continuous permafrost occur across both territories. The climate has been warming rapidly since the early 1990s, and climate models project an increase in temperature of 3-4 °C and an increase in precipitation of 10 to 25% for the middle of the century relative to the 1960-1990 period (see Chapter 2).

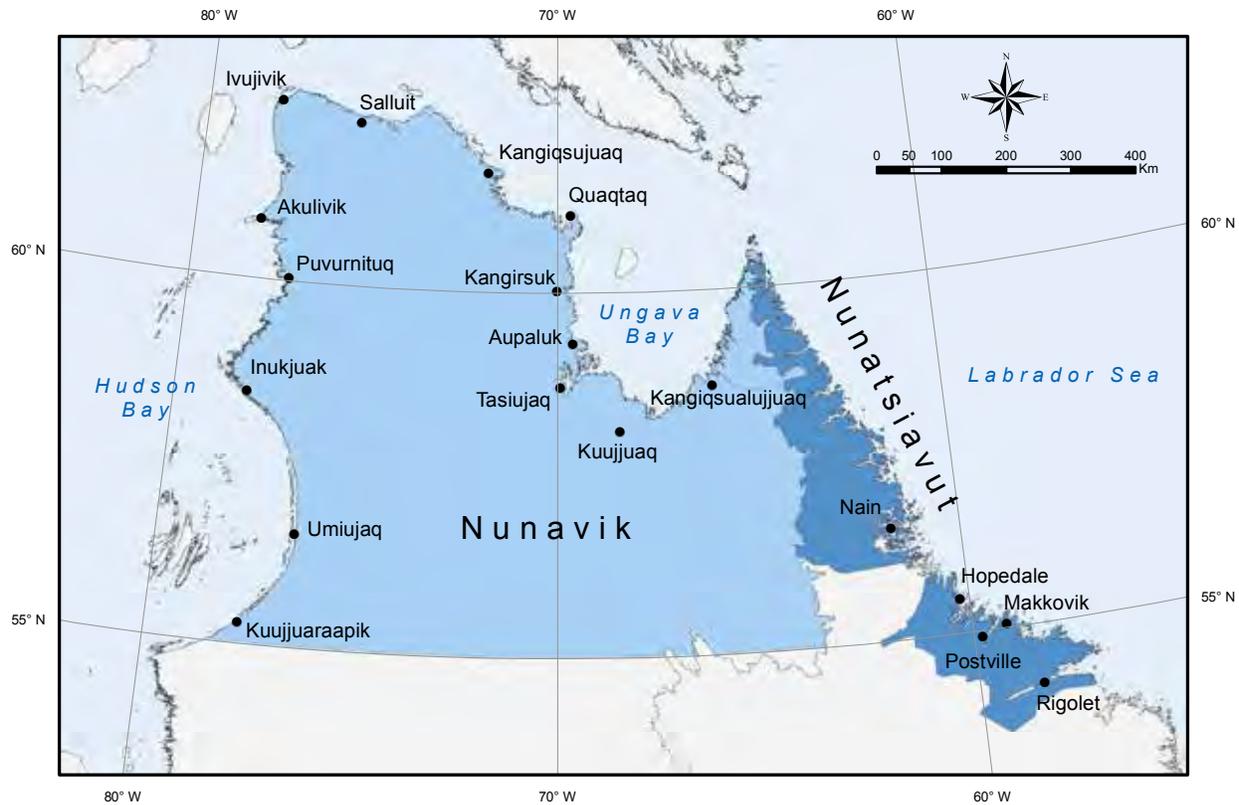


Figure 1. *The Nunavik and Nunatsiavut peninsula and its Inuit communities.*

The Eastern Subarctic IRIS region can be divided into four distinctive landscape regions: Hudson Bay coast, Hudson Strait coast, Ungava Bay coast and Labrador Sea coast (Figure 2). Many of the Inuit communities are located at the mouths of rivers or estuaries that drain large interior watersheds. The coastal landscape of Hudson Bay from Pointe Louis XIV (Cape Jones) to Inukjuak is characterised by *cuestas*, a structural geological setting which results in spectacular rocky topography with cliffs facing east on straights and gulfs and a gentle slope dipping under the waters of Hudson Bay. From Inukjuak to Ivujivik, the shoreline is made up of low rocky outcrops, small islands and discontinuous beaches. The tidal range along the Hudson Bay coast is small (generally less than 1.5 meters); however, the large fetch of the bay and the strong winds generate large storm waves. The coastal ice-cover lasts for about six months every year (from December to May).

The Hudson Bay coast is home to six Inuit communities (Kuujuaaraapik, Umiujaq, Inukjuak, Puvurnitua, Akulivik and Ivujivik) and one Cree first nation community, Whapmagoostui, which shares the delta surface of the Rivière Grande-Baleine with Kuujuaaraapik. In the 1950s, Inuit living in the Lac Guillaume-Delisle area moved to Kuujuaaraapik to live near an air force base of the mid-Canada line. Umiujaq was built in 1986 as the result of a clause of the Northern Québec and James Bay Agreement that aimed to allow Inuit to return to their original homeland. The village of Umiujaq is built on raised shorelines on the gentle *cuesta* slope of the Nastapoka geological formation. Both Kuujuaaraapik and Umiujaq are located in the region with the fastest postglacial uplift rate in the world, with an emergence rate of 13 cm per year. The outstanding landscape of Lac Guillaume-Delisle with its magnificent cliffs and its ecological richness is in the process of becoming a Québec National Park, which will extend inland

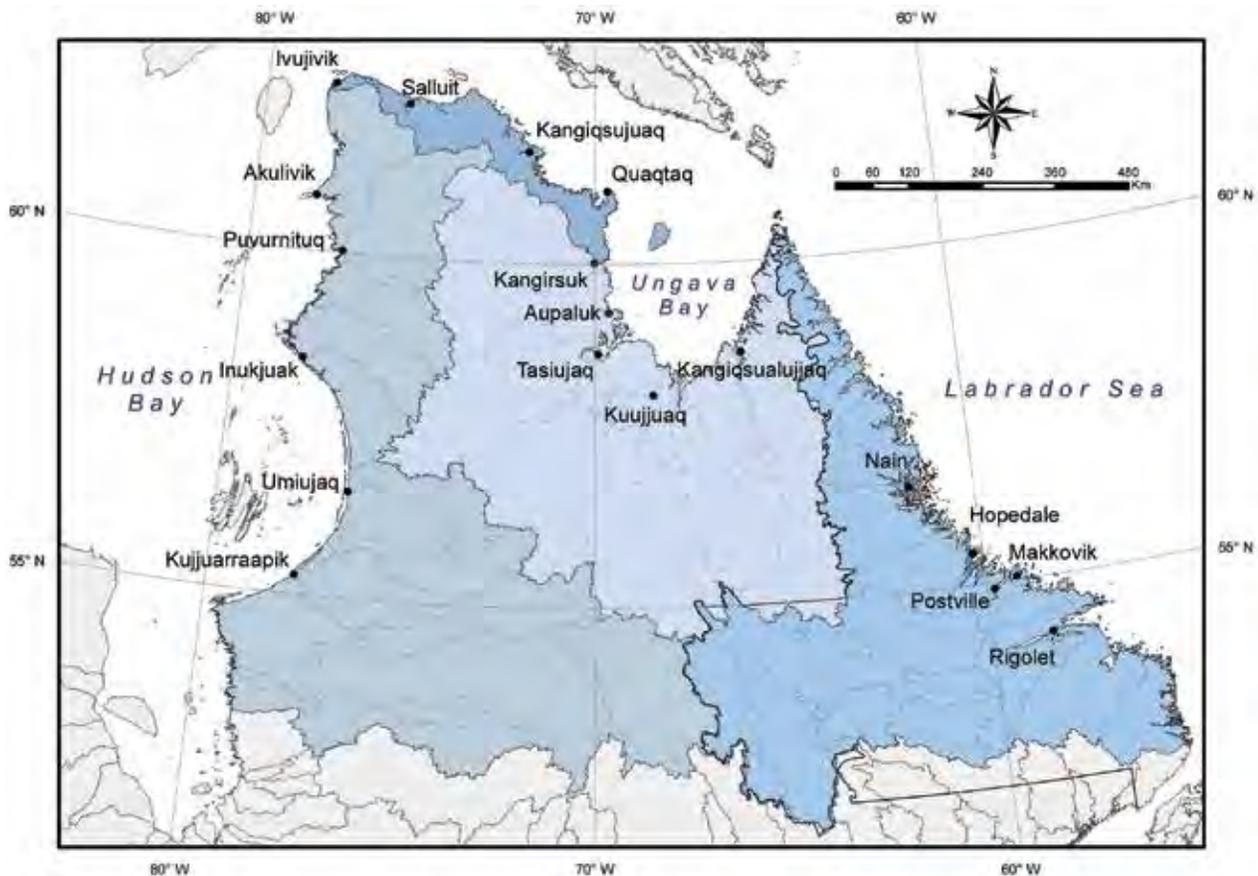


Figure 2. The four distinctive regions of the Eastern Subarctic IRIS region: Hudson Bay coast (western watershed), Hudson Strait coast (northern watershed), Ungava Bay coast (center watershed) and Nunatsiavut Sea coast (eastern watershed).

as far as the Lac à l'Eau-Claire area. The village of Kuujjuaraapik has no permafrost while the village of Umiujaq and its surroundings lie in the discontinuous permafrost zone. Umiujaq is located at the treeline.

Further north, both Inukjuak and Puvurnituaq are communities that grew at the mouths of large rivers and lie in the continuous permafrost zone. They are relatively large communities and Puvurnituaq is a regional centre because of the presence of its hospital. Akulivik is a small community nestled in an embayment near the promontory of Cape Smith; its physical setting is distinguished by the extremely shell-rich soil on which it was built. Ivvujivik is the northernmost village of Québec. It was built mainly

on bedrock and is surrounded by spectacular cliffs such as those of Cape Wolstenholme, which mark the transition point between Hudson Bay and Hudson Strait.

The coastal landscape of Hudson Strait is made up of a series of high promontories and fjords, which are deep embayments that provide sheltered ports and access inland via valleys and rivers. For instance, the communities of Salluit and Kangiqsujaq are located in fjords as is the port of Deception Bay, which provides access to the Katinnik mining fields. The tidal range is large, generally in excess of five meters. The fjords are frozen for about seven months per year. East of Kangiqsujaq, the large Diana Bay and the promontory of Cape Hopes Ad-

vance indent the coastline. Cape Hopes Advance marks the transition between the Hudson Strait and Ungava Bay coastlines.

Salluit is a large community that encounters serious land planning challenges due to the presence of ice-rich permafrost (see Chapter 6). Its airport is the terminus of the daily scheduled flights that arrive from Montréal and fly back via both the Ungava and the Hudson Bay coastal air routes, which makes the community a key location for travellers. Kangiqsujuaq is the gateway to the Pingaluit Québec National Park created around the New Québec crater. Located on the Cape Hopes Advance promontory, the village of Quaqtak is particularly susceptible to the maritime climate resulting in frequent humid and foggy weather.

Five Inuit communities are located along the west coast of Ungava Bay (Kangirsuk, Aupaluk, Tasiujaq and Kuujuaq) and Kangiqsualujuaq is located on the southeast shore, closest to Nunatsiavut. Several large rivers converge at the bay, the major ones being, from west to east, the Arnaud, Aux-Feuilles, Koksoak, à-la-Baleine and George rivers. Ungava Bay has very large tides with ranges of the same magnitude or even larger than the Bay of Fundy in eastern Canada and Baie du Mont Saint-Michel in France. Consequently, the lower reaches of the rivers are very dynamic estuaries. Ungava Bay and its tributaries constitute a unique coastal estuarine ecosystem not seen anywhere else in the Arctic.

Kangirsuk was developed on multiple levels on the steep rocky shore of the Arnaud River estuary, whereas Aupaluk is a very small community established in a bay, on the shore of a wide tidal flat. Tasiujaq is located at the mouth of Rivière Bérard, in the deep embayment of Baie-aux-Feuilles, at the head of a vast tidal flat. The largest tides in the world have been measured here. Kuujuaq, the regional capital of Nunavik, is located 53 km upstream from the mouth of the Koksoak River estuary in Ungava Bay. The natural hydrodynamic regime of the river was modified in 1981 by the construction upstream

of the Caniapiscou dam. Originally, the Inuit community and the Hudson's Bay Company installations were on the east side of the river, now a historic site called Old Fort Chimo. The community moved to its current site at the location of the old U.S. Army airport after WWII. Kuujuaq's airport is a regional hub between the South, Nunavik's other communities and Iqaluit. The community hosts a regional hospital, the Kativik Regional Government, the Makivik Corporation head office and the Nunavik Research Centre. Kangiqsualujuaq lies on the eastern shore of the George River estuary near Anikaskalak Bay, which becomes a wide tidal flat at low tide. There are deep-rooted human connections between this community and Labrador through migrations, family ties and even legends. Kangiqsualujuaq is the gateway to, and hosts the reception centre of, Québec's Kuururjuaq National Park, which lies adjacent to Torngat Mountains National Park of Canada (TMNP) in Nunatsiavut. It is also the final destination of many river paddlers who descend the George River.

The Nunatsiavut Sea coast is home to five Inuit communities, which are from north to south: Nain (administrative capital), Hopedale (legislative capital), Postville, Makovik and Rigolet. Spectacular fjords characterised by narrow inlets incised by glacial activity indent the northern coast of Labrador. Some of the fjords are deep sedimentary basins separated by rocky sills and surrounded by steep cliffs. The northern tip of the Nunatsiavut Peninsula offers an outstanding mountainous landscape, which is largely part of the Torngat Mountains National Park of Canada that covers about a third of Nunatsiavut (Figure 3). Torngait is the Inuktituk word for "place of spirits" and these mountains have been home to Inuit and their ancestors for thousands of years. The park extends from Saglek Fjord in the south, including all islands and islets, to the very northern tip of Labrador; and from the provincial boundary with Québec in the west, to the ice-berg-choked waters of the Labrador Sea in the east. The mountain peaks along the border with Québec are the highest in mainland Canada east of the Rockies, and are dotted with small glaciers. Polar bears hunt seals along

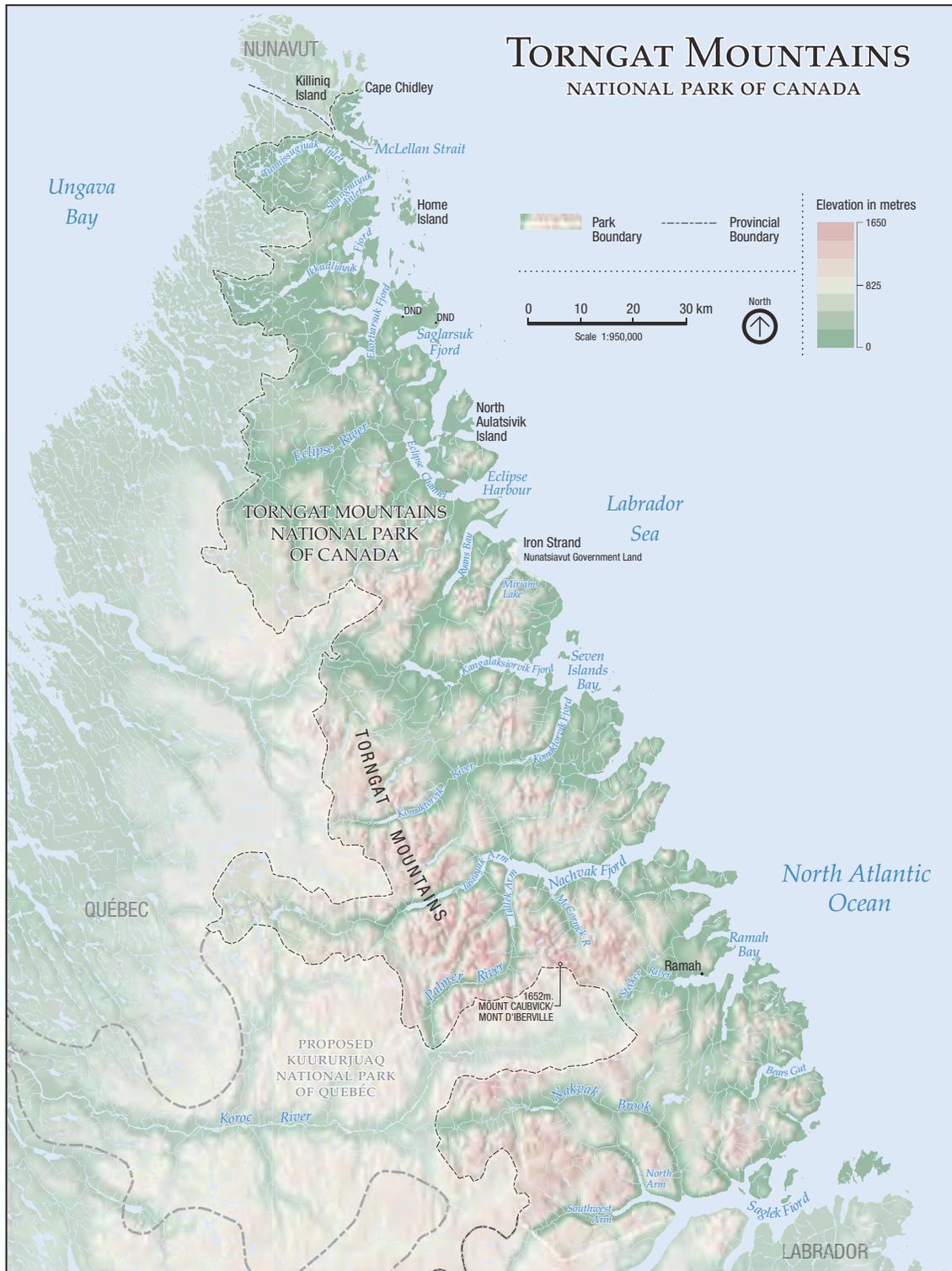


Figure 3. Map of the Torngat Mountains National Park (TMNP) of Canada that covers about a third of Nunatsiavut.



the coast, and both the Torngat Mountains and George River caribou herds cross paths as they migrate to and from their calving grounds. Today, Inuit continue to use this area for hunting, fishing, and travelling throughout the year.

The central Labrador coastline is represented by shallow, irregularly shaped and glacially formed inlets with more gently sloping sidewalls and large intertidal zones that are referred to as fjards. The fjords and fjards of the Nunatsiavut Sea coast are very dynamic and diversified marine ecosystems that are being influenced by Atlantic and Arctic water masses and by sediments, nutrients and freshwater inputs from glaciers and rivers. They provide climate shelters to the Nunatsiavut communities and host several natural resources on which the communities depend.

The five villages of Nunatsiavut are small and isolated communities. All of them are built in forested areas and lumber has traditionally been a local resource. The communities are inter-connected through scheduled coastal marine freight services that supply the north coast of Labrador. These coastal communities are also accessible by small aircraft (mainly Twin Otter) with flights originating from Happy Valley-Goose Bay, that are often weather dependent. Nain is the northernmost community and the largest, with approximately 1250 residents. Moravian missionaries founded the community in 1771; it is located at the eastern end of a peninsula facing the Labrador Sea, but sheltered to the east by a multitude of islands. The community of Nain has a long traditional maritime lifestyle and the local fish plant, operating from May/June to October, processes fresh and smoked charr, cod, scallop, and sometimes

turbot, halibut and other marine species. Nain also has two stone quarries operating on two local islands to extract granite containing Labradorite, a blue colored mineral, which is greatly prized worldwide. Hopedale is a small community of about 620 residents that was established in 1782 by Moravian missionaries. The Hopedale Mission building, which is still standing, is considered as one of, if not the oldest, building east of Québec. Makkovik is located in an embayment of Cape Makkovik and was founded in the 1850s as a post of the Hudson’s Bay Company. The population increased during the late 1800s due to the arrival of the Moravian settlers and Inuit of the area, becoming the southern-most outpost of the Moravian settlements. To the north-west of Makkovik is the community of Postville, which is located about 30 km along the Kaipokok Bay. Rigolet is located to the south of Nunatsiavut on the shore of a narrow passage at the entrance to Lake Melville.

1.3 Socio-economic context

In recent years, the Canadian Eastern Subarctic demographic profile has undergone significant changes that follow opposite trends in Nunavik and Nunatsiavut. In 2011, population was about 12 090 residents in Nunavik living in 14 communities and 2 617 in Nunatsiavut living in 5 communities. The recent population growth from 2006 to 2011 was very high in Nunavik with a value of 10.4% while that of Nunatsiavut increased by 8.40%. The highest population growth occurred in Tasiujaq, where an increase of 22% was noted between 2006 and 2011 (Figure 4). The communities of Akulivik and Quaqtaq also showed high growth rates with respective population increases of about 21% and 19%. This rising trend is even more significant using demographic data from 1996 to 2006 from the *Institut national de la statistique du Québec*. The total population has indeed increased by about 30% in 13 years upwards from 8 820 in 1996 to 10 784 in 2006.

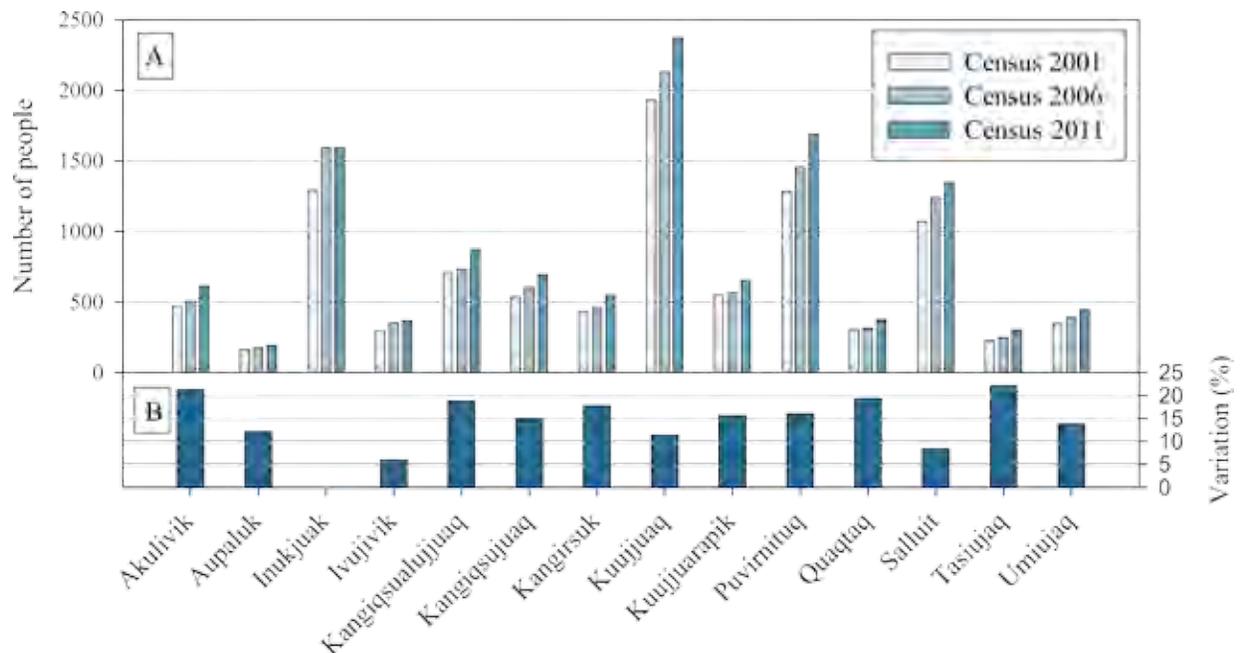


Figure 4. A) Comparison of the number of individuals per village in Nunavik between Statistics Canada censuses of 2001, 2006 and 2011 and B) the variation in % between 2006 and 2011 censuses.

1.3.1 Demographics and income sources in Nunavik

The population of Nunavik bears little resemblance to that of the rest of Québec. By comparison, it represents only a small portion of the overall population. Unlike the rest of the province, its population is largely Inuit and has a higher percentage of men than women - a fact that correlates with other Arctic regions. According to the Makivik Corporation, there are about 1000 non-Inuit residents living in Nunavik, which represents about 10% of the total population.

The Inuit population of Nunavik has grown rapidly since the 1960s, increasing from 798 in 1961, to 3278 in 1971, 4115 in 1981, 7693 in 1991 (Statistics Canada) and 10 784 in 2006 (*Institut national de la statistique du Québec* 2006). The demographic increase in Nunavik is mainly related to the important proportion of young people. Figure 5 shows that people under 15 represent a significant proportion of the population. With a higher proportion of children and a lower proportion of seniors, the average age is lower in Nunavik than in the rest of Québec. In 2006, 54% of the population was 24 years old or less. This means that, generally speaking, working-age people in Nunavik are responsible for more non-workers than are other Québécois.

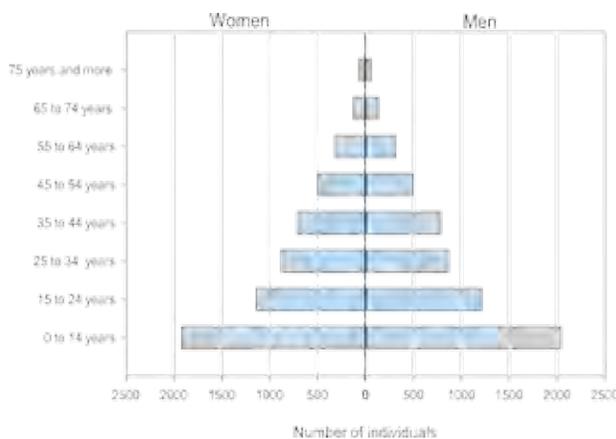


Figure 5. Nunavik's demographic context classified by age group.

The Nunavimmiut are overwhelmingly home-renters - most of these homes being state-owned. They generally occupy low-income housing in need of major repairs. As a consequence of the rapid population growth, the number of people per household is excessive. Over 25% of these homes are overcrowded and this is a major cause of aggressiveness and violence in the household. Familial violence is 6 to 10 times higher in Nunavik than in the rest of Québec (*Qanuippitaa?* Health survey 2004).

The level of education has in the past been lower in Nunavik than in the rest of Québec, but this is now on the rise along with the number of high-school graduates (Fuzessy 2002, Van Wagner 2007). The low level of education is certainly related to the absence of a learning facility at a level beyond high-school in Nunavik.

Nunavik's economy leans on the presence of government jobs - in fact, government activities are the region's most important industry. Government jobs in the health and education sectors represent over 40% of all employment. Adding in the other government services, this figure would easily surpass 50%. A higher proportion of the working-age population in Nunavik participates in the workforce than in the rest of Québec. However, fewer people are employed and the rate of unemployment is nearly twice that of the overall province.

Relative income is lower in Nunavik: Nunavimmiut aged 15 and over earn only 90% of their Québec's counterparts' wages, and slightly under 80% on a per-person basis. Taxation does not alter these figures, since they are identical before and after taxes. With income from other sources, such as contracts and self-employment, having less importance in Nunavik, salaried employment and social benefits make up a greater part of income than in the rest of Québec. Salaried employment accounts for over 80% of workforce revenue. Working-age Inuit play a key role in contributing to household income, even though their income is lower (Chabot 2003, 2004). Therefore, it is not surprising that a breakdown of the income of working-age Inuit shows proportionately fewer gains and more transfer payments than a similar breakdown across the working-age population, both Inuit and others.

1.3.2 Demographics and income sources in Nunatsiavut

The regional demographic context of Nunatsiavut is slightly different from that of Nunavik. In 2011, the Inuit population of Nunatsiavut was estimated at 2617. Nunatsiavut’s communities are small with populations generally under 1000 people. The village of Nain is the exception with a population of 1188 people, which represents 45% of Nunatsiavut’s total population (census of 2006, Statistics Canada). The population of Nunatsiavut increased from 2414 in 2006 to 2617 in 2011.

However, a decreasing trend is observed in two of the five Nunatsiavut communities (Figure 6). The community of Postville has shown the most important demographic decline as population dropped by about -5.9% between 2006 and 2011. The community of Makkovik has also shown slight demographic decline with a 0.3% change during the same period. Nain recorded the highest population growth, about 15%. The population change in Nunatsiavut has however been accompanied by an increased birth rate as shown in Figure 7. The age structure of Nunatsiavut’s communities is clearly dominated by the group of 0-14 year olds, which accounts for 20% of the population.

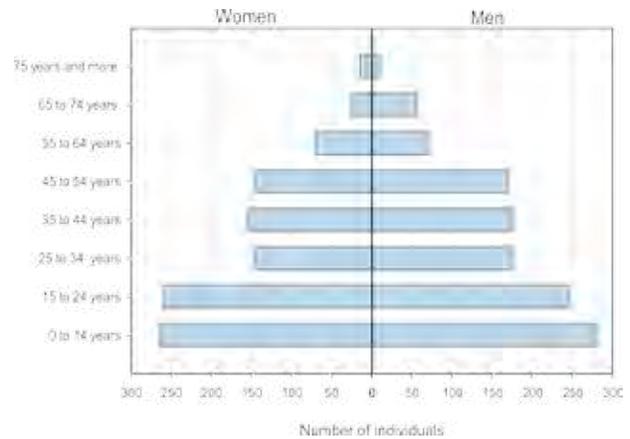


Figure 7. Nunatsiavut’s demographic context classified by age group. Data from Labrador’s Happy Valley-Goose Bay and Cartwright are not counted.

The average age is therefore lower in Nunatsiavut, thanks to a higher proportion of children under 15 years.

Despite the recent decreasing rate of population growth, the average number of persons per household is higher in Nunatsiavut than in the South. However, the differences between Nunatsiavut and the rest of Newfoundland are not as great as those between Nunavik and the rest of Québec. Similar to the situation in Nunavik, the propor-

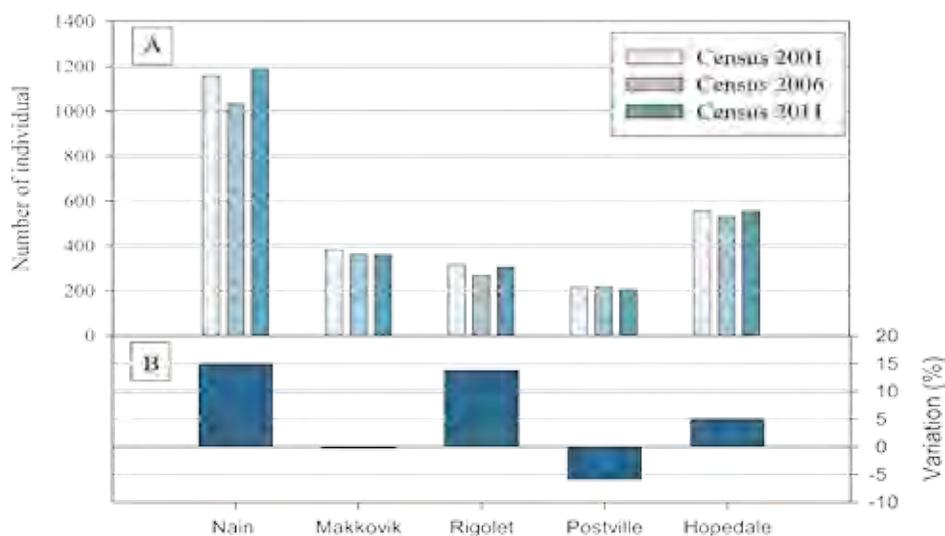


Figure 6. A) Comparison of the number of individuals per village in Nunatsiavut between Statistics Canada censuses of 2001, 2006 and 2011 and B) the % variation between 2006 and 2011 censuses.

tion of home-renters in Nunatsiavut is double that of the rest of Newfoundland, and four times as many housing units need major repairs as the provincial average. In Nunatsiavut, the working-age population is responsible for more non-workers than in the rest of Newfoundland. The level of education has been lower than in the rest of Newfoundland, but this is changing as more members of the younger generation gain high-school diplomas.

Nunatsiavut's economy is structurally similar to the rest of Newfoundland's. The primary employers are natural resources, health and education (less for secondary sectors and other services, these more so than in NL). However, there are few differences between Nunatsiavut and Nunavik in this regard, and the two regions participate equally in their respective workforces.

Nonetheless, there are important differences. In Nunatsiavut, employment is proportionally lower and the unemployment rate is almost twice that of the rest of Newfoundland. Relative revenue is lower: the people of Nunatsiavut aged 15 years and over earn 90% of their counterparts' earnings in Newfoundland, and slightly under 80% on a per-person basis. Taxation does not alter these figures, since they are identical before and after taxes.

With income from other sources, such as contracts and self-employment, having less importance in Nunatsiavut, salaried employment and social benefits make up a greater part of income than in the rest of Newfoundland. Salaried employment accounts for over 76% of the population's revenue and is a key contribution to household income (Richling 1989).

However, the median revenue of working-age Inuit people is lower than a similar comparison across the working-age population, Inuit and other. It is not surprising, therefore, that a breakdown of the income of working-age Inuit people shows proportionately fewer gains and more transfer payments than a similar breakdown across the overall working-age population. All these dif-

ferences are smaller than similar measurements between Nunavik and the rest of Québec.

1.3.3 Historical and current governance in Nunavik

The population growth of Nunavik is not expected to slowdown on a short or medium timescale as the economy is currently being stimulated by global development projects such as the Plan Nord, which responds to the international increase in demand for natural resources. However, in this globalization context, it is not yet clear how this ongoing and expected economic development will benefit Nunavik and what governmental framework will support and maximize the positive outcomes of this development. These are particularly relevant questions considering the current housing crisis that has persisted for several years, which indicates that federal, provincial and regional governments do not yet harbour the adequate structure and/or processes to cope with such major socio-economic development as lies ahead.

Historically, in the early 1900s, federal and provincial agencies had no clear responsibilities over northern residents and any governmental interventions attempted mainly to expand the Canadian territory in order to increase the natural resource reserves and support the economic development of the country (Duhaime 1985). During the 1940s, after a long period of isolation with scattered minor governmental interventions, the implication of the government in social and health policies increased with the opening of the first dispensaries and the adoption of the Family Benefits Program, which greatly contributed to the settlement process of Inuit and allowed for increases in their income (Saladin d'Angelure 1984, Damas 1996). However, the federal government was not in favour of this settlement trend at the time and ordained dissuasive rules in the 1950s such as the prohibition to sell construction materials to Inuit and one limiting access to health care only to Inuit that were practicing their traditional lifestyle (Duhaime 2001). This period is also marked by the relocation of Inuit from Inukjuak to Reso-

lute Bay and Grise Fjord, a drastic federal intervention that aimed to ensure Canadian sovereignty in the High Arctic, and also to control the demographic growth of Inukjuak (Saladin d'Angelure 1984).

After fighting against the settlement trend, the federal government finally decided to encourage the settlement of Inuit in permanent villages via diverse state interventions that attempted to assimilate Inuit by changing (or replacing) their traditional and cultural lifestyle with education and technologies from the south. The 1960s then marked the beginning of major governmental interventions among which the implementation of housing policies and programs (e.g. matchbox houses and social housing) should be noted. The involvement of the provincial government also increased during this decade and had a substantial impact on the spatial organization of public and residential developments in Nunavik's communities.

The increase in interest in the economic potential of the North in the 1960s, with the beginning of large mining and hydroelectric development projects, greatly contributed to stimulating the political evolution of the region. In 1962, the Direction générale du Nouveau-Québec was created to discuss the transfer of administrative responsibilities of Inuit of the Nouveau-Québec from the federal to the provincial government; the agreement was signed in 1964. As a protest and response to this agreement, the Northern Québec Inuit Association was created in 1971, which became the main organization representing the Inuit of the region (Saladin d'Angelure 1984, Damas 1996) and carrying the idea of Inuit Government. This was also the year of the announcement of the Bay James Hydroelectric management project by Québec's Prime Minister Robert Bourassa, a project that led to a legal conflict related to the claims for territorial and ancestral rights by First Nations and Inuit. The negotiations concerning the territorial rights over the entire territory of Nouveau-Québec

Box 1. The James Bay and Northern Québec Agreement (JBNQA)

The JBNQA embodies the principle that Québec recognizes the needs of Crees, Inuit and Naskapi, taking into account that their culture and way of life differ from the way of life of other Québécois. Under this Agreement, the territorial regime must respect the most important traditional occupations of the Native Nations - hunting, fishing and trapping - and any initiatives for the protection of the environment and development must include the participation of Native Peoples in governmental committees so they can play an active role in the decision-making processes. The territorial regime is implemented by a lands regime that includes three lands categories (category I, II and III), which determine the suitability, the modalities and the management responsibilities.



The goal for protecting ecosystems and living resources in Nunavik is to “protect endangered species and to ensure primarily the continuance of the traditional pursuits of the Native people, and secondarily the satisfaction of the needs of non-Native people for sport hunting and fishing” (JBNQA, art. 24.1.5). The Agreement also states that before getting a permanent status, national parks projects, planned biodiversity reserves and planned aquatic reserves must be submitted to an environmental evaluation regime that assumes the protection of both the natural and the social environments (Berrouard 2002).

led to the signature of the James Bay and Northern Québec Agreement (JBNQA) in 1975 (Box 1).

The main outcome of the JBNQA, other than financial compensation for the loss of Cree, Inuit and Naskapi territory and new land use (further discussed below) and resource regimes accompanied by a new process to conduct environmental assessments, was the creation of new governance structures. Indeed, the agreement allowed for the creation of Nunavik's municipalities, Kativik Regional Government (KRG), Kativik School Board (KSB), Nunavik Regional Board of Health and Social Services (NRBHSS) and the regional council of Nunavik development (Katutjiniq). Under this new governance structure, all municipalities are represented on the KRG board, which is responsible for local administration, transport, communications, police, training and management of workforce and skilled labor.

The JBNQA also led to the creation of Makivik Corporation in 1978, an Inuit organization having as its primary mission to promote the political and socio-economic development of Nunavik and to make sure that the agreement is always properly applied. As such, Makivik's mandate is to negotiate with public and private partners. It rapidly became the main driver of Nunavik's economic development and being a non-profit organization, Makivik has made very profitable investments and now owns many subsidiary companies, which are an important source of employment in Nunavik. Makivik and KRG work together on many social, environmental and economic matters to implement the JBNQA (Box 2).

Since the early 1980s, Nunavik has been continuously evolving towards administrative and political autonomy through diverse agreements with governmental and private organizations. In 1991, Nunavik's Inuit voted in favour of a proposition for a more autonomous Nunavik regional government. In 1999, the Nunavik Commission was created with representatives from Makivik, and Federal and Provincial governments to develop a new form of governance for Nunavik, which was submitted in 2001

and subsequently contested by the Kativik School Board (KSB). However, the Court rejected the contestation and an agreement for the creation of a Regional Government in Nunavik within the province of Québec was signed in two steps in 2003 and 2007. According to this agreement, the Regional Government was to be non-ethnic and include the three main public organizations (Kativik Regional Government, Kativik School Board, and Nunavik Regional Board of Health and Social Services). To be effective, this agreement had to be approved via a referendum, which was held in April 2011. A total of 7881 voters were asked to answer the following question: "Do you approve the Final Agreement on the creation of the Nunavik Regional Government?" The Final Agreement was rejected by a majority vote of 2842 (i.e. 67%). Only 1400 voters agreed with the agreement. Turnout was 54.5%. It should be noted that this agreement would not have resulted in significant new regional governance powers. The existing powers would have been redistributed in the hands of representatives (deputies) elected by the entire Nunavik population at the Regional Government level, who would have had to operate with financial support provided by provincial and federal agencies. Under this structure, a large part of the executive power would have remained in the hands of Makivik Corporation. In other words, the majority of voters apparently considered that merging KRG, KSB and NRBHSS into a Regional Government without integrating Makivik as proposed in the Final Agreement would not have offered enough changes and new powers to the Inuit of Nunavik. Currently, a new agreement proposal for the Nunavik Regional Government is being discussed by the different organizations and should be presented and submitted to a vote in the coming years.

Meanwhile, other agreements were signed to encourage the economic and municipal development of communities and to share the economic benefits of development among Inuit (Sanarrutik in 2002), and to facilitate the transfer of funds from Québec to Nunavik (Sivunirmut in 2004). Again, these agreements have contributed to providing Nunavik with more autonomy.

Box 2. Makivik Corporation, the Nunavik Research Center and the Kativik Regional Government

The Nunavik Research Center (NRC) based in Kuujjuaq is an initiative of the Makivik Corporation. The objective of the NRC is to monitor the toxic contaminants and heavy metals that can be found in traditional Inuit food resources. Therefore, the NRC conducts extensive studies on fish, marine mammals, waterfowl and caribou aiming to protect the health and monitor food security for the 14 Nunavik communities it serves.



Since it began operating, the NRC has largely benefited from its partnership with community members and local hunters for the gathering of information on traditional knowledge and for sampling across the territory. The data collected throughout the years is a significant contribution to the regional sustainable management of wildlife populations. The NRC also contributes through its cartographic service to the monitoring of environmental impacts related to mineral extraction, hydroelectric development and climate change effects helping to enhance security for Nunavik's communities.



The Kativik Regional Government is a public organization with jurisdiction over the Québec lands north of the 55th parallel. KRG acts on behalf of all residents of the Kativik Region. Included in the KRG's mandates flowing either from the James Bay and Northern Quebec Agreement, the Act respecting Northern Villages and the Kativik Regional Government (R.S.Q., c. V-6.1) (Kativik Act) or from agreements signed with governments are land use planning, environmental protection, parks development and management, subsistence harvester support, wildlife protection, transportation and technical assistance to the 14 Municipalities. In addition, based on these mandates, since 2004 the KRG has undertaken a series of climate change and adaptation projects with the communities, researchers, regional and other Governmental partners. These projects have focussed on safety, access to resources, community consultations, soil instability, and reducing the vulnerability of marine and community infrastructures.

In collaboration with Inuit Tapiriit Kanatami (ITK), the KRG employs an Inuit Research Advisor with funding assistance from ArcticNet, the Northern Contaminants Program and Nasivvik Center.

The James Bay and Northern Québec Agreement (JBNQA) was designed in such a way as to ensure that the rights and interests of Nunavik Inuit are fully protected and promoted. The KRG cooperates closely with Makivik Corporation in the implementation of these mandates.

1.3.4 Historical and current governance in Nunatsiavut

There is much archaeological evidence that Inuit have occupied Northern Labrador for about 4000 years. The Dorset people were living in Northern Labrador until the arrival of the Thule (the direct ancestors of today's Inuit) about 600 years ago. It is very likely that there was contact with the Vikings around the 11th Century. However, the coast of Labrador has also been visited by European fishermen and whale hunters since the 16th Century. Large scale trade exchanges with Europeans occurred during the 17th Century and began to be more regular following the establishment in 1752 of the first Moravian Missionaries in Northern Labrador. Colonialism had a strong impact on Inuit in the region. Since then, the Inuit of Northern Labrador have been through a long history of changes such as resettlement and progressive disconnection with their traditional way of life. During the past decades, the Inuit of Northern Labrador have strongly re-claimed control over their homeland, their socio-economic and traditional activities, as well as their political identity through self-government.

The Labrador Inuit Association (LIA) was created in 1973 to promote Inuit culture, to improve health and well-being and to protect the constitutional, democratic and human rights of Inuit. The LIA was also formed to develop Labrador Inuit claims and advance negotiations with Canada and Newfoundland towards self-government. In 2005, after three decades of negotiations, the signing of the Labrador Inuit Land Claims Agreement marked the beginning of a new era for the Inuit people of Labrador. Nunatsiavut became the first Inuit region in Canada to achieve self-government: the Nunatsiavut Government. The Labrador Inuit Land Claims Agreement and the Labrador Inuit Constitution adopted in 2002 came into effect at the first Assembly of the Nunatsiavut Transitional Government, held in Nain on December 1st 2005.

Among the core issues discussed during the negotiation process was the creation of the national park in the Torngat Mountains region of northern Nunatsiavut, which also

became effective in December 2005. This park was created with the consent of Nunavik Inuit provided through the Nunavik Inuit Land Claims Agreement and the consent of Nunatsiavut Inuit provided through the Labrador Inuit Land Claims Agreement. Without this consent and recognition of the two Land Claims the park would not have been established (see Box 3). The "Reserve" status was dropped on July 10th 2008 when the Nunavik Inuit Land Claims Agreement came into legal effect.

Other relevant outcomes of this negotiation process were the different agreements signed by the three parties (i.e. LIA, Newfoundland and Labrador and Canada) in 2002 concerning the development of the mining industry, such as the Voisey's Bay Interim Measures Agreement, the Inuit Impacts and Benefits Agreement also signed with Voisey's Bay Nickel Company Limited and Inco Limited, and the Voisey's Bay Environmental Management Agreement signed with the Labrador Innu Nation. These agreements were strongly influenced by the existing impact assessment studies and were affirmed to ensure the contribution of the proposed projects to local and regional sustainability. As a result of these agreements, the Voisey's Bay project is considered a significant achievement with regards to its requirements for integrating health concerns and for giving special consideration to traditional land-use activities, housing, quality of life, diet and country food dependency, and morbidity and mortality (Canada et al. 1997, Noble and Bronson 2005). These agreements also represent a considerable achievement in conflict resolution given the profound differences in background, culture, priorities and formal power involved (Gibson 2006).

1.4 Regional Land Use Plans

1.4.1 Nunavik's Master Plan for Land Use

The "Master Plan for Land Use of the Kativik Region" (The Plan, 1998) was elaborated to harmonize and integrate development endeavours as well as current and

Box 3. Parks across the border: one Inuit history

Eli Merkuratsuk points to where his mother was born many years ago in a place called Pitutik, situated at the mouth of Nakvak Brook. This is the starting point of a hike from Saglek Fiord up Nakvak Brook to the Koroc River in Nunavik. This hike follows an important traditional travel route that has connected Inuit for generations before Nunatsiavut and Nunavik were created. However, due to relocation policies of southern governments and institutions, Inuit have not spent much time here in recent years.

This route connects two parks (Torngat Mountains National Park of Canada in Nunatsiavut and Parc National du Kurrurjuaq in Nunavik) managed under Inuit Land Claims agreements and symbolizing a renewed emergence of Inuit and a re-occupation of a traditional homeland. But it symbolizes even more than this. It is about re-connecting Inuit with Inuit. It is about bringing youth and elders together, about renewing Inuit pride and identity, regaining ownership of their homeland and taking control over its management. It also represents the connection between two ways of knowing, of harmonizing western science and Inuit Knowledge in a way that validates the intrinsic value of Inuit experiences and knowledge. The route and the two parks help to rebuild these connections.



Youth and Elders from Nunatsiavut and Nunavik gathering at the commemorative Inukshuk near Pitutik. This place has come to symbolize the connections between Inuit and between generations. Torngat Mountains is a place of spirits and this location embodies the spirit of unity among Inuit and a connection to their homeland.

future management projects over the entire Nunavik territory. Adopted by the Inuit of Nunavik after community participation, interviews with elders and experts, data compilation, intense analytical work, mapping, and public consultations, the Plan includes the principles guiding territorial management, the main directions that are pursued by KRG in terms of land use and territorial management

and the rules for its application. The Plan identifies the major elements of the urban and natural environments, the areas traditionally and currently used by Inuit, the territorial breakdown into different land-use designations (Figure 8) and the zones representing a particular historical, esthetical and ecological interest (Figure 9). The Plan was prepared in accordance with the JBNQA, the Convention

du Nord-Est québécois (CNEQ), and the other laws applicable to the Nunavik territory.

One of the guiding principles of the Plan is conservation. In the context of the Plan, the conservation principle applies to all types of land and resource use, regardless of whether the resource is renewable, non-renewable or heritage-related. Overall, the objective is to preserve the heritage and traditional way of life of the peoples of the Kativik region, protect the environment and the wildlife while promoting sustainable development. The Plan emphasizes:

- Establishing areas that are considered “essential” and areas that are considered “important” for subsistence activities, where hunting, fishing and trapping are practiced by the local people. Because of their rich biodiversity, these essential areas are of capital importance to the pursuit of subsistence activities. The important areas have less biodiversity than the essential areas; however, they include the habitats of wildlife groups such as land mammals, birds and fish which are harvested on a more extensive and seasonal basis.
- Protecting the integrity of the important natural environments, in particular the ecosystems representative of the region’s environment, as well as the vulnerable and important wildlife areas (for example, caribou calving grounds, the nesting and staging areas of waterfowl, sectors in which marine mammals gather and their birthing areas, salmon rivers and spawning areas).
- Establishing a network of “areas of interest” consisting of sites that are representative of rare or endangered plant or animal species and which are of archaeological, historical, cultural, esthetic or ecological importance for the region to protect them from the harmful impacts of human activity and industrial activity while promoting their recognition and safe development. The areas of interest are, of course, subject to the rights and interests of Natives as stipulated in the JBNQA and the NEQA and the accompanying complementary agreements.

1.4.2 Regional Land Use Plan for the Labrador Inuit Settlement Area

The purpose of the Land Use Plan for the Labrador Inuit Settlement Area (LISA) is to maximize the social, cultural and economic well being of Inuit and other residents of LISA. The plan considers sustainable development in light of the principles of traditional Inuit land use and respect for the land. One interesting aspect of the Regional Land Use Plan of the LISA is the application of the precautionary principle that allows postponing decisions in the absence of full scientific certainty in order to meet society’s expectations that risks be addressed, that living standards be maintained and that potential threats of serious or irreversible impacts be managed. The Plan pursues three goals in order to achieve sustainable development: 1- to protect the environment within the LISA for future generations, 2- to manage land use and development to improve the health and quality of life for residents of LISA and, 3-to provide economic opportunities and development within LISA. To do so, the lands of the LISA are divided into six broad land use designations as shown in Figure 10:

- National Park Designation
- Environmentally Sensitive Area Designation
- Community Designation
- Heritage Area Designation
- Traditional Use Designation
- General Use Designation

The National Park Designation is mainly covered by the Torngat Mountains National Park, but it also includes the recently announced Mealy National Park Reserve at the southern edge of the LISA. The Environmentally Sensitive Area Designation is attributed to important ecological systems and critical wildlife habitats that are particularly sensitive to human activities, which are generally coastal areas. Development is quite limited within this land designation. The Heritage Area Designation is applied to sites of great historical, archaeological, spiritual and cultural significance to preserve the Inuit patrimonial legacy

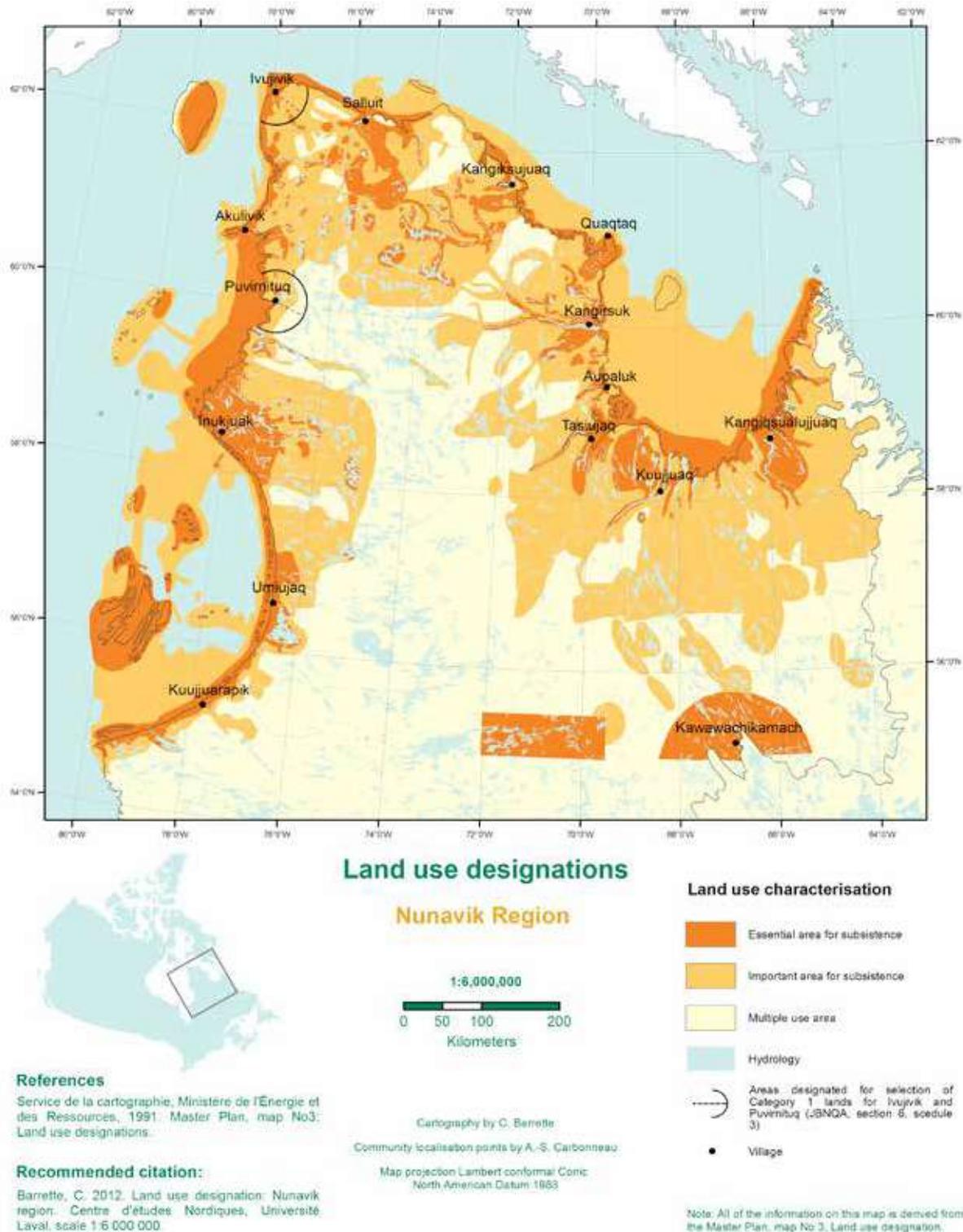
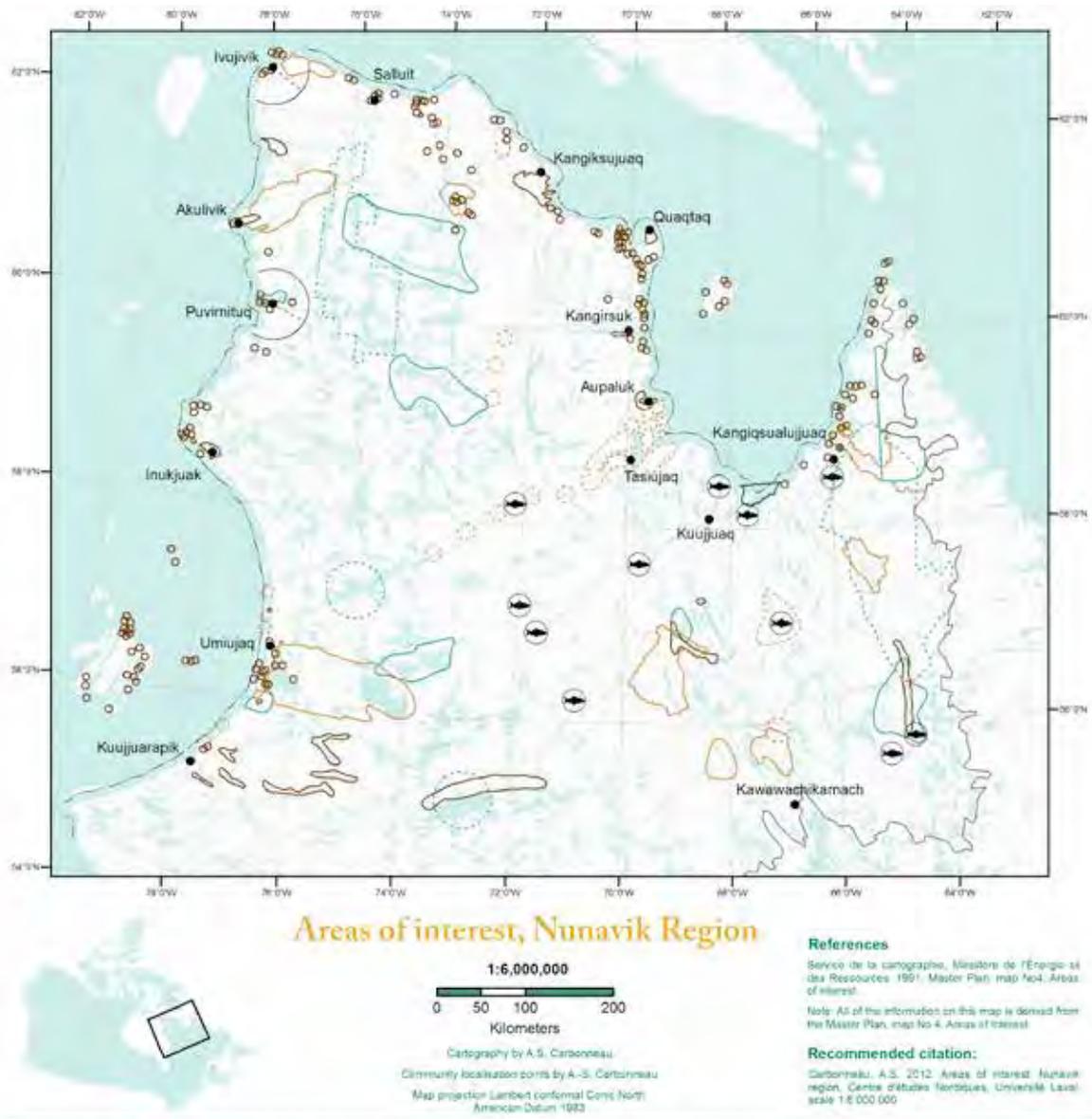


Figure 8. Map no. 3 of the Kativik Region's Master Plan showing the Land Use Designations.



Areas of interest characterisation

Historical

An area of historical interest includes all sites with a potential historical, cultural or sacred significance for the residents of the region and of significance to Quebecers in general.

Esthetic

An area of esthetic interest includes all sites that, because of their beauty or uniqueness, merit recognition, protection or development.

Area identified by the ministère de l'Environnement et de la Faune.

Area identified by the residents of the Kativik region; proposed for formal recognition and protection by government. (Undefined limits)

Ecological

An area of ecological interest includes all sites whose flora and fauna, both terrestrial and marine, have exceptional characteristics that merit recognition and protection.

Land areas representative of ecosystems (Potential ecological area).

Caribou calving grounds.

Caribou calving grounds (undefined limits). Area identified by the residents of the Kativik region; proposed for formal recognition and protection by government.

Mutual sanctuary. This zone is not under the jurisdiction of the KRG.

Foreshore (A 10 km wide coastal zone recognized for its biological diversity and its high biological productivity.) This zone is not under the jurisdiction of the KRG.

Areas designated for the selection of Category 1 lands for Ivujivik and Puvimittuq (JBNGA, section 6, schedule 3)

Salmon river.

Nasatopa estuary. This zone is not under the jurisdiction of the KRG.

NOTE: Offshore islands lie within the District of Franklin or the District of Keewatin, N.W.T.

Figure 9. Map no. 3 of the Kativik Region's Master Plan showing the areas of historical, esthetic and ecological interest.

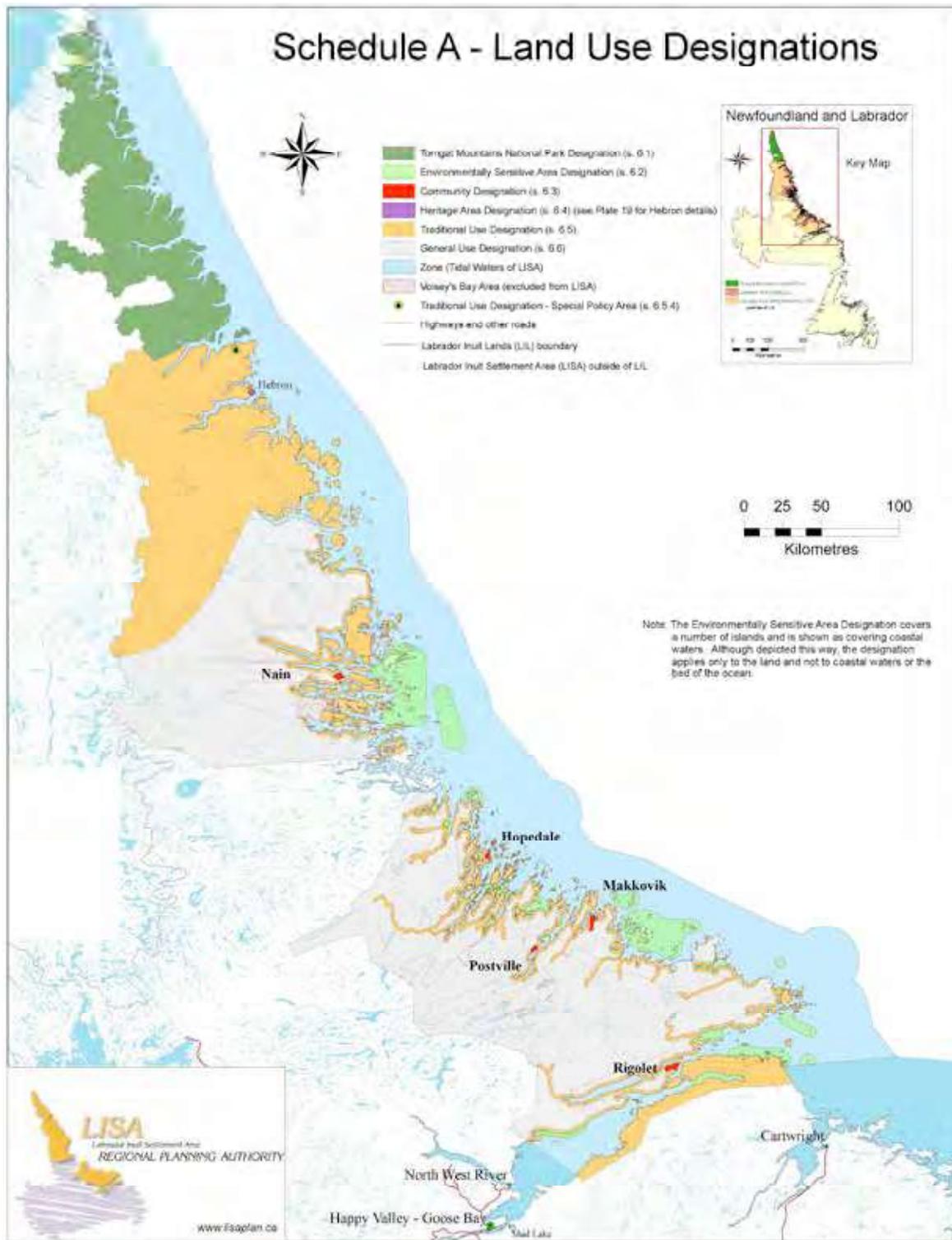


Figure 9. Land Use Designations of the Regional Land Use Plan for the LISA.



and showcase their history by promoting ecotourism activities. Traditional Land Use Designation is applied to areas used by Inuit for traditional activities such as hunting, trapping, fishing and berry picking. For instance, this latter designation has been assigned to the calving area of the George River Caribou herd to ensure that any development within this area will take into consideration its potential impacts upon the caribou herd population and health. Finally, the General Use Designation allows for a broad range of economic activities and development such as ongoing and future mineral exploration and exploitation, which remain subject to appropriate policies to protect the environment.

1.5 Potential industrial development and conservation

The planning of future protected areas needs to take into consideration overwhelming factors that will likely affect

the natural environment such as climate change and the pressure for industrial and commercial developments, keeping as a guideline the interests of Inuit which are well stated in both the Nunavik and Nunatsiavut land management plans.

For instance, the government of Québec has promised to preserve or protect a large percentage of the territory from industrial development. Thus, a positive context exists for achieving protection objectives of quality lands and the protection of biodiversity as a whole.

Among the industrial activities to be developed through Québec's Plan Nord, mining is probably the most important because of the great mineral potential of Nunavik and the current increase in demand for metals on international markets. A preliminary study led by the Ministère des Ressources Naturelles et de la Faune (MRNF) du Québec in collaboration with researchers from Université du Québec à Montréal (UQAM) and

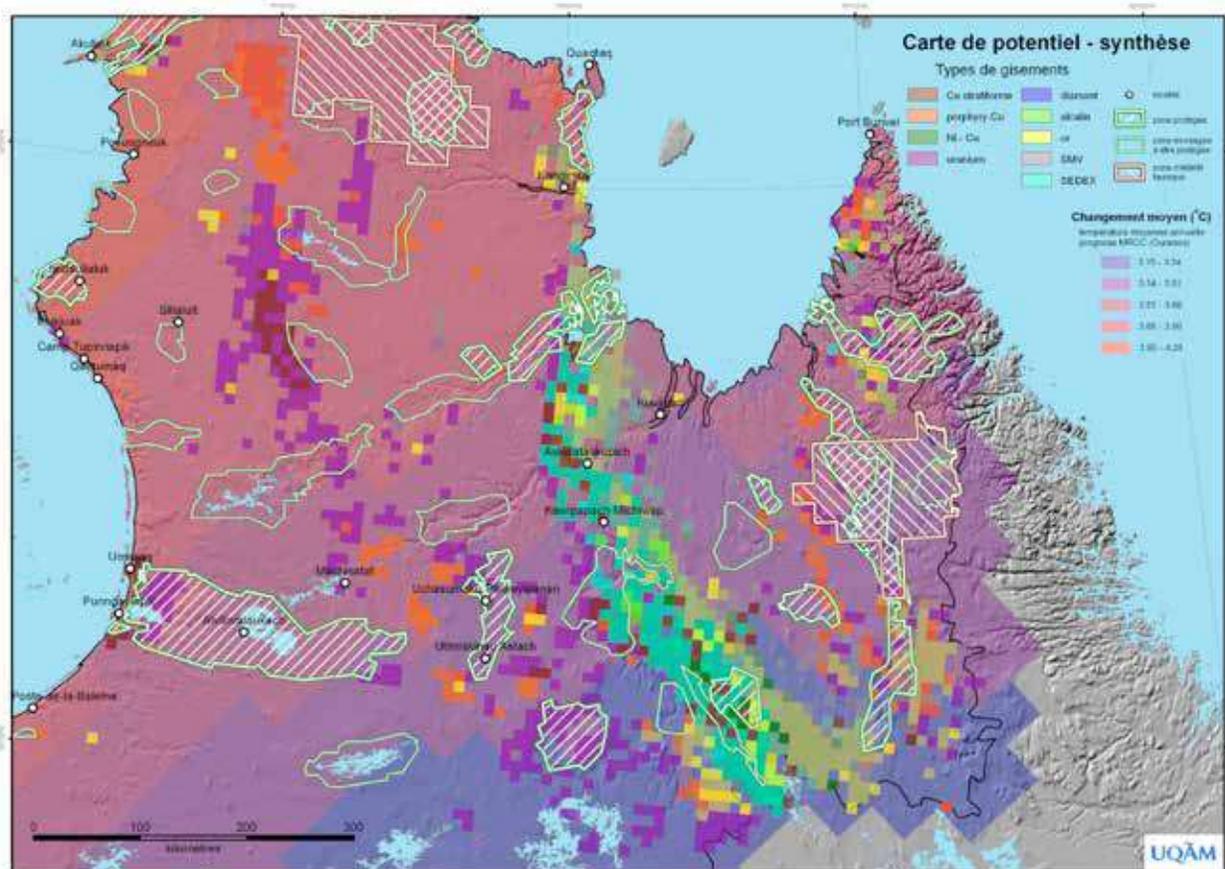


Figure 11. Synthesis map showing the mining potential in Nunavik with current and future natural protected areas and projected climate changes between the 1961-90 and 2041-70 periods. From Jébrak et al. 2010.

l’Institut National des Sciences de l’Univers (CNRS, France) shows that there are relatively few spatial overlaps between the zones of high mineral potential and the current and planned protected areas in Nunavik (Figure 11; Jébrak and al. 2010). However, the location of access corridors for mine sites relative to valuable Inuit ecosystems and the issue of ecosystem connectivity will be at the core of negotiations for launching mining projects. In Nunatsiavut, the Regional Land Use Plan for LISA already identifies “Exempt Mineral Lands” (EML). “Within EML identified in the Regulations there is a ban on staking mining claims”.

The potential development of hydro-electric projects poses a threat to the integrity of some major river basins

and estuaries that have a high ecological value and that would normally be given a protected status. Seeking alternative energy sources might be a component of the strategy used to protect these valuable ecosystems. Another important element is the need to maintain free connections between dispersed protected areas to maintain biodiversity over the whole territory, for instance by allowing plant and animal migrations, rather than running the risk of creating an archipelago of impoverished protected areas. Other aspects that will require consideration are the demographic variations of large animal populations, such as the caribou, and the geographical shift in distribution ranges of some species (both terrestrial and aquatic, e.g. charr and caribou; see chapters 7 and 9) that



climate warming has begun to provoke. A long-term dynamic vision of the functioning of the ecosystems over the territory that goes far beyond the basic idea of protecting fixed areas is required even though such areas add up to a large percentage of the territory.

In Nunavik, the protected areas network also builds on the main paths for improving the network's quality as highlighted in the publication *Portrait du réseau d'aires protégées au Québec – période 2002-2009* (Brassard et al. 2010). However, additional scientific knowledge is still necessary to better support the process for improving the protected areas network in the 2010-2015 period, in particular knowledge linked with adaptive measures to climate change. Nunatsiavut also has great mining potential and will surely have to deal with the increased pressure from this industrial sector while planning protected areas.

As the Kurrurjuaq-Torngat Mountains dual park system shows, landscapes, ecosystems and human history have little concern for political borders. Neither have the caribou...

1.6 Conclusion

The Inuit of Nunavik and Nunatsiavut live in coastal communities on the rich shores of a large peninsula, but the whole territory used to be their living area. They share a common cultural, even family, history that spans the last several thousand years. They share similar experience in terms of contact with western society. The Inuit of Nunavik and Nunatsiavut have territorial agreements with provincial governments and with the federal government. Thanks to travel, education and electronic communication, Inuit are active members of the World society. Affected by economic and social difficulties, they also face

challenges associated with the impacts of climate warming on every aspect of life. These challenges come at the same time as a huge international economic interest in the natural and mostly non-renewable resources of the territory, which may bring various benefits.

The vast amount of integrated Inuit knowledge and collective thinking behind the development of the comprehensive Land Management Plans for both Nunavik and Nunatsiavut strongly demonstrate that the challenges of climate change adaptation and modern sustainable development will be tackled with the willing leadership of Inuit. The achievement of further development rests on this leadership.

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Chapter 2. Climate variability and change in the Canadian Eastern Subarctic IRIS region (Nunavik and Nunatsiavut)

Lead authors

Ross Brown^{1,2} and Mickaël Lemay³

¹Environment Canada, ²Ouranos, ³ArcticNet, Centre d'études nordiques, Université Laval

Contributing authors

M. Allard, N.E. Barrand, C. Barrette, Y. Bégin, T. Bell, M. Bernier, S. Bleau, D. Chaumont, Y. Dibike, A. Frigon, P. Leblanc, D. Paquin, M. J. Sharp and R. Way

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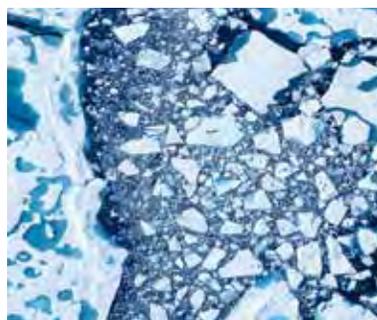
Ouranos played an important role in the development of this IRIS assessment by providing output from the Canadian Regional Climate Model as well as climate-related expertise to the scientists working in the diverse fields covered in the assessment. This information is an essential building block for the assessment and development of local and regional adaptation strategies. Daniel Caya in particular is acknowledged for providing detailed and constructive review comments of the draft chapter.

CONSORTIUM ON REGIONAL CLIMATOLOGY
AND ADAPTATION TO CLIMATE CHANGE



Key messages

- * Paleoclimate reconstructions indicate the climate of the Nunavik-Nunatsiavut IRIS region has experienced a long-term cooling trend over the past approximately 3000 years, with major climate fluctuations in the Medieval Warm Period (warming) and Little Ice Age (cooling). The climate began to warm during the 20th Century with a marked warming pulse after 1993 that has triggered a rapid response in the environment, especially the cryosphere (snow and ice cover, permafrost, and glaciers). Dendroecological evidence and climate observations show evidence of long term significant increases in precipitation over the region.
- * There is some uncertainty in the timing of the recent period of warming. Satellite snow cover data and vegetation monitoring suggest the climate has been changing for at least 30-40 years while air temperature observations from coastal sites show warming did not occur until 1993. These differences may reflect different climate regimes between coastal areas and inland areas and/or different response processes.
- * The cryosphere (solid precipitation, snow and ice cover, glaciers and permafrost) is responding very rapidly to recent warming. Snow and ice cover are forming later and melting earlier with annual losses of snow and ice cover duration on the order of 0.5 to 1.0 days/yr. Warming of permafrost by 2°C has resulted in a dramatic increase in the number of thermokarst lakes and active layer detachments, and glaciers in the Torngat Mountains lost ~20% of their area between 2005 and 2007. Traditional knowledge indicates that these changes are outside the envelope of previous community experience.
- * Climate change projections for the 2041-2070 period (compared to the 1971-2000 period) indicate warmer temperatures and increased precipitation over the region. The largest changes are projected to occur in the winter season with the spatial pattern of projected changes typically exhibiting a NW-SE gradient with the largest changes over the north-western part of Nunavik. The results suggest a shortening of the snow and ice cover season by 3-4 weeks, an increase in growing season length by 2-3 weeks with up to 50% more growing degree days, and increases in annual precipitation of 15-25% with a larger fraction of annual precipitation falling as rainfall.
- * The climate of the Nunavik-Nunatsiavut IRIS region is strongly influenced by variability in atmospheric and oceanic circulation at annual to multi-decadal scales. In particular, the year-to-year variability of the climate of Nunatsiavut is closely linked to the North Atlantic Oscillation. For some variables such as local precipitation, the internal climate variability will likely dominate any climate change signal over the next 30-50 year time period.
- * Reliable and sustainable environmental monitoring and prediction systems are essential to supporting decision making and adaptation in the Nunavik-Nunatsiavut IRIS region. The merging of traditional and scientific knowledge in community-based monitoring initiatives appears to be a useful framework for improved monitoring and understanding of changing environmental conditions with the relevant connections to ensure that new information is translated into enhanced safety and improved decision making.



2.1 Introduction

The purpose of this chapter is to highlight the key characteristics of the climate of Nunavik and Nunatsiavut that are important for natural systems, ecosystem services and human activities, and present scenarios of projected changes in key climate variables and indicators that may occur over the next ~50 years. Climate is the key driver of processes such as snow and ice formation, frozen ground, spring thaw, water cycling, and plant growth that define the environment and sustain ecosystem services (see examples in Table 1). In this sense, climate represents a “resource” that influences the value and the quality of the environment, but it also entails management of “risks” particularly in the context of a changing climate (“Climate as Resource, Climate as Risk”, Stehr and vonStorch 2009).

The organization of the Chapter is as follows: Section 2.2 provides an overview of the sources (and limitations) of the information available for characterizing the climate

of the region and its variability and change; Section 2.3 presents a general description of the main drivers of the climate of Nunavik and Nunatsiavut with sub-sections providing more detailed information on variability and change in important components of the climate system over the period of available historical and paleoclimatic data; Section 2.4 presents a summary of the climate change projections for 2050 provided in detail in Appendix A at the end of this Chapter. The Chapter ends with a summary and conclusions in Section 2.5 that are encapsulated in the “key messages” shown above.

2.2 Climate observations and information

There are a number of challenges to characterizing the climate of Nunavik and Nunatsiavut, foremost of which is the uneven spatial and temporal coverage of climate observations. Daily climate observations of temperature

Table 1. *Examples of climate sensitivities identified in this IRIS assessment report.*

VARIABLE/ACTIVITY	CLIMATE SENSITIVITY
Freshwater Resources (Chapter 4)	The amount, timing, temperature and chemical and biological properties of freshwater are sensitive to air temperature and to precipitation amount and type.
Traditional Foods (Chapter 5)	Winter hunting activities are particularly sensitive to snow and ice conditions. A projected shortening of the ice and snow cover seasons will affect both availability and access to fresh meat.
Infrastructure (Chapter 6)	Projected warming and increased winter snow accumulations contribute to permafrost thawing, a deepening of the active layer, and a host of related phenomena such as active layer detachments and enhanced erosion of coastal areas, all of which pose additional challenges for northern infrastructure.
Arctic Charr (Chapter 7)	Fish abundance and habitat are sensitive to ice cover, water temperature and water quality.
Vegetation Dynamics (Chapter 8)	Warming and changes in precipitation regimes are contributing to an increase in woody vegetation and a northward and up-slope expansion of treelines.
Caribou Dynamics (Chapter 9)	Caribou are sensitive to ice cover (migration routes), rain-on-snow events (affect access to winter forage), summer snow cover (residual snow patches reduce insect harassment) and the timing of vegetation green-up.

and precipitation are available for most communities but the length and period of observations are quite variable. For example, only Kuujuaq, Goose Bay and Cartwright have continuous daily climate data available from pre-1950 to date; many of the other stations stopped reporting in the early 1990s or started reporting in the 1980s. The climate observing network is also almost completely co-located with coastal communities and may not necessarily reflect what is going on further inland. The main locations of the climate stations used in this Chapter are Inukjuaq, Kuujuarapik, Kuujuaq and Schefferville in Nunavik, and Goose Bay, Cartwright, Makkovik, and Nain in Nunatsiavut (for location map see Figure 1, Chapter 1).

Climate data are also subject to random and systematic errors related to observers, instrumentation, and changes in measurement site and observing procedures. For example, precipitation is one of the more difficult climate variables to measure accurately, particularly snowfall (Doesken and Judson 1997, Goodison et al. 1998), and it has much more spatial and temporal variability than air temperatures and may not be adequately sampled over a particular region of interest. This is especially true of Nunavik and Nunatsiavut where there are only a handful of stations with sufficiently long periods of record suitable for monitoring variability and change in precipitation over the past 50–60 years, and most of these are located on the coast. Major data gaps exist over Ungava Peninsula and the Torngat Mountains so not much can be said about precipitation variability and change in these regions from the historical climate data archive. Satellite data can help fill in the gaps in surface networks for some variables e.g. surface temperature (Hachem et al. 2009) and snow cover extent (Brown 2010), but the period of coverage tends to be relatively short and there are few surface observations for validating satellite products over the interior. Longer-term climate information can be inferred from environmental indicators such as the areal extent of glaciers (Section 2.3.5), permafrost conditions (e.g. active layer depth and permafrost temperature – see Section 2.3.6) and various proxy sources of climate-related information such as permafrost temperature (e.g. Chouinard et al. 2007),

temperature reconstructions from tree rings (e.g. Jacoby et al. 1988), reconstruction of past climates from analysis of fossil chironomids and pollen (e.g. Kerwin et al. 2004, Fallu et al. 2005) and reconstruction of information on snow depth and water levels from dendroecological analysis of tree morphology and ice abrasion (e.g. Lavoie and Payette 1992, Bégin and Payette 1988, Lemay and Bégin 2008).

Traditional knowledge is another useful source of information for documenting anomalous events and trends, particularly ice and snow cover, that have major impacts on hunting and transportation. While this information is not quantitative, it provides a local-scale record of environmental change. For example, Elders of Quaqtaq, Umiujaq and Kuujuaq report that since the 1980s ice forms later and melts earlier, rain is more frequent, there is less snowfall and wind patterns have changed in Hudson Bay and Hudson Strait (Tremblay et al. 2009, Clerc et al. 2011).

2.3 The climate of Nunavik and Nunatsiavut

Nunavik and Nunatsiavut are located between 55° and 63°N on the eastern margin of the North American continent (see Figure 1 in Chapter 1). The region is bounded on three sides by water bodies: Hudson Bay to the west, Hudson Strait and Ungava Bay to the north, and the Labrador Sea to the east, with a major north-south mountain chain (the Torngat Mountains with elevations of ~1500 m) in northern Nunatsiavut that acts as a barrier to Atlantic air masses moving into Nunavik. The geography of the Nunavik-Nunatsiavut IRIS region means it experiences a continental-type climate but with higher snowfall amounts than similar latitudes west of Hudson Bay (Phillips 1990). Snow and ice cover are present on average from November to May (Tables 2 and 4), and the region is affected by winter storms that follow preferred tracks up Hudson Bay to Foxe Basin, and up the Labrador Coast to Baffin Bay (Brown et al. 1986). These contribute to a dynamic coastal sea ice regime (Canadian Coast Guard,

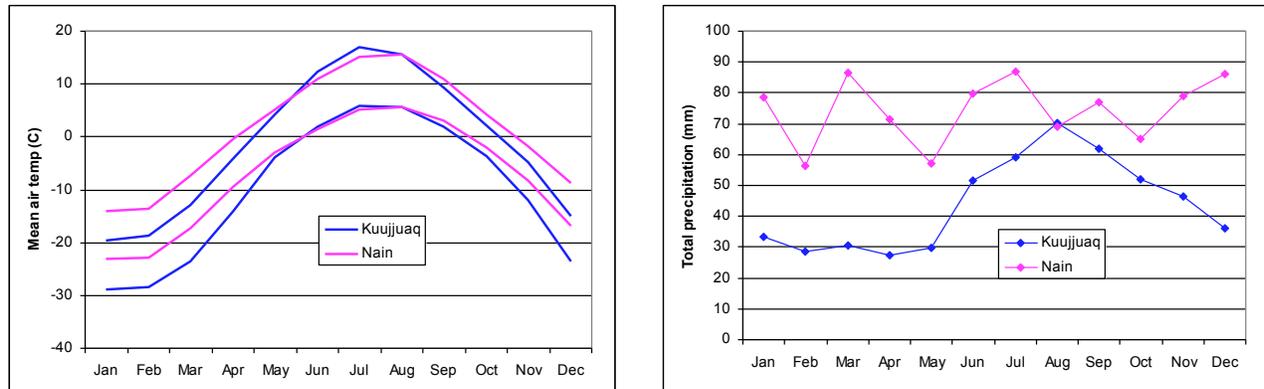


Figure 1. Comparison of monthly mean maximum and minimum air temperatures (left) and monthly mean total precipitation (right) at Kuujjuaq (blue) and Nain (magenta) over the 1971-2000 period. Values obtained from online climate normals provided by Environment Canada at www.climate.weatheroffice.gc.ca/climateData/canada_e.html.

Ice Navigation in Canadian Waters, <http://www.ccg-gcc.gc.ca/e0010736>). The region is also characterized by strong northwest-southeast gradients in air temperature and precipitation (see Figure 2, p. 35, ArcticNet 2010), and strong coastal gradients in climate particularly over Nunatsiavut. Some idea of the gradient in climate is obtained by contrasting the temperature and precipitation regimes of Kuujjuaq and Nain either side of the Torngat Mountains (Figure 1).

The particular location of the Nunavik-Nunatsiavut IRIS region downstream from the North Pacific and adjacent to the North Atlantic means the climate is also influenced on time scales ranging from years to decades to centuries by modes of natural climate variability such as the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), the Pacific North-American pattern (PNA) (Leathers et al. 1991), the Atlantic Multidecadal Oscillation (AMO) (Trenberth et al. 2007) and the North Atlantic Oscillation (NAO) (Rogers and van Loon 1979). Recent studies (Sveinsson et al. 2008, Brown 2010) have shown that the influence of these modes of natural climate variability on the hydro-climate of Québec is highly dynamic in space and time with the zones of influence exhibiting strong gradients over Québec. In addition, there is evidence (Walter and Graf 2002, Yu and Zwiers 2007, Yu et al. 2007) that some of the major modes of circulation dynamically inter-

act with each other (e.g. PDO and PNA, and AMO and NAO) which further complicates efforts to characterize and understand natural climate variability over northern Québec and Labrador.

2.3.1 Air temperature

Air temperature is a key climate variable in cold region climates where many processes are sensitive to changes in temperature e.g. freeze-up, spring melt, vegetation growth, ground thawing and freezing. Information on temperature variability over Nunavik and Nunatsiavut for the period of historical climate observations from the 1920s was obtained from the CRUtem3v (CRU) land-based surface air temperature data set of Brohan et al. (2006) for Québec and Labrador north of 55°N. The seasons are defined on the basis of the snow and ice cover (Figure 2) where fall (Oct.-Nov.) and spring (April-May) correspond to the periods of snow cover onset and snow melt. Summer (Jun.-Sept.) is usually free of snow and ice, and Winter (Dec.-Mar.) corresponds to the period with continuous snow and ice cover with the maximum snow accumulations typically occurring in March-April. It should be noted that the climate station data used in the CRU gridded dataset is biased to coastal locations, and there are larger uncertainties in regionally-average temperature series derived from the CRU dataset before

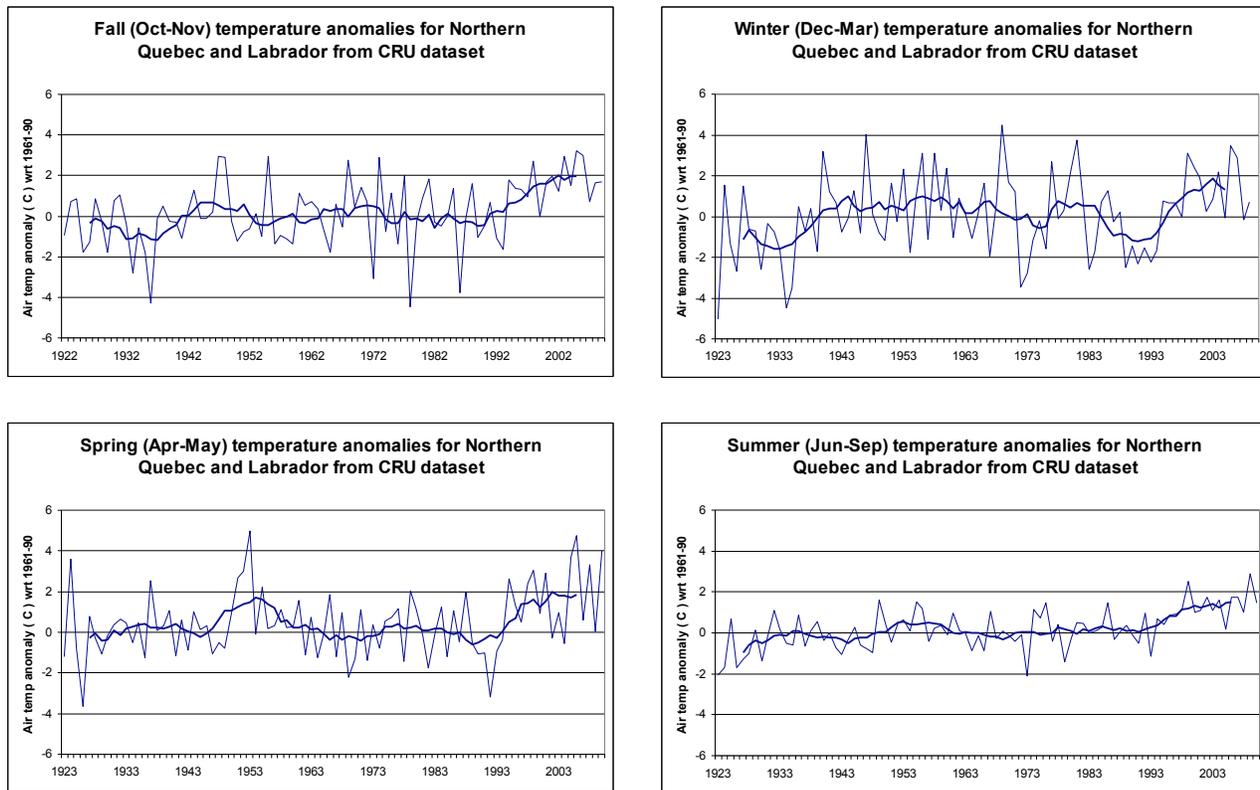


Figure 2. Regionally-averaged seasonal air temperature anomalies (with respect to a 1961–1990 reference period) for northern Québec and Labrador (north of 55°N) from the CRU gridded temperature dataset. The smoothed line is the result of applying a 9-term binomial filter.

~1950 when there were fewer stations making observations. A single regionally-averaged temperature series covering both Nunavik and Nunatsiavut was used to document temperature variability over the IRIS region as separate Nunavik and Nunatsiavut series were found to be essentially identical using data from either the CRU dataset or the National Center for Environmental Prediction (NCEP) Reanalysis (Kalnay et al. 1996).

Figure 2 shows that temperature exhibits large interannual variability in all seasons except summer, with periods of winter cooling in the 1930s and late-1980s. The later period of the 20th Century is characterized by a rapid warming of about 2°C that is present in all four seasons. The exact reasons for this abrupt warming are unclear but it may be linked in part to a warming phase of the previously mentioned AMO cycle of sea surface temperature

variability over the north Atlantic (Chylek et al., 2009). A short-lived period of spring warming is also apparent in the early 1950s that coincided with the last warm period peak in the AMO. The CRU regionally-averaged temperature series agree closely with series computed from the NCEP Reanalysis (Kalnay et al. 1996) available from 1948 (not shown). This provides a somewhat independent verification as the NCEP reanalysis does not assimilate land station air temperature observations directly (it assimilates temperature soundings from balloons, aircraft and satellites as well as sea-surface temperatures – see Kistler et al. 2001). Paleo temperature reconstructions have identified previous warm episodes affecting the region such as the Mid-Holocene Warming and the Medieval Warm Period (see Section 2.3.6). Traditional knowledge indicates that the recent warming is outside the envelope defined by previous community experience.

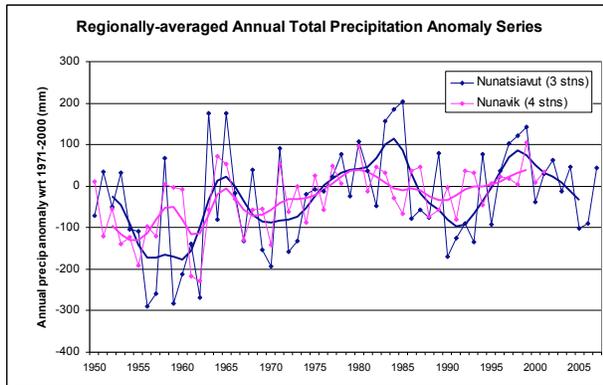


Figure 3. Regionally averaged total annual precipitation amount anomalies (mm) with respect to a 1971-2000 reference period for climate stations with at least 40 years of data in the period since 1950 in the rehabilitated monthly precipitation dataset of Mekis and Hogg (1999; updated to 2008). There were insufficient stations to compute a regional average for Nunavik after 2001. The smoothed lines are the result of applying a 9-term binomial filter.

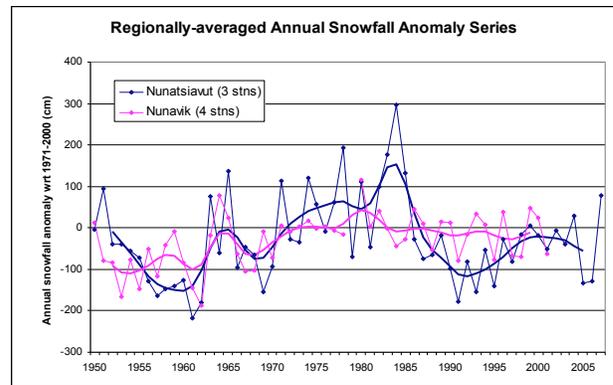


Figure 4. Regionally averaged total annual snowfall (cm) with respect to a 1971-2000 reference period for climate stations with at least 40 years of data in the period since 1950 in the rehabilitated monthly precipitation dataset of Mekis and Hogg (1999; updated to 2008). There were insufficient stations to compute a regional average for Nunavik after 2001. The smoothed lines are the result of applying a 9-term binomial filter.

2.3.2 Precipitation

Precipitation is a key climate variable for the snow cover, water resources and ecology of the region. Regionally-averaged annual anomaly series (with respect to a 1971-2000 reference period) of annual total precipitation and annual total snowfall for the period from 1950 were generated from the rehabilitated monthly precipitation dataset of Mekis and Hogg (1999, updated to 2008) that includes corrections for data homogeneity and regional differences in average snowfall density (Mekis and Brown 2010). The dataset includes four stations in or near Nunavik (Inukjuaq, Kuujjuaq, Kuujjuarapik, and Schefferville) and four stations in or near Nunatsiavut (Goose Bay, Cartwright, Makovik and Nain). There were insufficient data at Nain to include it in the Nunatsiavut regional series which means the regional average is biased toward the southern part of the region. However, Nain annual snowfall data from 1985-2007 were found to correlate significantly (0.05 level) to the regional average ($r=0.56$) so the regional average is still capturing some of the variability seen further north.

Figure 3 shows that the regional series from both regions follow a similar pattern with strong interannual variability superimposed on cyclical variations of ~10-20 years with a significant (0.05 level) increase in annual precipitation in both regions over the period since 1950. Over the 1950-2001 period precipitation increased 17% for the stations included in the Nunavik regional average and 13% for the stations included in the Nunatsiavut regional average. The increase in precipitation appears to be part of a longer-term trend based on dendroecological evidence of increasing lake-levels since the 17th Century (Bégin and Payette 1988) as well as evidence from climate observations of hemispheric-wide 20th Century increases in precipitation over higher latitudes (Min et al. 2008). The results for total annual snowfall (Figure 4) show patterns of variability similar to total precipitation but with decreases in snowfall amount after ~1985 over Nunatsiavut. Over the 1950-2001 period annual snowfall amount increased 23% (significant at the 0.05 level) for the stations included in the Nunavik regional average and 8% (not significant) for the stations included in the Nunatsiavut regional average. The rapid drop in annual precipitation and snowfall amounts over Nunatsiavut from 1984-1993

is driven in part by more frequent positive NAO years (especially the strongly positive NAO winters of 1989 and 1990) that are associated with cold-dry conditions over the Labrador coast (Brown 2010). The influence of NAO on temperature and precipitation drops off quickly moving inland from the Labrador coast (see Figure 8) which may be why this decrease is less pronounced in the Nunavik series.

2.3.3 Snow cover

Snow covers land and ice in Nunavik and Nunatsiavut for more than six months of the year from November to May (Figure 5 and Table 2) and plays key roles in climate (e.g. insulates soils, modifies ice growth, and influences energy and water budgets), ecosystems (e.g. winter protection for plants and animals), and human activities (e.g. transportation and shelters). The key snow cover properties for

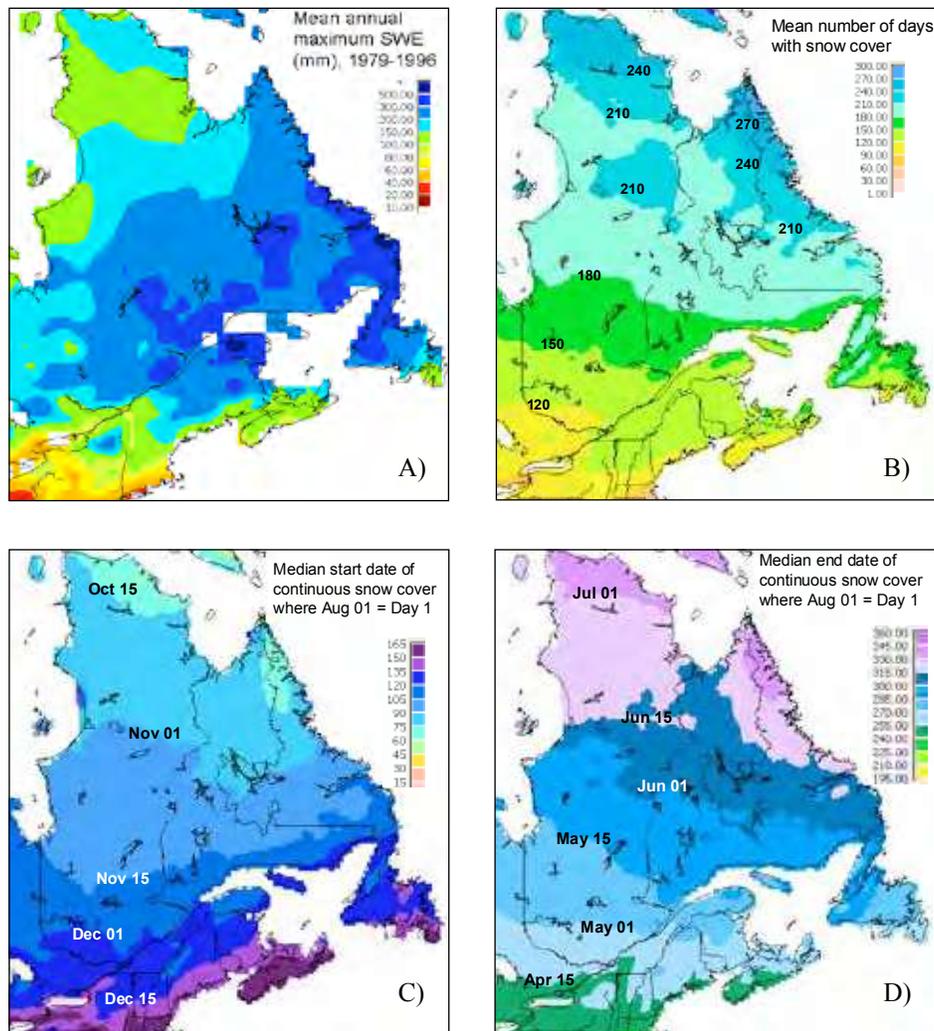


Figure 5. (A) Estimated mean annual maximum snow accumulation in mm water equivalent for 1979-1997 period from Brown et al. (2003). (B) Mean duration of snow cover (days) and (C) Median start and (D) end dates of continuous snow cover over the 2000/01-2008/09 snow seasons based on the NOAA 24-km daily snow cover analysis product (Helfrich et al. 2007). Start (end) date was defined as the first day with 30 consecutive days of snow (no snow).

Table 2. 1971-2000 mean snow cover conditions at climate stations within or adjacent to the Nunatsiavut-Nunavik IRIS region with at least 10 years of daily snow depth observations in the 30 year period. Mean annual snowfall amounts were computed from the rehabilitated precipitation dataset of Mekis and Hogg (1999; updated to 2008). Source: R. Brown, *Env. Canada*, March 2010.

NUNATSIAVUT REGION				
VARIABLE	GOOSE BAY	CARTWRIGHT	MAKKOVIK	NAIN
Station elevation (m)	46	14	66	6
Number of years data	30	30	15	18
Latitude, Longitude (°)	53.3°N, 60.4°W	53.7°N, 57.0°W	55.1°N, 59.2°W	56.5°N, 61.7°W
First date of any snow on the ground	Oct 9	Oct 14	Oct 7	Oct 8
First date of continuous snow cover*	Nov 13	Nov 18	Nov 7	Nov 9
Last date of continuous snow cover**	May 15	May 26	May 29	May 29
Last date of any snow on the ground	May 29	Jun 2	Jun 7	Jun 9
Annual snow cover duration (days)	182.9	191.3	203.4	197.9
Annual snowfall (cm)	530.6	653.2	593.6	683.6
Maximum snow depth (cm)	118.5	195.7	97.4	135.8
Date of maximum depth	Feb 27	Mar 16	Mar 31	Mar 17
Avg snow depth (cm) over period with continuous snow cover	53.1	87.7	47.1	58.9

NUNAVIK REGION				
VARIABLE	SCHEFFERVILLE	KUUJJUARAPIK	KUUJJUAQ	INUKJUAQ
Station elevation (m)	522	21	34	3
Number of years data	21	28	30	21
Latitude, Longitude (°)	54.8°N, 66.8°W	55.3°N, 77.8°W	58.1°N, 68.4°W	58.5°N, 78.1°W
First date of any snow on the ground	Sep 21	Oct 3	Sep 27	Sep 19
First date of continuous snow cover*	Oct 25	Nov 2	Nov 1	Oct 28
Last date of continuous snow cover**	May 23	May 13	May 20	Jun 2
Last date of any snow on the ground	Jun 6	Jun 5	Jun 7	Jun 22
Annual snow cover duration (days)	216.0	193.7	204.6	221.1
Annual snowfall (cm)	575.9	338.6	368.4	306.3
Maximum snow depth (cm)	104.2	46.8	62.6	57.8
Date of maximum depth	Mar 11	Mar 5	Feb 24	Apr 1
Avg snow depth (cm) over period with continuous snow cover	53.2	26.9	32.7	33.4

* Defined as the start of the first two week period with snow depths ≥ 2 cm

** Defined as the start of the first two week period with snow depths < 2 cm

ecosystem services are the duration of the snow cover, the depth, the amount of water stored in the snowpack (referred to as the snow water equivalent or SWE), and the physical structure of the snowpack which includes a range of properties such as the density, crystal structure, and the presence of surface crust and/or ice layers. These snow properties have implications for the ground thermal regime, transportation, snow shelter construction, and caribou grazing. Analysis of recent satellite snow cover data (Figure 5) shows that the longest seasonal snow cover in the IRIS region is found over the northern part of the Torngat Mountains (~270+ days) with the shortest snow cover season (~180 days) in the Hudson Bay coastal region around Kuujjuarapik. The main drivers of the regional pattern of snow accumulation are proximity to moisture sources and preferred tracks of winter storms, and terrain elevation. In the Nunavik-Nunatsiavut IRIS region the largest snowfall amounts and snow accumulations are found along the Nunsiavut coast and over the Churchill Falls region (Table 2 and Figure 5A). The depth of snow that accumulates each year varies greatly with terrain, vegetation and elevation as snow deposition in open environments is strongly affected by blowing snow processes (Pomeroy and Gray 1995, Liston and Sturm 1998). This is evident in Figure 6 that shows SWE observations made every ~3 m along a ~1.7 km transect near Puvirnituq in late-February 2008. The large peaks in SWE coincide with terrain conditions that favour snow deposition while the low SWE areas are where snow was exposed to wind scour.

Providing reliable information on snow accumulation over the Nunavik-Nunatsiavut IRIS region is a challenge because of the paucity of surface observations and difficulties developing reliable satellite-based methods for monitoring SWE or snow depth over forest and tundra. Development of new satellite boreal and tundra algorithms specific to the Arctic region (e.g. Derksen et al. 2008, Lemmetyinen et al. 2009) may overcome some of the limitations of previous global satellite SWE retrievals. Surface-based SWE observations are made from weekly snow surveys at several hundred sites in Québec and Labrador but the station distribution is strongly biased to southern regions and over the main hydro-electric producing corridor traversing the La Grande Basin into Churchill Falls. The number of survey sites also varies considerably over time and there are no sites in Nunavik or Nunatsiavut with consistent long term data for looking at variability and trends in SWE. A number of gridded SWE datasets have been developed over Québec in recent years (e.g. Brown et al. 2003, Brown and Tapsoba 2007, Brown 2010) and multi-decadal series of simulated SWE information are available from runs of the Canadian Regional Climate Model (CRCM) driven by reanalysis data (Frigon et al. 2008). Dorsaz (2008) showed that there are large differences between the various SWE products over Nunavik and Nunatsiavut.

There are relatively few climate stations with long periods of snow cover observations for monitoring changes in snow cover conditions in Nunavik and Nunatsiavut.

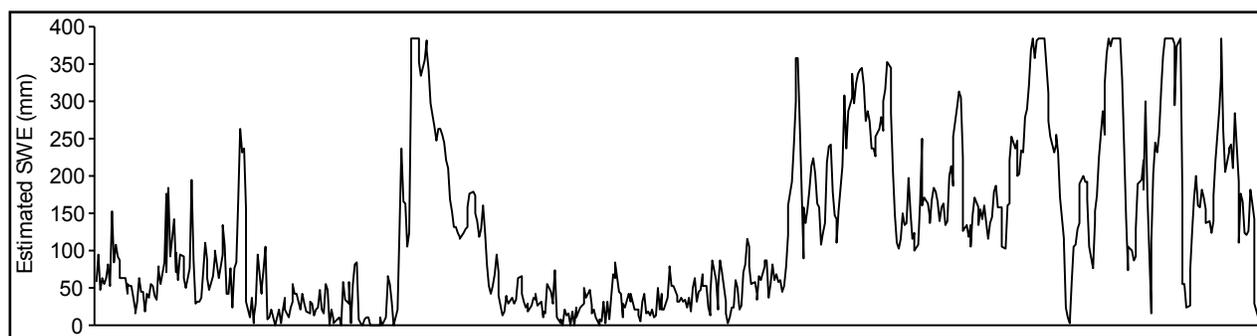


Figure 6. Variation in snow water equivalent along a 1.7 km transect near Puvirnituq on February 26th, 2008. Source: P. Toose, *Env. Canada*.

Table 3. Change in snow cover variables over the 1950/51 to 2006/07 snow seasons from daily snow depth observations made at open sites. Trend was computed using the Mann-Kendall method (Zhang et al. 2000) with a minimum of 45 years data required to compute a trend. Changes significant at the 0.05 level are shown with an asterisk.

VARIABLE	GOOSE BAY	CARTWRIGHT	KUJJUARAPIK	KUJJUAQ
First date of continuous snow cover	7.6 days later	6.9 days later	5.2 days later	14.3 days later*
Last date of continuous snow cover	3.8 days earlier	7.5 days later	13.1 days earlier	30.6 days earlier*
Snow cover duration in Aug-Jan period (days)	-12.8	0.1	-4.0	-17.3
Snow cover duration in Feb-Jul period (days)	-11.9*	6.3	-7.9	-32.7*
Annual snow cover duration (days)	-28.4*	5.1	-12.8	-42.1*
Annual snowfall amount (% of 1971-2000 mean)	-5.4	11.2	-1.7	7.2
Maximum snow depth (cm)	-19.0	114.0*	-85.3*	-64.8*
Date of maximum depth (days)	-0.2	-0.2	-40.5	-43.2*

Of the eight stations summarized in Table 2, only four had sufficiently complete data to compute trends over the 1950/51 to 2006/07 period (Goose Bay, Cartwright, Kuujuarapik and Kuujuaq). The results (Table 3) show decreases in snow cover duration and maximum snow depth at three of the sites. Cartwright was the exception showing a rather dramatic increase in maximum snow depth of over 1 meter over the 57 years. It is unclear what is driving this increase as total annual snowfall only increased by 11% over the same period, and Goose Bay located just over 200 km inland showed no evidence of any increases in maximum depth or snowfall. The two Nunavik sites differed from the Labrador sites with trends toward an earlier date of maximum snow depth of ~40 days over the 57 years. Of the four sites, Kuujuaq showed the most significant changes in snow cover over the 57 year period with a more than 40 day reduction in snow cover duration driven by 30 day earlier melt in the spring, with a 60 cm reduction in annual maximum snow depth.

It is important to note when discussing the above snow trends that daily snow depth observations at climate stations are made at open grassed sites, often near airports, that may not be representative of the surrounding terrain.

These sites will certainly not reflect any changes in snow accumulation related to enhanced growth of arctic shrubs (Sturm et al. 2001 and Chapter 8 of this report). However, analysis of trends in snow cover from the National Oceanic and Atmospheric Administration (NOAA) satellite dataset (Robinson et al. 1993) for the period from 1972 to 2010 (Figure 7) confirm the station trends showing that the strongest reductions in snow cover in the Nunavik-Nunatsiavut IRIS region are found over northern areas with the largest changes in the melt season. According to the satellite data, annual snow cover duration has decreased 3-4 weeks over Nunavik and Nunatsiavut since 1972.

Analysis of reconstructed snow cover over the 1948-2005 period by Brown (2010) provided evidence of a clear north-south gradient in trends in annual maximum SWE (SWE_{max}) and spring snow cover duration over Québec, with significant local decreases over southern Québec and significant local increases over north-central Québec. The increase in SWE_{max} over northern Québec is consistent with reconstructed lake levels (Bégin 2000), analysis of black spruce growth forms (Lavoie and Payette 1992), hemispheric-wide trends of increasing precipitation over higher latitudes (Min et al. 2008), projec-

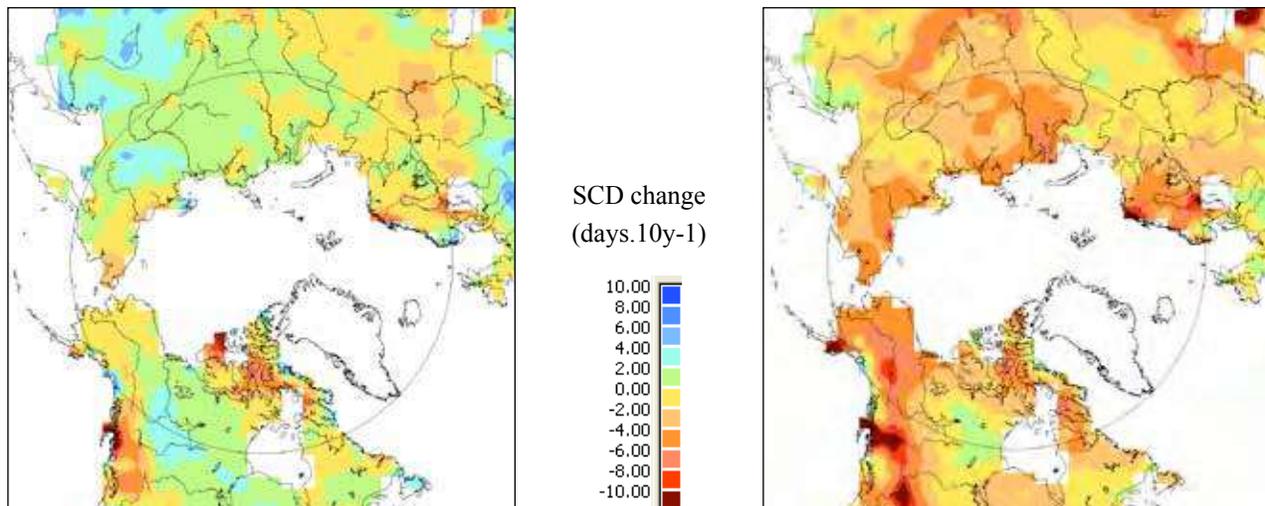


Figure 7. Trend ($\text{days} \cdot 10\text{y}^{-1}$) in snow cover duration (SCD) at the start (left) and end (right) of the snow season over 1972/73 to 2009/2010 snow seasons from the NOAA weekly dataset of Robinson et al. (1993). Trends were computed using the method of least squares. Source: R. Brown, EC.

tions of global climate models (Räisänen 2007, Brown and Mote 2009) and the RCM runs provided in Appendix A (Figure A12).

Snow cover variability in Québec is significantly linked to most of the major atmospheric circulation patterns affecting the climate of eastern North America but the influence is characterized by strong multidecadal-scale variability (Sveinsson et al. 2008, Brown 2010). The North Atlantic Oscillation (NAO), defined previously, has a particularly

important influence on temperature, precipitation and snow cover along the Labrador coast, but the influence, especially for precipitation, does not extend far inland (Figure 8).

2.3.4 Ice cover

Lake, river and sea ice are major components of the winter environment in Nunavik-Nunatsiavut with a wide range of related climate-sensitive ecosystem services in-

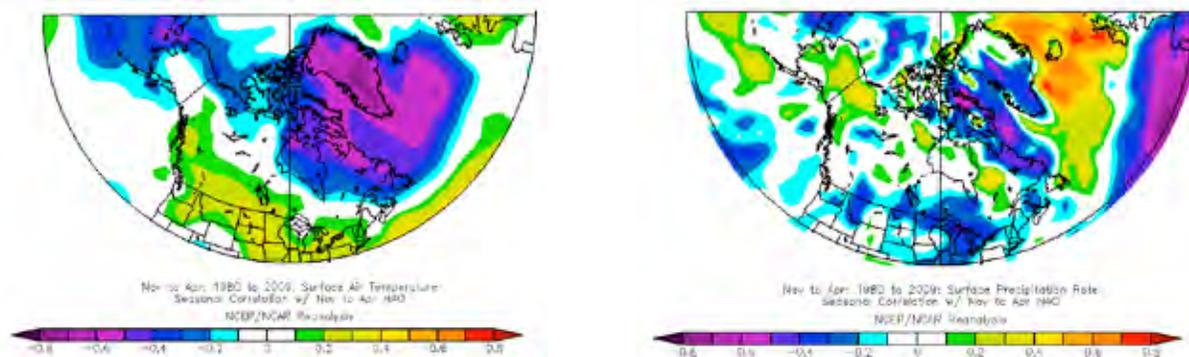


Figure 8. Correlation of mean surface air temperature (left) and precipitation rate (right) from the NCEP Reanalysis for the November to April period with the corresponding seasonally-averaged values of the NAO index over the period 1980-2009. Source: NOAA/ESRL Physical Sciences Division (<http://www.esrl.noaa.gov/psd/data/correlation/>).

Table 4. Summary of ice thickness information from weekly ice thickness measurements made over 1972-1990. The first and last measurement dates provide a rough indication of when ice was safe to travel on. Source: R. Brown, *Env. Canada, March 2010*.

SITE	NYRS	MAX THICKNESS (CM)		DATE OF MAXIMUM THICKNESS		DATE OF FIRST THICKNESS MEASUREMENT		DATE OF LAST THICKNESS MEASUREMENT	
		AVG	STD	AVG	STD (DAYS)	AVG	STD (DAYS)	AVG	STD (DAYS)
Inukjuak	18	226.8	30.2	Apr. 24	17.0	Dec. 10	8.6	May 30	9.3
Kuujjuaq	19	143.2	20.4	Apr. 25	14.8	Nov. 06	9.3	May 18	12.4
Kuujjuarapik	19	142.6	25.3	Apr. 08	15.4	Dec. 17	14.5	May 03	13.8
Schefferville	17	132.5	12.6	Apr. 22	11.3	Nov. 06	10.8	May 24	11.2
Cartwright	19	110.9	21.8	Apr. 10	17.2	Dec. 21	10.1	May 14	11.2
Goose Bay	18	99.2	15.1	Apr. 12	14.3	Dec. 06	12.5	May 08	14.8

cluding over-ice transport, hydroelectric production, human infrastructure and numerous ecological and water quality characteristics (Beltaos and Prowse 2009, ArcticNet 2010). Recent changes in the precipitation regime and the length and intensity of the cold season (Furgal et al. 2002, Lafortune et al. 2006, Tremblay et al. 2009) are adversely affecting ice trails and safe access to the territory and its resources with important socioeconomic consequences for Northern residents (Furgal and Tremblay 2010). Ice cover formation, melt and dynamics are sensitive to a range of meteorological variables (e.g. wind speed, temperature, precipitation (rain and snow), cloudiness, solar radiation and humidity) and changes in any of these can influence ice composition, thickness, stability and the complex interactions between hydrodynamic, mechanical and thermal processes (Beltaos and Prowse 2001, Morse and Hicks 2005, Beltaos 2007, Prowse et al. 2007a,b, Hicks 2009, Shen 2010). Coastal zones and particularly large river mouths where settlements tend to be located have been shown to be particularly sensitive environments to recent change (ArcticNet 2010), and ice conditions in these environments can be especially hazardous due to the dynamic nature of the ice regime.

There are a number of challenges for monitoring changes in the ice climate of Nunavik. There are few in situ records (Duguay et al. 2006) and satellite observations have various limitations related to the frequency, consistency and length of coverage. Regular weekly measurements

of ice thickness close to shore were made at a number of communities in the region over various periods from the 1950s to the 1990s. Analysis of the period with the most complete data (1972-1990, Table 4) shows that for this particular time period, ice safe enough to travel on was present for approximately six months from December to May, with maximum ice depths of 1 to 2 m in April. For the six sites with data, maximum ice thickness varies approximately with latitude; the thickest ice forming at Inukjuak (58.5°N) and the thinnest at Goose Bay (53.3°N).

Unfortunately there are few ice measurements after the early-1990s to document the response of ice cover to the recent period of warming (Duguay et al. 2006). Freeze-up and break-up observations from the Koksoak River near Kuujjuaq (Figure 9) over the period from 1951 to 1995 show a statistically significant trend toward earlier melt by 0.7 days/yr over the period but no trend in date of freeze-up. However, the net impact on ice cover duration was offset by a compensating trend toward earlier ice onset up to ~1980. The greater variability evident in ice onset date compared to ice-off date is typical as the former is more sensitive to a wider range of processes than melt (Duguay et al. 2006, Brown and Duguay 2010). The ice cover duration inferred from Figure 9 stayed relatively constant until the early 1980s when duration decreased rapidly and became more variable in response to trends toward later ice formation and earlier ice melt. While

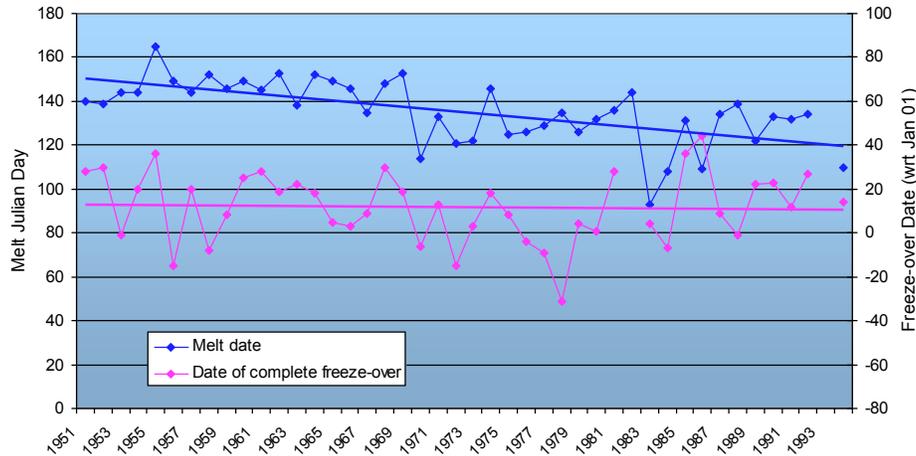


Figure 9. Annual variation in dates of complete freeze-up and melt for the Koksoak River at Kuujjuaq from 1951-1995. Complete freeze-up dates are plotted with respect to Jan 01 as the date can vary from December to February. Source: Figure prepared by R. Brown with data from Lenormand et al. (2002).

these results are only from one site, the observed trend toward a shorter ice season at Kuujjuaq is consistent with trend analysis of lake ice cover from remote sensing and in-situ observations that showed ice break-up is occurring earlier and freeze-up later for most lakes in Canada (Lati-fovic and Pouliot 2007). The trend toward earlier melt

of freshwater ice is also seen offshore. Recent analysis of trends in summer sea ice concentration in Canadian waters over the 1968-2008 period (Figure 10, Tivy et al. 2011) shows that some of the largest and most significant decreases have occurred in marine areas adjacent to the Nunavik-Nunatsiavut IRIS region (e.g. Hudson Strait: $-16.0 \pm 3.4\%$ per decade; North Labrador Sea: $-17.8 \pm 4.8\%$ per decade). Summer sea ice concentration trends in East Hudson Bay were also negative ($-11.5 \pm 6.8\%$ per decade) but not statistically significant. Atmospheric teleconnection patterns have also been shown to play a role in the regional response of lake ice over North America (Walsh et al. 2005, Bonsal et al. 2006), although the results from Bonsal et al. (2006) suggest the linkages are strongest over western Canada.

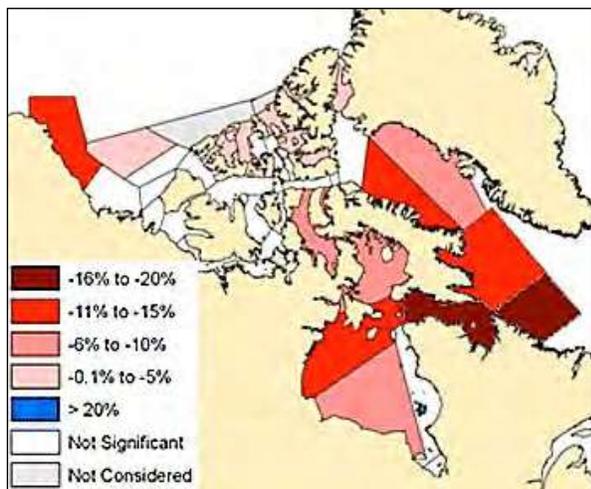


Figure 10. Trend in summer sea ice concentration from 1968 to 2008; units are % per decade. Only trends significant to the 95% confidence level are shown. From Tivy et al. (2011).

The decreasing ice cover observed at Kuujjuaq is also consistent with the previously documented trends toward a shortening of the snow cover season and with traditional knowledge. For example, a general decrease of ice thickness has been observed on rivers and lakes in Nunavik during winter (Furgal and Prowse 2008) and, the Kuujjuamiut have reported an increase of ice instability on the Koksoak River that has triggered safety concerns and al-



tered traditional ice routes for harvesting and subsistence purposes (Tremblay et al. 2009, Clerc et al. 2011). Northern communities in the Northwest Territories, Nunavut and Alaska have reported similar experiences (Tremblay et al. 2006a,b). Elders of Quaqtuaq, Umiujaq and Kuujjujaq have observed later ice formation, earlier spring thaw, more rain, reduced snow fall and a change in wind patterns in Hudson Bay and Hudson Strait since the 1980s (Clerc et al. 2011).

While we have a reasonable understanding of how climate changes will affect the thickness and duration of ice cover (Dumas et al. 2006, Dibike et al. 2011a,b), our understanding of how climate change will alter other freshwater-ice processes such as ice-cover composition and break-up dynamics remains poor (Prowse et al. 2007a,b, Beltaos and Prowse 2009). Real-time satellite information on ice cover properties and dynamics is a potentially useful tool for gaining this understanding and adapting to a changing ice regime. Synthetic Aperture Radar (SAR) has been shown to be very effective for monitoring ice conditions in coastal environments and rivers as the information is

obtained at high resolutions and is not limited by solar illumination or cloud cover. The high resolution (8 m for RADARSAT 1 in Fine beam) and very high resolution (3 m for RADARSAT-2 Ultra-fine mode) also allow for the monitoring of medium sized rivers and more recently the Koksoak Estuary (Weber et al. 2003, Gauthier et al. 2006, Drouin 2007, Unterschultz et al. 2008, Bleau 2011). The radar signal is sensitive to the ice roughness (surface scattering) and to the shape, size and density of air inclusions within the ice cover (volume scattering), and can be used to discriminate different freshwater ice types or ice formations (Gherboudj et al. 2007). Further efforts have been made to merge RADARSAT all-weather ice monitoring capabilities with local knowledge of ice conditions at several northern communities (www.noetix.on.ca/floedge.htm) and for the Koksoak River at Kuujjujaq (climatechange.krg.ca/kuujjujaq.html). For example, Figure 11 shows a close match between aerial observations and a RADARSAT-derived map of river ice conditions (Gauthier et al. 2010). Traditional knowledge has been incorporated in the process of ice cover classification and mapping from RADARSAT at Koksoak River.

Table 5. Description of river ice cover classes shown in Figure 11 based on traditional knowledge interpretation of RADARSAT imagery. Modified from Gauthier et al. (2010).

CLASS	MAP LEGEND DESCRIPTION	CLASSES FROM USER WORKSHOP (TRADITIONAL KNOWLEDGE)	INUKTITUT TERMS
#1	Open water		
#2	Smooth, clear lake ice or border ice. May apply to water with some moving ice floes	Smooth ice cover / Undisturbed ice cover	Uluaguti / Tuvaq
#3	Sparse to moderately dense moving ice floes / Rougher lake ice	Drifting frazil pans	Sikuat
#4	Dense moving ice floes to agglomerated ice floes / Rough ice in side channels or on sand banks	Ice pans start to concentrate and agglomerate together	Puttaat / Ittiniit
#5	Agglomerated ice (rough)	Agglomeration completed	Puttaat / Ivuniit
#6	Consolidated ice (rougher)	Thermal or frazil ice blocks piling up	Ivuniit / Maniiligaat

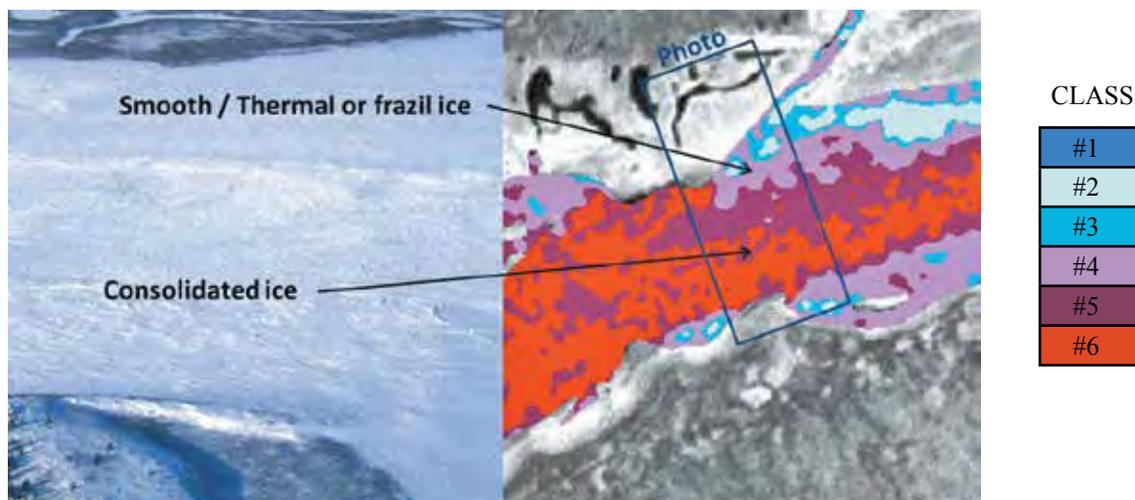


Figure 11. Positive match between aerial observation and RADARSAT derived river ice map for Consolidated (class # 6 and 5) and smoother ice (class # 2 to 4) on the 29 February 2008. Modified from Gauthier et al. (2010).

Table 5 presents the classified ice types shown in Figure 11 and the corresponding Inuktitut terminology based on consultations with local elders carried out as part of an International Polar Year project.

The installation of moored upward looking sonar systems for continuous measurement of river ice thickness would complement RADARSAT all-weather ice monitoring capabilities (Marko and Jasek 2010). There are ongoing challenges to make such systems fully operational at lo-

cations not serviced with AC power and more effort is needed to expand capabilities for baseline observations of ice conditions in Nunavik and Nunatsiavut in support of adapting to a dynamic changing ice regime. The merging of traditional and scientific knowledge in community-based monitoring initiatives (Huntington 2008) appears to be a useful framework for improved monitoring and understanding of changing ice conditions with the relevant connections to ensure that new information is translated into enhanced safety and improved decision making.

2.3.5 Glaciers of the Torngat Mountains, northern Labrador: how many and for how long?

Although the occurrence of glaciers in northern Labrador is largely unknown to Canadians and their contribution to Canadian terrestrial ice volume is negligible, their geographic importance as the only glaciers on mainland North America east of the Rocky Mountains and the southernmost glaciers along the highland rim of the Eastern Canadian Arctic makes them of particular interest for scientific study. The glaciers are located in the Torngat Mountains National Park and as such comprise an important component of the natural landscape of Labrador's arctic wilderness; the dependence of other local ecosystems - from tundra vegetation to fiord habitats - on glaciers and their meltwater is not well understood. The glaciers occupy and form part of the natural and cultural landscape of the Labrador Inuit whose Inuktitut term for glacier - *simmik* - translates to Never Melting Ice (Willie Etok, personal communication 2008).

Many will be surprised to learn that the earliest photographic documentation of one of the Torngat glaciers dates back over 100 years. In 1908, E.S. Bryant and H.S. Forbes hiked up from the coast and photographed a small north-facing glacier on Mt. Tetragona from the position of a small recessional moraine (i.e. a ridge of debris formed at the stationary margin of a glacier during overall retreat) located several hundred metres from the ice front (Figure 12). N.E. Odell and B. Morris subsequently revisited the glacier during D.L. Forbes' expedition to northern Labrador in 1931 - they refer to it as Bryant's Glacier - and photographed the ice terminus from the same ground position (Figure 12). Over the intervening 23 years the glacier margin had retreated 70 to 90 m (Odell 1933). In 1956 the ice terminus was photographed by J.D. Ives (Ives 1957). In commemoration of the first photograph and as a legacy of the third International Polar Year, Bryant's Glacier was revisited and re-photographed in 2008 by T. Bell and employees of Parks Canada and the Nunatsiavut Government (Fig-

ure 12). Over the course of a century, Bryant's Glacier has shrunk significantly and is now largely composed of two smaller ice masses only partially visible in the 2008 photograph (Figures 12 and 13).

Several inventories have been made of the glaciers of northern Labrador, but unfortunately they are either incomplete or unpublished. The earliest inventory was conducted for the Forbes 1931 northern Labrador mapping expedition. The map published by Forbes (1938) shows 61 glaciers in the region north of Nachvak Fiord. As Mercer (1958) and Fahn (1975) noted, "*some of these are extremely small, however, and may not deserve the name 'glacier'*" (p. 676). A Glacier Map of southern Baffin Island and northern Labrador was compiled by W.E. Henoeh and A. Stanley and published in 1968. It contained a total of 62 glacier locations also in the region north of Nachvak Fiord (Henoeh and Stanley 1968).

J. Stix (Dartmouth College, New Hampshire) conducted a reconnaissance inventory of glaciers in the Nachvak Fiord region in 1979. He photographed and reported on the flow conditions of ten ice masses, which he classified as cirque glaciers, cirque glacierettes or upland ice/snowfields (Stix 1980). He compared the ground photography in 1979 with 1:62,572-scale aerial photographs from 1964 to detect any changes in ice extent. He concluded that two of the cirque glaciers may have been advancing, while the others were stagnant or retreating.

More recently, Leblanc and Bell (2008) generated a composite inventory of glaciers in the region using previously published data, National Topographic Series 1:50,000-scale maps, and an unpublished observational database from Parks Canada (A. Simpson, personal communication 2008). The composite inventory of all previous observations suggested that there may be as many as 86 ice bodies in the Torngat Mountains, 65 north of Nachvak Fiord and the remainder farther south, but no assessment of glacier activity was made.

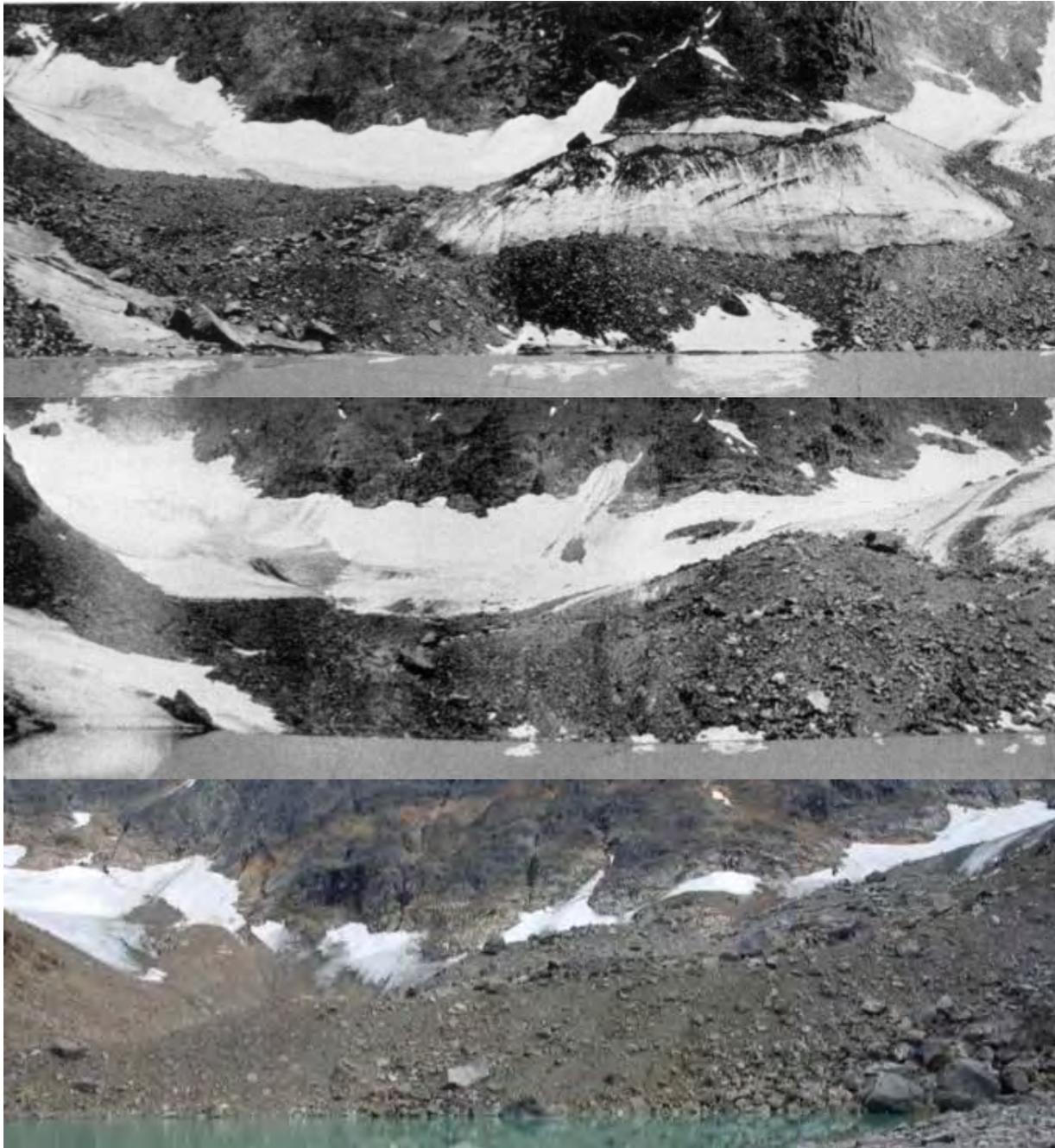


Figure 12. *A century of change at the terminus of Bryant's Glacier on the north face of Mt Tetragona in the Torngat Mountains. Top: Bryant and Forbes, 1908; Middle: Odell, 1931; Bottom: Bell 2008. The active ice front is located at the moraine in the foreground in 1908. By 1931, the terminus is located 70-90 m behind the moraine. In 2008, the glacier is almost split in two with the termini of the two tributary glaciers located on either side of the bottom photograph. See Figure 13 for an aerial perspective of the proposed ice loss and the location of the photographer's position on an end moraine in front of the glacier..*



Figure 13. An aerial perspective of a century of ice loss on Bryant's Glacier. The 1908 and 1931 ice margins are interpreted from the ice outline visible in ground photographs (see Figure 12) and the overall form of the glacier in the 2005 aerial photograph. The 2008 ice margin was mapped from SPOT5 HRS satellite imagery. The total decrease in aerial extent of Bryant's Glacier between 1908 and 2008 is estimated to be 0.344 km² or 38%. For comparison, the recent change between 2005 and 2008 was measured at 0.144 km² or 16% of its 1908 area.

The first scientific study of the glaciers was undertaken by R.J. Rogerson of Memorial University of Newfoundland in the early 1980s. He and his field crew spent 4 seasons (1981-84) measuring the mass balance and morphological characteristics of four glaciers that drain into Ivitak Valley (Ivitak is the Inuit name for the McCornick river valley that appears on NTS topographic maps), on the south side of Nachvak Fiord. During this

period, two glaciers experienced overall positive net mass balance (i.e. the difference between accumulation from snowfall and ablation from melting on a glacier) while the other two were consistently negative; interestingly, the smallest glacier with a negative mass balance advanced its terminal position in each of the study years by an average of 1.2 m (Rogerson 1986).

The current study of the glaciers of the Torngat Mountains was initiated as part of ArcticNet's Nunatsiavut Nuluak project, in partnership with Parks Canada and the Nunatsiavut Government. It has as its primary goal to establish a baseline of current glacier conditions to be used for future monitoring, recent change detection and local hydrological assessment. The research plan involves remote sensing, field surveys and local knowledge from Inuit elders who lived and travelled in the Torngat Mountains. Here we present a brief summary of the first systematic assessment of glacier extent, together with a preliminary estimate of glacier change over the period 2005-2008, using remote sensing techniques only. Data sources and analytical methods were reported in Barrand et al. (2010).

A total of 103 active glaciers were mapped from 1:40,000-scale, colour aerial photographs taken in 2005. The glaciers ranged in size from 0.02 to 1.26 km² for a total glacier area of 19.8 km². Of the 103 glaciers, 17 were not identified in previous inventories; however, it is unlikely that these glaciers have grown in recent decades and more probable that they were missed in previous mapping. The glaciers occur within a coastal region defined by latitude 58.59° and 59.84° North. Most of the glaciers (80%) are smaller than 0.25 km² and only one is larger than 1 km². Glaciers in the Torngat Mountains typically occupy cirque basins with high backwalls and many are heavily debris-covered at lower elevations (Figure 14). Roughly 70% have a northerly aspect (315-45° azimuth), which would maximize the shading effect from high backwalls, but significantly, 10% face south (135-235° azimuth). The elevations of the glacier ter-



Figure 14. View looking south at Abraham (left) and Hidden (right) glaciers in the Cirque Mountain Range, south of Nachvak Fiord. Note the high backwalls shading the accumulation zones of both glaciers.

mini vary from 290 m to 1140 m above sea level (asl), with 14 (14%) having a terminus above 1000 m asl. Approximately 78% of the glaciers are located within 30 km of the Labrador coast.

Glacier mapping from 2008 SPOT5 HRS satellite imagery produced a total of 96 glacier outlines, seven less than the 2005 inventory due to cloud and snow cover masking ice margins. The 96 glaciers covered an area of 16.99 km² and ranged in size from 0.014 to 1.25 km². This represents a decline of 1.74 km² or 9.3% of the 2005 area covered by the same 96 glaciers. Eighty-seven or 91% of the glaciers experienced an areal decrease, with an average discernable decline of 0.024 km². Twenty-two glaciers recorded a change in area of less than 0.05 km², which given the spatial resolution of the imagery likely means an undetectable change.

For the first time there is a complete inventory of northern Labrador glaciers, a measurement of their aerial extent and an assessment of their recent change. The 9.3% reduction in the areal extent of Torngat Mountain glaciers between 2005 and 2008 is dramatic, but needs to be viewed in the context of long-term trends in areal extent and climate. A study of the former is in progress but available published data suggest that glaciers in the Nachvak Fiord region were in retreat in the late 1970s and early 1980s (Stix 1980; Rogerson 1986). The overall mean of the annual net mass balances of four glaciers in Ivitak Valley between 1981 and 1984 was -0.26 m water equivalent per year (Rogerson 1986). Climate data for the period 1997-2008 for the Nachvak Fiord region (see Table 6 caption for details of climate data) indicates an anomalously warm decade compared to the average summer temperature conditions for the past 60 years (Table 6). In fact, 2007 and 2008 were the two

Table 6. *Anomalies for summer temperature (June-August) and winter precipitation (September-May) relative to the average condition for the period 1948-2009 in the Nachvak Fiord region (-5.39°C and 1.76E-04 kg/m²/s, respectively). The temperature data represent conditions at the 700 kPa level to approximate glacier elevations and are from NCEP/NCAR Reanalysis. Precipitation values are also from the 700 kPa level, expressed as a precipitation rate, and are from NMC Reanalysis. Data were accessed from the Royal Dutch Meteorological Institute website (climexp.knmi.nl) on March 25, 2010. Both data sets were derived from an area enclosed by latitude 57.14-61.25°N and longitude 58.75-66.25°W.*

YEAR	SUMMER TEMPERATURE ANOMALY (°C)	WINTER PRECIPITATION ANOMALY (KG/M ² /S)
1999	-0.28	-1.78E-05
2000	1.04	-5.97E-06
2001	0.11	-9.64E-07
2002	0.22	1.40E-05
2003	1.29	-9.14E-06
2004	0.93	4.08E-05
2005	-0.60	3.62E-05
2006	0.22	4.18E-05
2007	1.74	9.42E-06
2008	2.57	-1.74E-05

warmest summers on record, and 2008 was 2.57°C warmer than the 60-year average.

Rogerson (1986) concluded that winter precipitation is the controlling climatic variable in the mass balance of the four study glaciers. Winter precipitation for 2005-2007 was above average for the past 60 years or so; but perhaps of greater relevance was the extended period of below-average precipitation since 1983 (16 of 22 years) and for 5 of the 7 years prior to 2005 (Table 6). The dramatic recent decline in areal extent may therefore be primarily a response to a multi-decadal trend in lower winter precipitation, coupled with anomalously warm summers.

It is too early in our analysis to determine a long-term prognosis for the survival of glaciers in the Torngat Mountains. We are currently applying a distributed, temperature-index melt model (cf. Hock 2003) to analyse the mass balance sensitivity of selected glaciers to climate variables, topographic conditions and surface debris cover and simulate glacier responses to future climate scenarios (King et al. 2009). Once our analysis is complete and we have a longer-term perspective on glacier change, we will be able to test Rogerson's (1986) hypothesis that:

“The survival of glaciers in the Torngat Mountains seems likely for the immediate future even if climate improves slightly. Warmer temperatures in the winter could cause high snowfalls... Furthermore, even if higher temperatures caused much [surface] melt and substantially eroded the glaciers, any reduction in the surface elevation of the glaciers would increase the amount of shading...” (pp 217-218).

2.3.6 Permafrost as a climate indicator

Permafrost's presence and temperature are directly related to local and regional climate, albeit through conditions at the ground surface (e.g. vegetation and snow cover). A description of the permafrost regime in the Nunavik-Nunatsiavut IRIS region is provided in Chapter 6 along with a map showing the spatial distribution of the zones of continuous, discontinuous and sporadic permafrost (see Chapter 6, Figure 1). At depths in the order of tens to hundreds of meters, the vertical temperature profile in permafrost records variations of past surface temperatures, providing a means to reconstruct past climates. Another way to reconstruct paleoclimates in permafrost terrain is to analyse and date (with C-14) the paleosoils and peat layers associated with changes in the dynamics of soil structures and surface landforms (polygon network, palsas, etc.) since these soil features are found under variable surface climatic conditions. This approach uses reconstructed past surface conditions as a proxy for past climates.

In Nunavik, deep borehole thermal profiles were recently used for past climate reconstruction (Chouinard et al. 2007). Ice wedges were studied for several years in an attempt to identify climate thresholds that control ground frost cracking and to reconstruct periods of warm and cold climate regimes (Allard and Kasper 1998, Kasper and Allard 2001). Also, the radiocarbon dating of summital peat on top of palsas (peat covered mounds in the subarctic region near the treeline) in the Umiujaq region determined the period when their surface first heaved above bog level and dried up because of ice formation in the ground and inception of permafrost during cold periods (Marchildon 2007).

Deep borehole temperature profiles at the Raglan Mine in northern Nunavik were used to reconstruct ground surface temperature histories (GSTH) (400 and 800 yr) and to capture Little Ice Age (LIA) cooling (for more details on methods see Chouinard et al. (2007)). They clearly detected the onset of the LIA (800 yr reconstitution) characterised by a drop in ground surface temperature to 0.42 K below the mean surface temperature reference ($\sim -8.57^\circ\text{C}$) (Figure 15). Their results also highlight the warming that took place in the early 20th Century, some cooling in the second half of the Century and the recent warming observed since the early 1990s.

Results from ice-wedge studies, frost cracks and past active layer thickness variations by Kasper and Allard (2001) in northern Nunavik revealed the presence of six distinctive climate periods in the 3400 year period prior to 2000. Although these methods did not provide accurate temperature reconstruction values, the highlighted climate periods corresponded to those identified using other methods such as pollen analyses, climate reconstruction through deep permafrost thermal profiles (central Ungava Peninsula) (Taylor and Judge 1979, Richard 1981), and backward modelling of temperature profiles in Greenland ice cores of the GRIP and Dye 3 drilling projects (Dahl-Jensen et al. 1998). All of these studies showed a general cooling around 3200 BP, followed by a warming associated with the Medieval Warmth (950 to 1100). A clear

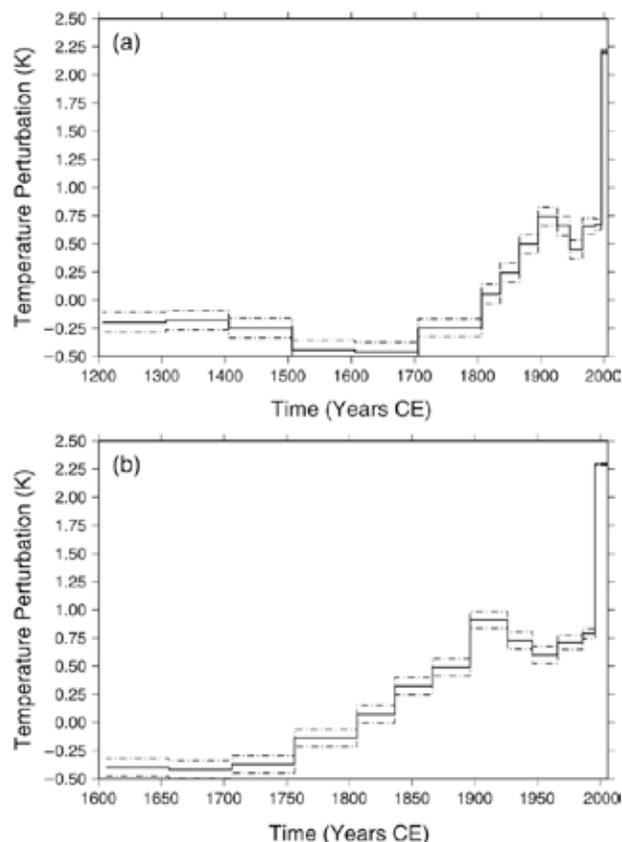


Figure 15. Results of the Monte Carlo inversion for the temperature profile in borehole 0615 for 800-yr GSTH (a) and 400-yr GSTH (b). The solid line represents the average of all temperatures retained for each interval and the dashed lines represent the average \pm one standard deviation. From Chouinard et al. (2007).

signal of a cold climate was highlighted during the LIA (Table 7). In the Subarctic, the discontinuous permafrost wetlands in palsa fields had a first major expansion phase starting around 2300 years ago. The period from 1000 to 500 years ago was warmer as some palsas thawed, but the period from 500 to 100 years ago (roughly from the late 13th Century to the end of the 19th Century, corresponding to the Little Ice Age) was particularly cold.

In the early twentieth-century, a warming trend was detected through cessation of ice-wedge activity (Kasper and Allard 2001). A continuous ground surface warm-

Table 7. General climate period identified through ice-wedge activity and paleoecological interpretations. Timescale is not linear. 0 is year 2000. Modified from Kasper and Allard (2001).

PERIOD	CLIMATE	VEGETATION	ICE-WEDGE ACTIVITY
50-0	Cooling	Sedge and moss	Progressive reaction of ice-wedges
100-50	Warm	Sedge and moss	Cessation of activity
500-100	Cold(est)	Moss dominated Aeolian activity Slope process	Intense activity
970-500	Cooling	Grass dominated Aeolian activity Slope process	Activity generally increasing
1860-970	Generally moist and warm	Sphagnum dominated	Activity generally decreasing Alteration of activation and deactivation
3400-1860	Generally cold and dry	Sedge dominated Aeolian activity	Generally active. Formation of low-center polygons

ing reaching 0.9 K above the reference temperature by the end of the period 1750-1925 was also observed by Chouinard et al. (2007) who highlighted a cooling trend between 1946 and the 1980s with temperature decreases of about 0.3 K. This cooling matched the regional trend reported in other literature (Allard et al. 1995, Wang and Allard 1995, Kasper and Allard 2001) and was identified as the coldest period within the past 100 years. A progressive reactivation of ice-wedge activity associated with cooler temperatures during this period was also noticed by Kasper and Allard (2001).

In the last 10 to 15 years GSTHs provided by Chouinard et al. (2007) showed a clear increase of 2.3 K above the reference temperature. The total temperature perturbation inferred since the end of the LIA (-0.4 K) showed an increase of 2.7 K above the reference temperature by the end of the 1990s. For the past 15 years, results from Chouinard et al. (2007) inferred an increase of about 1.8 K (Figure 15), which is also supported by the recent increase in SAT modeled from the North American Regional Reanalysis (Mesinger et al., 2006) air temperatures for northern Nunavik. Furthermore, these results correlate with the regional air temperature portrait given by meteorological

station measurements of Environment Canada in Iqaluit, Kuujuaq, Inukjuak and Kuujuarapik. The observed temperatures show increasing trends for the last several years which are also reflected by the ongoing degradation of permafrost landforms observed throughout Nunavik (Marchildon 2007, L'Hérault 2009, Payette et al. 2004).

In summary, paleoclimate reconstructions using permafrost temperature profiles, landforms and soil structures provide a general history of climate cooling in Nunavik during the Late Holocene, i.e. roughly since 3000 years ago. The reconstructions also identify two important climate periods. The Medieval Warm Period from roughly the year 1000 to the 14th Century was somewhat warmer, but variable and gradually cooling. The Little Ice Age stands out as having been particularly cold. The 20th Century was characterized by gradual warming ending with a warm pulse that has continued into the 21st Century.

2.4 Climate change projections

Climate change scenarios for the Nunavik-Nunatsiavut IRIS region were developed at Ouranos by physically downscaling outputs from Global Climate Models

(GCMs) run at a 200–400 km to 45 km resolution using the Canadian Regional Climate Model (CRCM) (Caya et al. 1995, Caya and Laprise 1999, Plummer et al. 2006, Music and Caya 2007). The projected changes are derived from the difference between 30 year averages computed over a 1971–2000 “current climate” period and a 2041–2070 “future climate” period corresponding to the 2050 time-frame, and assumed the SRES A2 scenario for future greenhouse gas emissions (Nakicenovic et al. 2000). The 2050 time-frame was selected as this corresponds to a period when the climate change signal is apparent over Eastern North America (Christensen et al. 2007) and corresponds to the planning horizon for many decision makers. A total of six pairs of current and future climate runs from the latest version of CRCM 4.2.3 (de Elia and Côté 2010) were used; five driven by the third generation Canadian Coupled Global Climate Model (CGCM3) (Scinocca et al. 2008, Flato and Boer 2001) and one driven by the ECHAM5 global model from the Max Plank Institute (Roeckner et al. 2003, Jungclaus et al., 2006). The calculated mean change (Δ) from the six different CRCM runs was mapped over the study region along with the standard deviation (STD) of the projected changes to provide some idea of the consistency (or uncertainty) which in this case is mainly related to the internal variability of the climate system as simulated by CGCM3. A more complete de-

scription of the methodology including an evaluation of the climate model performance is provided in Appendix A at the end of this Chapter.

A total of 14 variables were selected for scenario construction based on previous studies (Sharma et al. 2009, Williamson et al. 2009) and their relevance to Nunavik-Nunatsiavut IRIS ecosystems. Further details on the justification for variable selection and the definitions are provided in Appendix A.

- Annual, winter (Oct. to Apr.) and summer (May to Sept.) air temperature
- Sums of thawing degree-days and freezing degree-days with respect to a 0°C threshold
- Sum of growing degree-days with respect to a 5°C threshold
- Start and end dates of summer season with respect to a 0°C threshold
- Annual total precipitation and total solid precipitation
- Mean and maximum snow depth
- Duration of snow cover in first (Aug.-Jan.) and second (Feb.-Jul.) halves of the snow year
- The frequency of winter thaws, freeze-thaw cycles and rain-on snow events

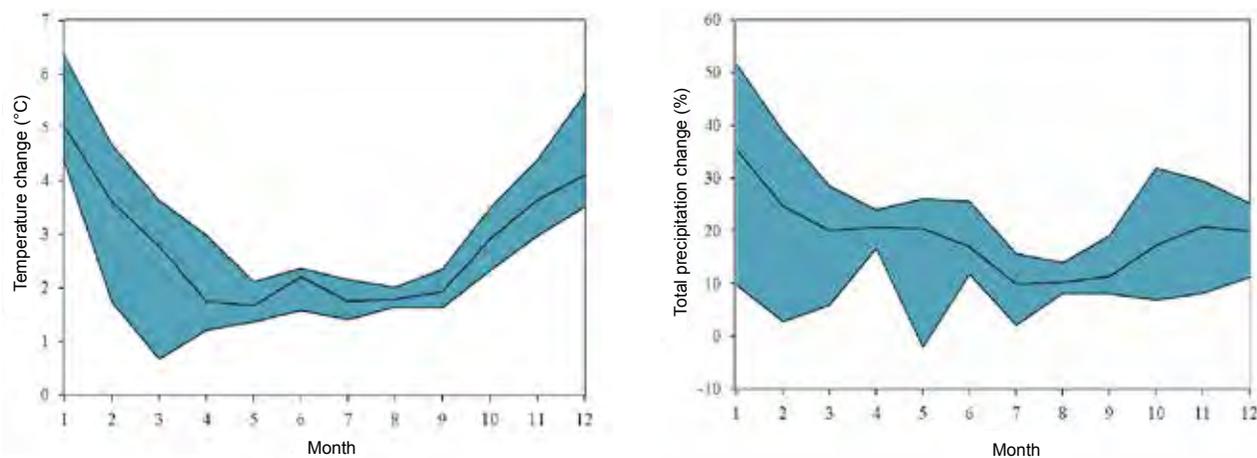


Figure 16. Seasonal character of projected change in monthly mean temperature (left panel) and total precipitation (right panel) from six CRCM runs for 2050 period, averaged over all grid cells in the study region. The outer lines represent the range in the six simulations.

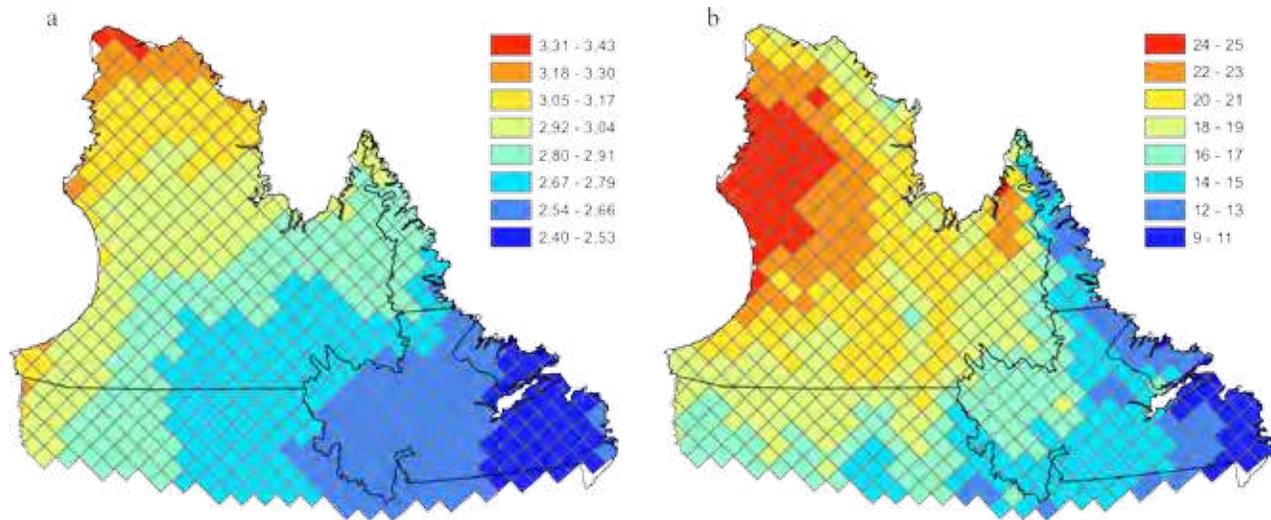


Figure 17. Projected change in (a) mean annual temperature ($^{\circ}\text{C}$) and (b) mean annual total precipitation (%) for 2050 period from six CRCM runs.

Interactive lake and coastal ice processes are not included in the current version of the CRCM but results from recent lake and sea ice modelling studies (Dibike et al. 2011a,b, Dumas et al. 2006, Joly et al. 2010) were examined and are discussed in Appendix A.

The amplitude and seasonal pattern of the projected changes in air temperature and total precipitation averaged over the entire study domain are shown in Figure 16, while the spatial pattern of the changes in annual temperature and precipitation are shown in Figure 17. These two figures encapsulate most of the key features observed in the various climate indicators presented in Appendix A. The two main points are: (1) the largest changes are projected to occur in the winter season with an average 5°C warming and 35% increase in precipitation in January; (2) the spatial pattern of projected changes typically exhibits a NW-SE gradient over the region with the largest changes over the NW part of Nunavik (although this pattern can be inverted depending on the variable selected). A summary of the magnitude and regional pattern of change in each of the 14 variables is presented in Table 8 for Nunavuk and Nunatsiavut. The results suggest a markedly different

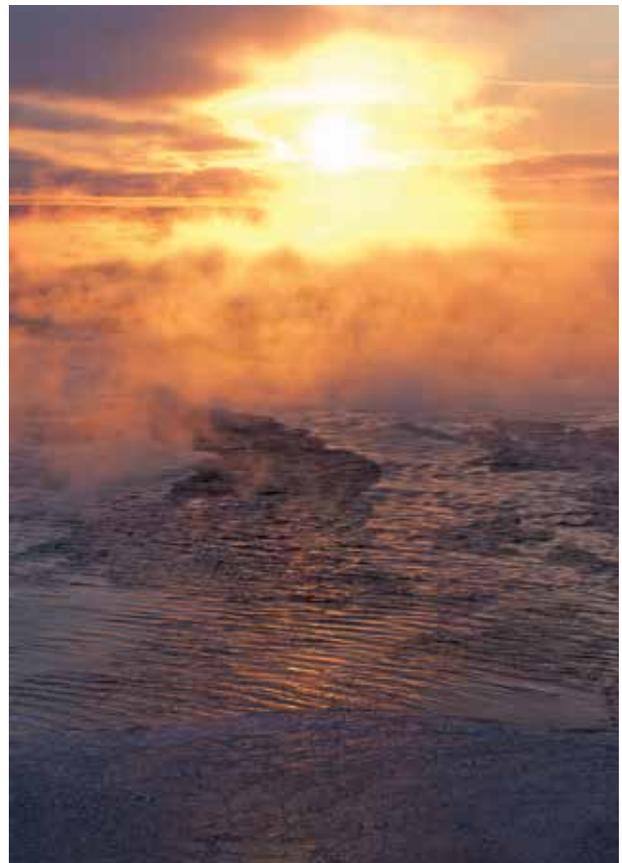


Table 8. Summary of projected changes in climate variables for Nunavik and Nunatsiavut corresponding to 2050. Maps showing the spatial pattern of the projected changes are included in Appendix A. Results are from Ouranos CRCM runs unless specified otherwise. Continued on next page.

CLIMATE VARIABLES	NUNAVIK		NUNATSIAVUT	
	PROJECTED CHANGE OVER REGION	COMMENTS	PROJECTED CHANGE OVER REGION	COMMENTS
Winter air temperature	+3.0 to +5.0°C	NW-SE gradient with strongest warming over northwestern Ungava	+3.0 to +5.0°C	N-S gradient with strongest warming over Cape Chidley area
Summer air temperature	+1.5 to +2.0°C	Strongest warming over north and south with lowest warming over Hudson Bay coastal region	+1.5 to +2.0°C	Strongest warming over Torngat Mountains; less warming in southern coastal region
Summer start date	6 to 11 days earlier	Largest changes over northeastern Ungava; smallest change over southwest region around James Bay	6 to 11 days earlier	Largest changes over Torngat Mountains and coastal areas; smallest changes around Lake Melville
Summer end date	8 to 19 days later	Largest change over southwest region around James Bay and Hudson Bay coast; smallest change over Ungava Peninsula	9 to 12 days later	Largest changes in southern part of region
Thawing degree-days	30 to 65% increase	Largest relative changes over northeastern Ungava; smallest change over southwest region around James Bay	30 to 65% increase	Largest relative changes over Torngat Mountains and coastal areas; smallest changes around Lake Melville
Growing degree-days	50 to 150% increase	Largest relative changes over northeastern Ungava; smallest change over southwest region around James Bay	50 to 130% increase	Largest relative changes over Torngat Mountains; smallest changes around Lake Melville
Annual total precipitation (rainfall + snowfall)	12 to 25% increase	Largest relative increases over western Ungava Peninsula and Hudson Bay coast; smallest increases over southern margins	10 to 15% increase	Little spatial variability over region with slightly higher values inland; Lowest relative increases over southeast coast
Annual solid precipitation (snowfall)	1 to 24% increase	Largest relative increases over northern Ungava Peninsula; smallest increases over southeast	5% decrease to 10% increase	Decreases over southeast; increases over Torngat Mountain region
Winter thaw events (not shown)	Little change	No pattern	Little change	No pattern
Freeze-thaw cycles (not shown)	Little change	No pattern	Little change	No pattern

CLIMATE VARIABLES	NUNAVIK		NUNATSIAVUT	
	PROJECTED CHANGE OVER REGION	COMMENTS	PROJECTED CHANGE OVER REGION	COMMENTS
Start of snow season	5 to 14 days later	Largest change over coastal region north of James Bay; smallest change over Ungava Peninsula	10 to 15 days later	Largest change over southeast coastal region
End of snow season	3 to 11 days earlier	Largest increases over northern Ungava Peninsula; smallest increases over southwest region around James Bay	6 to 11 days earlier	Largest change over Torngat Mountains and southeast coastal region
Mean snow depth	-7 to +7%	Decreases dominate with one area of increase over northern Ungava Peninsula; largest decreases over southern and eastern regions	-10 to -20%	Largest decreases over southeast coastal region
Maximum snow depth	0 to +15%	Same as mean snow depth	0 to -10%	Same as mean snow depth
Rain-on-snow days	Increase of 1-2 ROS days per year	Increases confined to southern part of Nunavik	Increase of 1-2 ROS days per year	Increases confined to southern part of Nunatsiavut
Lake ice freeze-up (Dibike et al. 2011a)	8-14 days later	Largest changes along Hudson Bay coast	8-10 days later	Little spatial variability over region
Lake ice break-up (Dibike et al. 2011a)	14-18 days earlier	Largest changes along west coast of Ungava Peninsula	12-20 days earlier	Largest changes over northern region
Lake ice maximum thickness (Dibike et al. 2011a)	20-30 cm less ice	Largest changes along west coast of Ungava Peninsula	20-30 cm less ice	Largest changes over northern region
Sea ice freeze-up (Joly et al., 2010)	25 to 30 days later over Hudson Bay, James Bay and Foxe Basin	Ungava Bay and James Bay regions most strongly affected in the results presented in Joly et al. (2010)	n/a	
Sea ice break-up (Joly et al. 2010)	22 to 24 days for Foxe Basin and Hudson Bay; 39 days earlier for James Bay	Ungava Bay and James Bay regions most strongly affected in the results presented in Joly et al. (2010)	n/a	
Sea ice thickness (Joly et al. 2010)	30 to 50% reduction in winter ice thickness in coastal zone	Ungava Bay and James Bay regions most strongly affected in the results presented in Joly et al. (2010)	n/a	

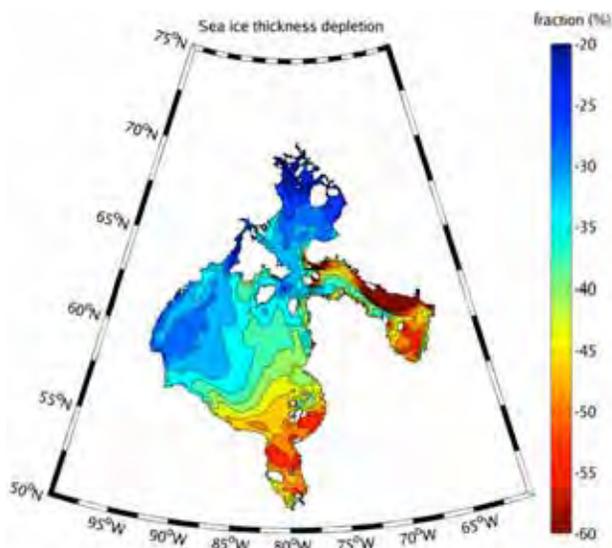


Figure 18. Relative change (%) in winter-averaged (JFMA) sea-ice thickness for 2050 based on CGCM3 downscaled temperature change assuming the SRES A2 emission scenario. Source: Joly et al. (2010).

climate in the Nunavik-Nunatsiavut IRIS region in 2050: the snow and ice cover season will be shortened by 3-4 weeks, the growing season will be 2-3 weeks longer with up to 50% more growing degree days, and there will be increases in precipitation of 15-25% with a larger fraction of annual precipitation falling as rainfall. The sea ice modelling scenarios presented by Joly et al. (2010) for the Hudson Bay region show extensive reductions in early winter ice amount in all coastal regions of Nunavik, with the largest relative decreases in ice thickness over eastern Hudson Bay north of James Bay (in the vicinity of the community of Whapmagoostui) and also in Ungava Bay off Kuujuaq (Figure 18).

It should be noted that 45 km resolution of the RCM used to generate the results shown in Appendix A is still too coarse to capture much of the smaller scale topographic variability over Nunavik and Nunatsiavut. Brown and Mote (2009) showed that the response of snow cover to changes in temperature and precipitation depends strongly on the climate regime and elevation, with the strongest responses in maritime mountainous regions. This point

was also raised in Chapter 8 where it was noted that in Labrador during the relatively warm winter of 2009-10 (characterized by strongly negative NAO conditions) there were increased amounts of snowfall above 600 m but more frequent rain and thaw events at lower elevations. Additional downscaling of the CRCM output to meet the needs of local decision makers can be carried out through a variety of approaches (e.g. Mearns et al. 2003). Higher resolution runs of the CRCM at 15 km will be available in the next few years.

2.5 Summary and conclusions

The available paleo-climate, historical climate and proxy information from the Nunavik-Nunatsiavut IRIS region suggest the climate of the region has been in a period of gradual cooling over the past ~3000 years apart from a short period of warming in the Medieval Warm Period (950-1250) and markedly cooler temperatures during the Little Ice Age (1400-1900). Various data sources show that the second half of the 20th Century has been warmer, but there is some uncertainty as to when the recent period of warming began due to the large interannual variability of the climate of the Nunavik-Nunatsiavut IRIS region. The instrumental temperature record shows a period of rapid warming starting in the early 1990s but there is evidence from a number of other sources (e.g. snow cover trends, tree-ring records, vegetation changes) suggesting the climate has been warming over the past 40-50 years. This can clearly be seen in summer maximum temperature reconstructions from tree-ring data back to 1800 (Figure 19) where summer max temperatures are relatively stable from the late-1800s until 1950-1975 when a warming trend emerges. The differences between the various data sources are likely related to a number of factors including different regional responses to climate warming (e.g. the historical temperature record for the Nunavik-Nunatsiavut IRIS region reflects coastal locations that are strongly influenced by ocean temperatures), and different processes (e.g. ground temperatures respond to changing

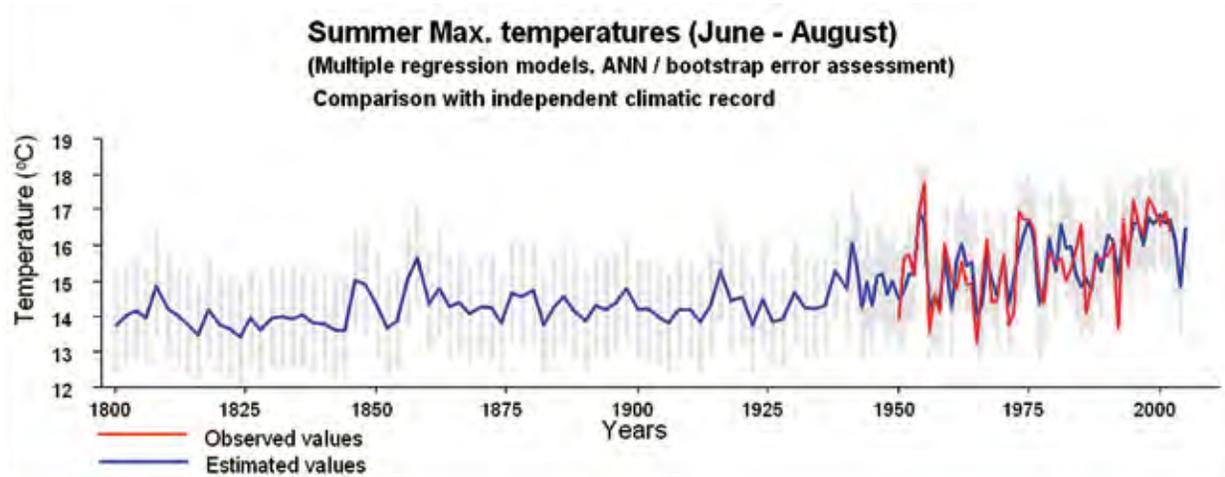


Figure 19. Summer maximum air temperature reconstructed from tree rings in the Caniapiscaw/Ashanipi/Churchill river basins. Source: Yves Bégin, ARCHIVES project, INRS-ETE and Centre d'études nordiques.

vegetation and snow cover as well as to mean annual air temperatures).

While there may be some uncertainty as to the timing of the recent period of warming over the Nunavik-Nunatsiavut IRIS region, there is no denying the rapidity of the changes that have occurred over the last few decades. Air temperatures have warmed by more than 2°C since 1993, snow cover duration has decreased 3-4 weeks over northern Nunavik and Nunatsiavut since regular satellite observations began in the early 1970s, ice on the Koksoak River at Kuujuaq in the 1990s (when observations ceased) was melting an average of 3 weeks earlier than it did in the 1950s, warming of permafrost has resulted in a dramatic increase in the number of thermokarst lakes and active layer detachments (Chapter 6), glaciers in the Torngat Mountains lost ~20% of their area between 2005 and 2007 (Section 2.3.5), and marked increases in tree and shrub abundance have been documented at many locations (Chapter 8). The unusual nature of these changes is clearly visible in the paleo-temperature records (e.g. Figure 15) and is confirmed from traditional knowledge (Tremblay et al. 2006a,b).

The future changes projected by the climate models are, for the most part, a continuation of current trends with

the largest increases in air temperature and precipitation projected over the northern Ungava Peninsula. Projected changes are generally of similar magnitude and sign over Nunavik and Nunatsiavut with the exception of snowfall which is projected to increase over Ungava Peninsula and decrease over much of Nunatsiavut. The future climate may also include changes in the frequency and severity of extreme events such as warm spells and heavy rainfall events (Meehl et al. 2007b). There is already documented evidence of increasing precipitation over the Arctic region as well as evidence of increases in the frequency of extreme precipitation events, both attributable to human influences on the climate system (Min et al. 2008, 2011). Scenarios for changes in extreme events were not presented in this chapter as these need to be developed based on particular user needs and locations using the most appropriate downscaling methods for the variables being considered (e.g. Kallache et al. 2011). On a final note, it should be reiterated that the Nunavik-Nunatsiavut IRIS region is characterized by important sources of climate variability that influence the regional climate on decadal and multi-decadal time scales. For some variables such as local precipitation, the internal climate variability will likely dominate any climate change signal over the next 30-50 year time period.

2.6 Acknowledgements

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Appendix A. Climate Change Projections for Nunavut and Nunatsiavut for 2050

Carl Barrette¹, Line Bourdages³, Ross Brown^{2,3}, Diane Chaumont³, Yonas Dibike⁴, Anne Frigon³, Travis Logan³, Dominique Paquin³

¹ArcticNet, Centre d'études nordiques (CEN), Université Laval, ²Climate Research Division Environment Canada,

³Ouranos, ⁴Water and Climate Impacts Research Centre, Environment Canada at University of Victoria

I. Introduction

A number of methods can be used to provide climate change scenarios for adaptation and planning purposes (Mearns et al. 2001) ranging from simple extrapolation of observed trends for shorter time periods, to longer-term simulations from climate models that take into account the future evolution of the concentration of greenhouse gases (GHG) in the atmosphere. The latter approach was used here as climate models suggest that increasing GHG will result in significant changes in the climate of eastern North America over the 2041-2070 period (Christensen et al. 2007). The spatial resolution of the Global Climate Model (GCM) runs available from the most recent IPCC assessment and contained in the CMIP3 dataset (Meehl et al. 2007) is on the order of 200-400 km which is too coarse to resolve the topography and coastline of the study region, and is not optimal for many applications. The “downscaling” of GCM output to the resolution required by decision makers can be achieved through statistical relationships or by using the GCM output to drive a higher resolution climate model focused on a smaller region (a Regional Climate Model or RCM – see review by Laprise 2008). The latter approach was used here as it represents a physically-based, consistent way to provide higher resolution information for a wide range of user needs.

Users of climate change scenarios derived from climate model output need to be aware of the “cascade of uncertainties” involved (Jones 2000). These include: the emission scenarios used to drive the GCM climate change projections; the physics and parameterizations used in the GCMs and RCMs; the driving and lateral boundary conditions used in RCM downscaling; and the “natural”

or internal climate variability present in the climate system (and simulated by global climate models). De Elia et al. (2008) undertook an evaluation of the uncertainties in CRCM-simulated climate over North America and concluded that the errors from internal RCM climate variability and configuration set-up are much smaller than those related to the choice of driving GCM and are not a major obstacle to climate downscaling. The magnitude of the uncertainties is also location dependent. Some idea of the relative magnitude of these uncertainties over a particular region and for a particular variable can be obtained by analyzing the output from multiple GCM and RCM runs following Rowell (2006). However, only a limited number of RCM runs were available for the Nunavik-Nunatsiavut IRIS study which precluded carrying out a Rowell-type analysis. The approach used here to generate scenarios and take account of uncertainty is outlined in the following section.

II. Methodology

The projected climate changes over the Nunavik-Nunatsiavut IRIS region are computed from the Canadian regional climate model (CRCM) (Caya et al. 1995, Caya and Laprise 1999, Plummer et al. 2006, Music and Caya 2007) which provides dynamical downscaling at a spatial resolution of 45 km compared to the ~200-400 km resolution of the driving GCMs. The projected changes are computed from the difference between 30-year averages over a 1971-2000 “current climate” period and a 2041-2070 “future climate” period corresponding to the 2050 time-frame. The 2050 time-frame was selected as this corresponds to the planning horizon of decision makers. The CRCM has been extensively validated against various ob-

servational datasets and has been found to provide realistic simulations of the climate, snow cover and hydrology with some regional biases (see Box 1).

A total of six pairs of current and future climate runs from the latest version of CRCM 4.2.3 (de Elia and Côté 2010) were provided by Ouranos to analyze projected climate changes (Table A1). These included five sets of CRCM runs driven by the third generation Canadian Coupled Global Climate Model (CGCM3) at a T47 resolution (~400 km) (Scinocca et al. 2008, Flato and Boer 2001) that includes uncertainties related to the natural climate variability (simulated by the various members of the driv-

Table A1. List of CRCM simulations used in the IRIS report. CRCM version 4.2.3 was used for all runs over the North American domain (AMNO 200x192 at 45-km resolution). The driving GCM future runs used the SRES A2 emission scenario.

CURRENT (1971-2000)	FUTURE (2041-2070)	DRIVING MODEL AND MEMBER
aez	afb	CGCM3-1
afa	afc	CGCM3-2
aev	afd	CGCM3-3
aet	aew	CGCM3-4
agx	aeu	CGCM3-5
	agz	ECHAM5-1

Box 1. Notes about CRCM validation

A preliminary evaluation of the air temperature and precipitation simulated by CRCM4 over the study region (specifically runs CGCM3#4 (aet/aeu), CGCM3#5 (aev/aew) and ECHAM5#1 (agx/agz)) was carried out in comparison with gridded observations from the Climatic Research Unit (CRU version ts_2.02; Mitchell and Jones 2005). It should be stressed that over the Nunavik-Nunatsiavut IRIS region there are few observations included in the CRU data set and those that are tend to be biased toward coastal locations. The evaluation results must therefore be treated with some caution.

Air temperature: CRCM seasonal temperature differences with CRU observations are less homogeneous geographically than those for precipitation and tend to vary according to the driving data. When driven by CGCM3, the CRCM is generally too cold, with a bias that can reach -8°C in winter along the coast. However, when driven by ECHAM5 (#1), there is no systematic behavior in the bias, with differences that can be either positive (for example +5°C for Tmax in spring) or negative (for example -4°C for Tmin in the fall) (Paquin 2010).

Precipitation: CRCM's seasonal precipitation bias is generally smaller than 1 mm/day, with peaks that can reach around 1.5 mm/day. The bias tends to be negative (underestimation) over the eastern part of the area and positive in the western part (Paquin 2010).

Snow cover: Dorsaz (2008) showed that CRCM provided realistic simulations of the mean snow cover climate over Québec but with a tendency toward too much snow early in the snow season (related to the cold bias), low values of annual maximum SWE (due to a deficit of solid precipitation linked to the cold bias) and too rapid melt in the spring period. Interannual variability in snow-off date was better simulated than snow-on date based on the available observational datasets. CRCM's ability to capture interannual variability in annual maximum SWE was unable to be established clearly as there was poor agreement between observational datasets. Evaluation of CRCM snow cover over northern parts of the Nunavik-Nunatsiavut IRIS region is difficult as there are few surface-based observations and the available satellite and reanalysis datasets differ considerably.

ing CGCM3, differing only in their initial conditions), and one set of CRCM runs driven by the ECHAM5 global model from the Max Plank Institute (Roeckner et al. 2003, Jungclaus et al. 2006) to take into account some of the uncertainty related to differences in driving GCMs. The future climate runs all used the A2 emission scenario (Nakicenovic et al. 2000). The calculated mean change (Δ) from the six different CRCM runs are mapped over the study region along with the standard deviation (STD) of the projected changes to provide some idea of the uncertainty.

As a first step, the projected changes in mean annual temperature and precipitation over the study domain from the six CRCM runs were compared with results from 86 GCM runs from the CMIP3 dataset (Meehl et al. 2007) that includes different emission scenarios as well as multiple model runs of the same models run with different initial conditions (Fig. A1). This process provides some indication of where the CRCM runs used here are located in the spectrum of projected changes. The analysis shows that the simulations used are located around the middle of the projected mean annual temperature change in the 2–4°C range, while the projected precipitation changes of ~15–20% lie in the upper range of the various GCMs.

III. Variable selection and definition

The selection of variables to analyse was based on their potential to be impacted by climate change and their relevance to northern communities. With respect to the latter, five key components of the northern ecosystem were identified by researchers and communities for development of climate change scenarios:

- Vegetation
- Caribou
- Permafrost
- Aquatic ecosystems
- Arctic charr

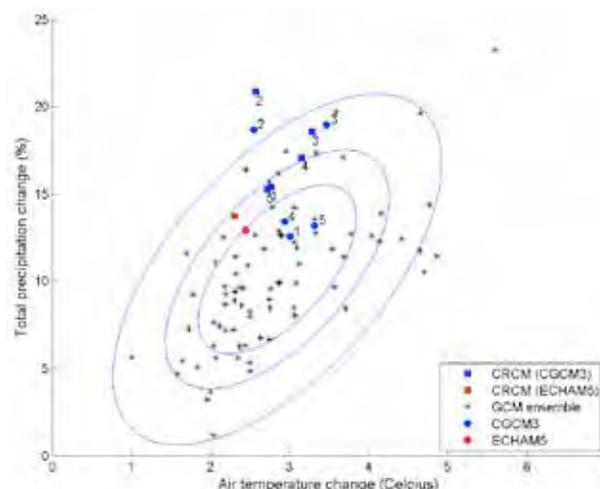


Figure A1. Projected changes in mean annual air temperature (°C) and total precipitation (%) for 2050 over the Nunavik and Nunatsiavut regions. The red dot represents the ECHAM5 simulation used in this study, and the blue dots represent the five different CGCM3 runs that were used. The coloured squares represent the CRCM result runs with each GCM (numbers correspond to CGCM3 members) while the black asterisks represent 86 different runs from the GCMs included in the CMIP3 dataset (Meehl et al. 2007).

Relevant climate variables and indicators for these key components have been developed previously (e.g. Sharma et al. 2009, Williamson et al. 2009) and are defined as follows for the present analysis:

Air temperature (T_a): Air temperature is a fundamental climate indicator as many arctic processes are closely linked to temperature thresholds particularly around the freezing temperature. Two seasonal averaging periods were used to present the temperature change scenarios corresponding to the two dominant seasons over northern Québec and Labrador: a winter season from October to April (T_a mainly $<0^\circ\text{C}$), and a summer season from May to September (T_a mainly $>0^\circ\text{C}$).

Precipitation: Mean annual total precipitation (Pt) and annual solid precipitation (Ps) were obtained from 6-hourly averaged precipitation rate output from CRCM. Calcula-

lations were made over a calendar year for Pt and from October to May for Ps. Precipitation was assumed to be solid when surface air temperature was $< 0^{\circ}\text{C}$.

Maximum and mean snow accumulation (Maxzn and Mzn): Knowledge of changes in the amount of snow on the ground is important for the ground thermal regime (Hinkel and Hurd 2006), water resources, transport and a wide range of ecological impacts such as ungulate foraging (Tews et al. 2007, Bourque and Simonet 2008). Mzn and the Maxzn were computed from daily CRCM snow depth series over the snow cover duration period (SCD) defined below.

Degree-days (DD): Degree-days are defined as the departure of daily mean temperature from a given threshold. Degree-days can be used to calculate different indices. For example, the sum of mean daily temperatures above 0°C is used to calculate the thawing degree days (TDD) or melting degree days that are closely linked to melt processes such as the depth of the permafrost active layer (L'Hérault 2009). The initiation and duration of snowpack ablation is also closely related to TDD.

An index of plant growth can also be obtained from the sum of degree-days above a threshold temperature corresponding to a plant's physiology, e.g. the sum of daily mean air temperatures above 5°C is used to estimate growing degree days (GDD) in Arctic environments. Inversely, degree-days can be used to calculate indices related to cooling, e.g. freezing degree days (FDD) calculated as the sum of degree-days under 0°C are closely linked to ice growth (see USACE 2002). Degree-day indicators are also linked to ungulate population dynamics as they influence the amount of forage through the length of the growing season and the amount of primary production (Sharma et al. 2009).

Summer season length: The duration of the period with above-freezing air temperatures affects a wide range of environmental processes such as evaporation, precipitation type, and plant growth conditions. The duration of

the summer season was computed from 0°C crossing dates using a centred 20-day moving average of daily mean air temperature.

Freeze-thaw cycles: The early winter and spring periods in particular, are characterized by daily freeze-thaw cycles that play an important role in mechanical weathering as well as in the formation of ice layers in or under the snowpack with potential effects on the soil thermal regime, vegetation and ungulate grazing. Results for this variable are taken from analysis of changes in the number of freeze-thaw cycles for 2050 from eight CRCM runs assuming the SRES A2 emission scenario (Logan et al. 2011). Freeze-thaw cycles were defined as the number of days where daily $T_{\text{max}} > 0^{\circ}\text{C}$ and daily $T_{\text{min}} < 0^{\circ}\text{C}$.

The number of winter thaw (Nthaw) and rain on snow (ROS) events: Winter thaw events can have major impacts on Arctic ecosystems, especially ungulates, by producing ice layers within or under the snowpack that may limit access to forage (Tyler et al. 2008). ROS and freezing rain events can similarly cause problems for ungulate foraging by creating a hard surface ice layer (Putkonen and Roe 2003, Rennert et al. 2009). Nthaw was computed by summing the number of days where daily maximum air temperature passed above the freezing point ($>0^{\circ}\text{C}$) during periods where the centred running mean of daily mean air temperature over 29 days was below -5°C . The latter criterion was applied to limit thaw events to the main winter period and avoid generation of frequent events during the start and end of the winter season (these are captured by the daily freeze-thaw cycle index). The number of ROS days was defined following Rennert et al. (2009) as the number of days with daily total rainfall > 3 mm where there was snow on the ground with a snow water equivalent > 3 mm.

Snow cover duration (SCD): SCD is important for transportation, ground thermal regime and ecology. The snow cover season was defined as the period with at least 10 cm snow depth which corresponds to a complete snow cover on the grid tile in the CLASS land surface scheme

used to simulate snow processes in the CRCM (Canadian LAnd Surface Scheme; Verseghy 2000). The start (end) date of the snow season was defined as the first (last) 5 consecutive days with snow depth above (below) the defined threshold.

Ice cover: Important changes are expected in the thickness and duration of ice cover in response to projected warming (Drobot et al. 2008) with wide-reaching impacts on transportation and ecosystems (e.g. Williamson et al. 2009, Sharma et al. 2009) and indigenous peoples' way of life (Williamson et al. 2009). Interactive lake and coastal ice processes are not included in the current version of CRCM but results from recent modelling studies of lake ice response to climate change (Dibike et al. 2011a,b) and sea ice response to warming in the Hudson Bay region (Joly et al., 2010) are relevant for this report, as well as fast ice change scenarios presented by Dumas et al. (2006). Results from these studies are presented and discussed in Section IV.IV.

IV. Results

The following section presents the climate scenario results for each of the main variables/indicators. A tabular

summary of the projected climate changes for Nunavik and Nunatsiavut is provided in Chapter 2, Table 8.

IV.I Projected changes in air temperature and related indices

Figure A2 presents the mean projected change in mean annual air temperature (ΔT_a) for 2050 from the six CRCM runs. The results show a northwest-southeast gradient with the largest increases of 3.0 to 3.5°C over northern Nunavik and Nunatsiavut, with increases in the 2.5 to 3.0°C range for southern Nunatsiavut and Nunavik.

For Nunavik, three temperature change zones can be identified: 1) the northern zone (Quaqtaq, Ivujivik and Puvirnituq) characterised by the highest projected temperature changes of about 3.0 to 3.4°C; 2) the east-central Nunavik region (Tasiujaq, Aupaluk and Kuujuaq) with the lowest increases of about 2.8°C; and 3) the Hudson Bay region (Kuujuarapik, Umijujaq, Inukjuak) with intermediate increases of about 3.0°C (Figure A2). There is a marked increase in the STD between runs over northern Ungava peninsula indicating there is greater uncertainty in the model projections in this region.

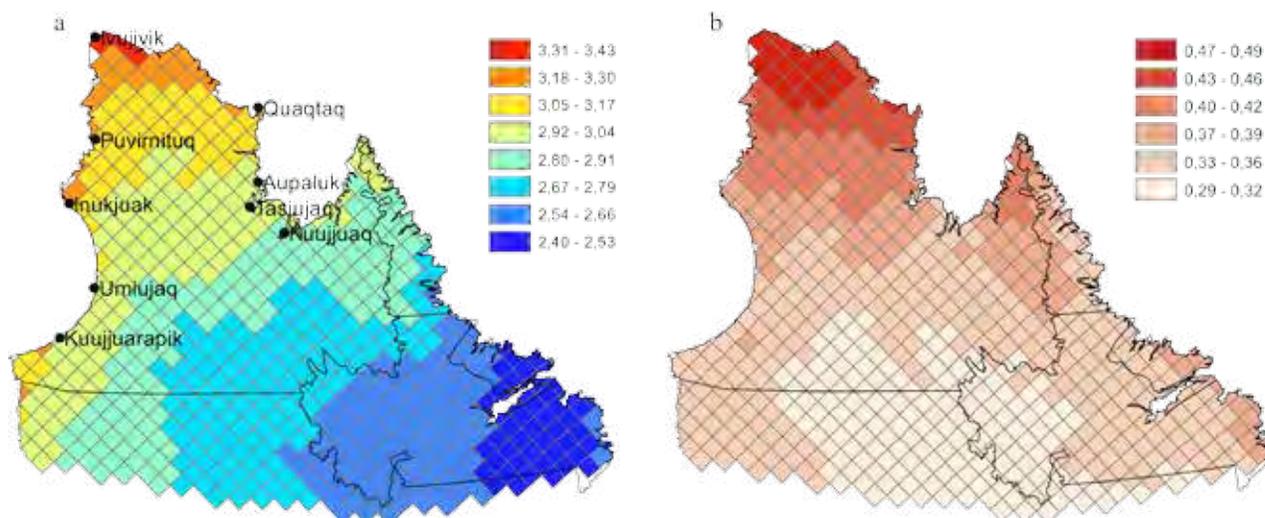


Figure A2. a) Average projected change (ΔT_a , °C) in mean annual air temperature for 2050, from six CRCM runs; b) the STD of ΔT_a for the six runs (°C).

The winter and summer season results (Figure A3 a and c) show that winters have larger projected temperature increases ranging between 2.8 to 4.6°C over the study region, while summer projected increases range from 1.5 to 2.1°C. The largest winter warming is projected over the areas around Hudson Bay and Hudson Strait reflecting large-scale polar amplification of the climate warming signal and regional warming from less sea ice (Gagnon

and Gough 2005). The largest summer warming (~2.0°C) is projected over the northernmost region of Nunavik from Ivujivik to Quaqtaq and over the Torngat Mountains.

Figure 16 of Chapter 2 (left panel) provides a more detailed picture of the seasonal character of projected changes in mean air temperature averaged over the Nunavik-Nunatsiavut IRIS region. Projected winter warming

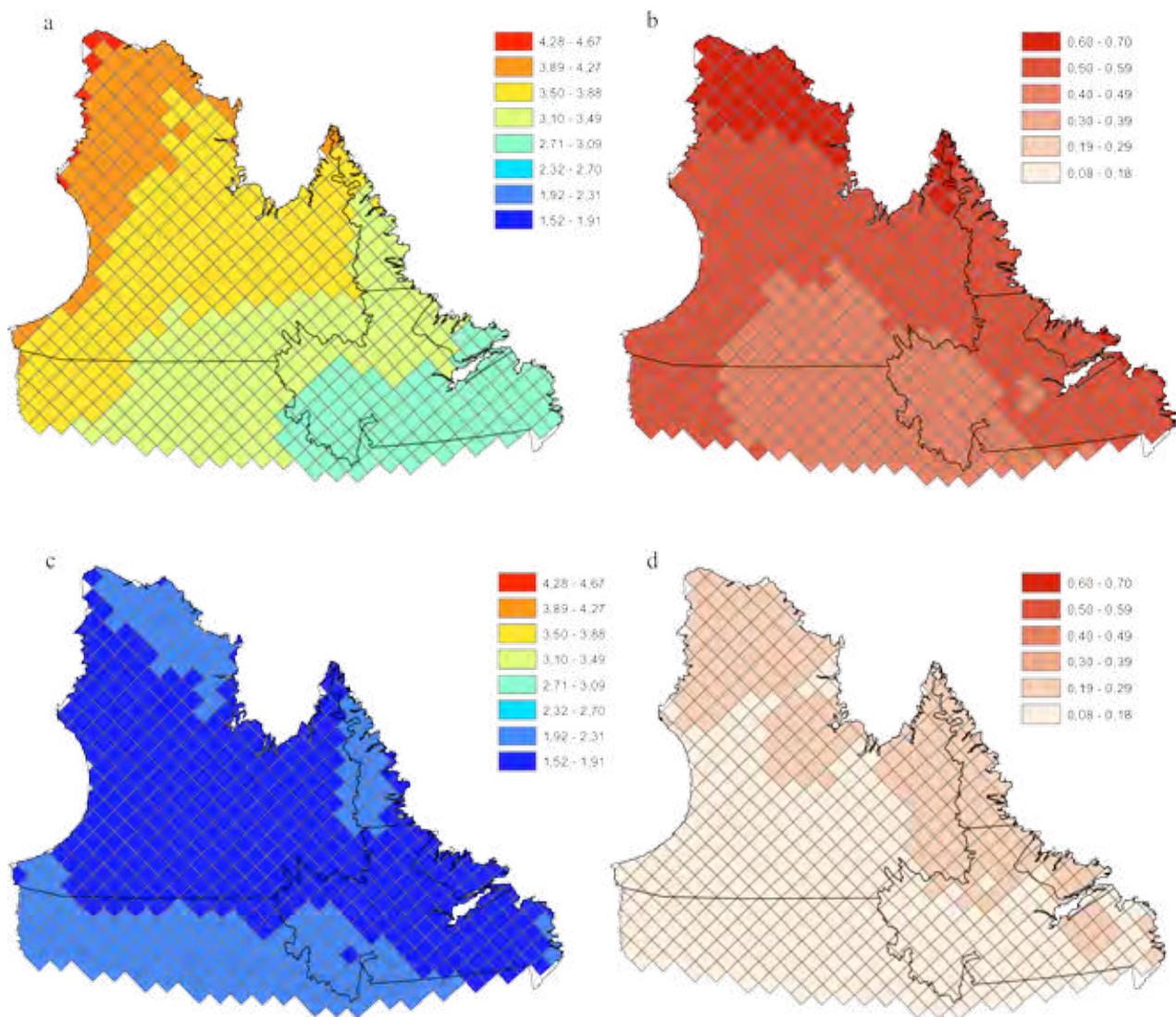


Figure A3. Average projected change in (a) winter (Oct.-Apr.) and (c) summer (May-Sept.) mean air temperature from six CRCM runs (°C). The corresponding STDs for the six runs are shown in (b) and (d).

reaches a peak of 4-6°C in January with the largest variability between model runs in February and March. This contrasts with the summer months where the internal climate variability of the region is much lower (the seasonal contrast in interannual variability is clearly seen in the observed seasonal temperature series provided in Figure A3).

The projected changes in thawing degree-days (TDD) (Figure A4a) are largest over the southern part of the region

with increases between about 300 to nearly 400 TDD. However, in terms of a percentage change (Figure A4c), the northern part of Nunavik including the communities of Ivujivik, Salluit, Kangiqsujuaq and Quaqtaq are projected to have the largest relative change with increases in the 50-70% range. The Torngat Mountains are projected to have similar large relative increases in TDD. The uncertainty related to internal climate variability is higher over these two northern regions (Figure A4d).

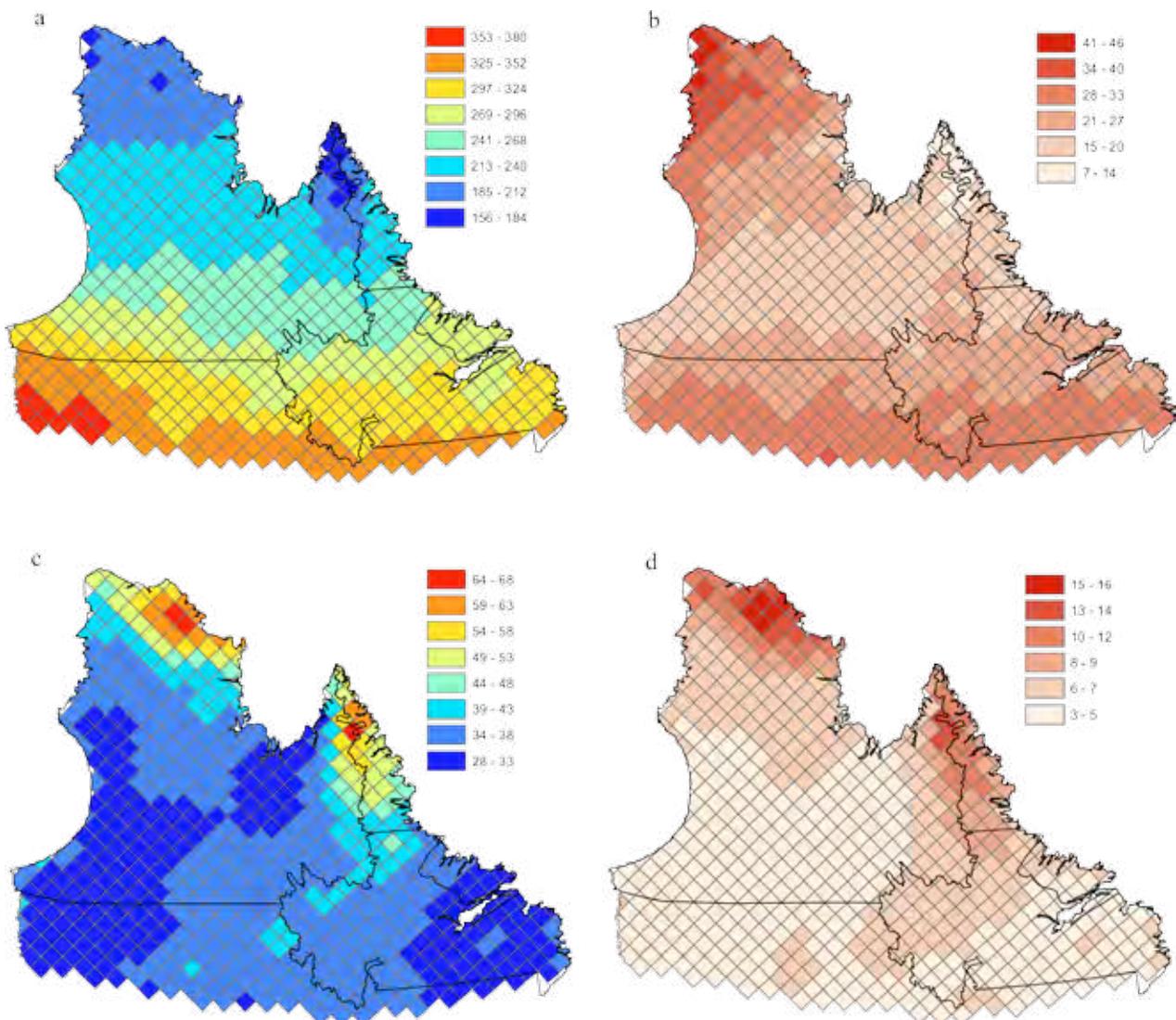


Figure A4. Projected change in mean thawing degree days (TDD) for 2050 from an ensemble of six CRCM runs: a) mean projected change in TDD, b) STD for change in TDD, c) change in TDD as a percentage of the mean current climate TDD and d) STD for change in TDD as a percentage of the mean current climate TDD.

Figure A5 presents the projected change in growing degree-days (GDD) i.e. the number of degree days above 5°C, which corresponds to changes in growing season length. The spatial pattern of the projected change is essentially identical to TDD as the longer snow-free season is the main process driving the temperature response. However, the relative increases are much larger ranging from ~50% around the Hudson Bay coastal region north of James Bay, to ~150% over the northern Ungava Peninsula.

Figure A6 shows the average projected changes in the start and end date of the summer season (period with mean air temperatures >0°C). The largest changes to start date of summer (around 10 days earlier) are projected over the northern regions of Nunatsiavut and Nunavik (Figure A6a) including the communities from Iuvjivik to Quaqtaq in Nunavik and the community of Nain in Nunatsiavut. The largest potential changes to end date of summer (extension by ~15 to 18 days) are projected over the Hudson

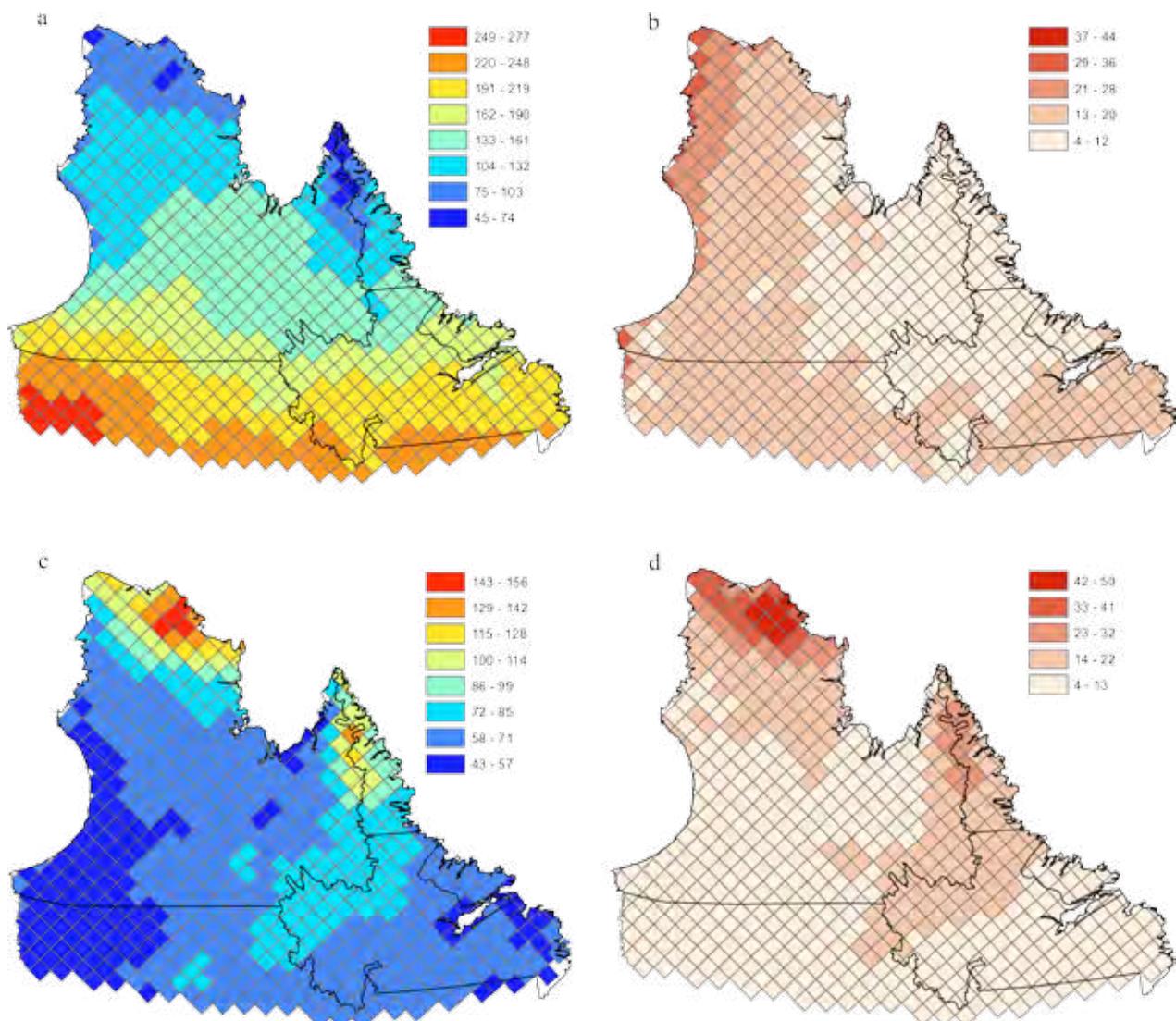


Figure A5. Projected change in mean growing degree-days (GDD) for 2050 from an ensemble of six CRCM runs: a) mean projected change in GDD, b) STD for change in GDD, c) change in GDD as a percentage of the mean current climate GDD and d) STD for change in GDD as a percentage of the mean current climate GDD.

Bay coastal region north of James Bay (Figure A6c) including the communities of Kuujjuarapik, Umiujaq and Inukjuak. The results suggest a projected potential lengthening of the summer season by 3-4 weeks over most of the Nunavik-Nunatsiavut IRIS region by 2050.

Analysis of changes in freeze-thaw cycles (Logan et al. 2011) (not shown) indicated important seasonal shifts

in the timing of the period with freeze-thaw cycles but only small changes (decreases) in the annual frequency of cycles over most of the IRIS region. Similarly, the results for projected change in the number of winter thaw events (not shown) indicated slight decreases related to a reduction in the length of the winter season, but no evidence of any distinct spatial patterns.

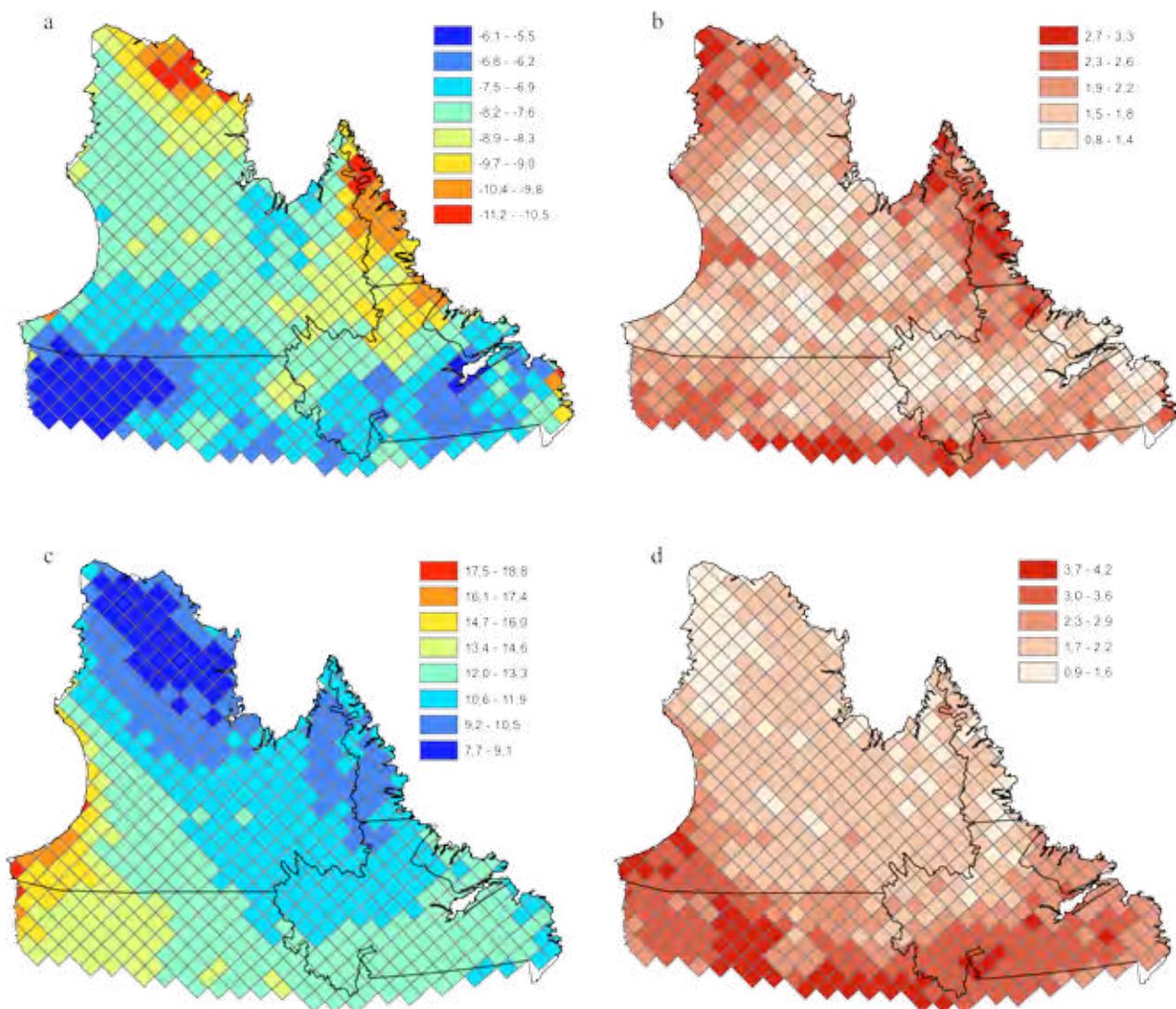


Figure A6. Projected change in the extension of summer season for 2050 from an ensemble of six CRCM runs: a) average start date of mean temperatures above 0°C, b) STD for start dates, c) average end date of mean temperatures above 0°C and d) STD for end dates. Negative (positive) values indicate changes to earlier (later) dates.

IV.II Projected changes in precipitation and related indicators

The projected changes in total precipitation over the study region from the CRCM runs (Figure A7a,b) show an overall increase of 10 to 25% by 2050. The largest increases (20 to 25%) are projected to occur over Nunavik in the western Ungava Peninsula and the eastern part of Ungava Bay. For Nunatsiavut, precipitation changes are projected

to be in the +10 to 15% range. The pattern of projected changes in total annual snowfall (Figure A7c,d) is similar to total precipitation with increases of 16 to 23% over the northern Ungava Peninsula. However, solid precipitation is projected to decrease slightly in coastal regions of Nunatsiavut especially in the southern parts of the region (Makkovik to Cartwright). The increase in STD between model runs over the eastern part of the region in Figure A7 b is likely linked to sources of climate variability such

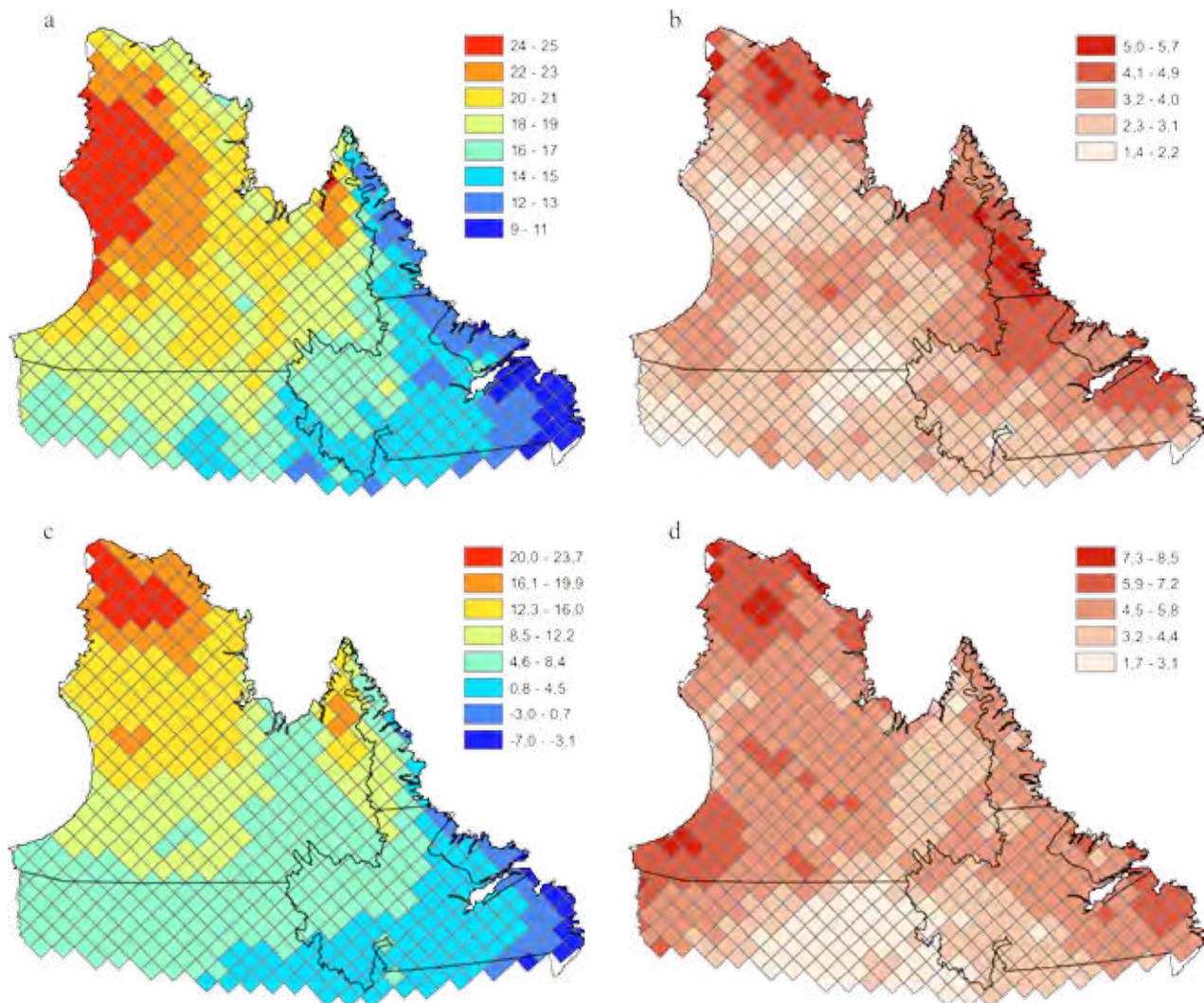


Figure A7. (a) Projected % change in total annual precipitation (ΔPt) for 2050; (b) standard deviation in ΔPt from six CRCM; (c) projected % change in total annual solid precipitation (ΔPs) for 2050; (d) standard deviation of ΔPs from six CRCM runs for 2050. Precipitation is classified as solid or liquid in the CRCM based on a 0°C temperature threshold.

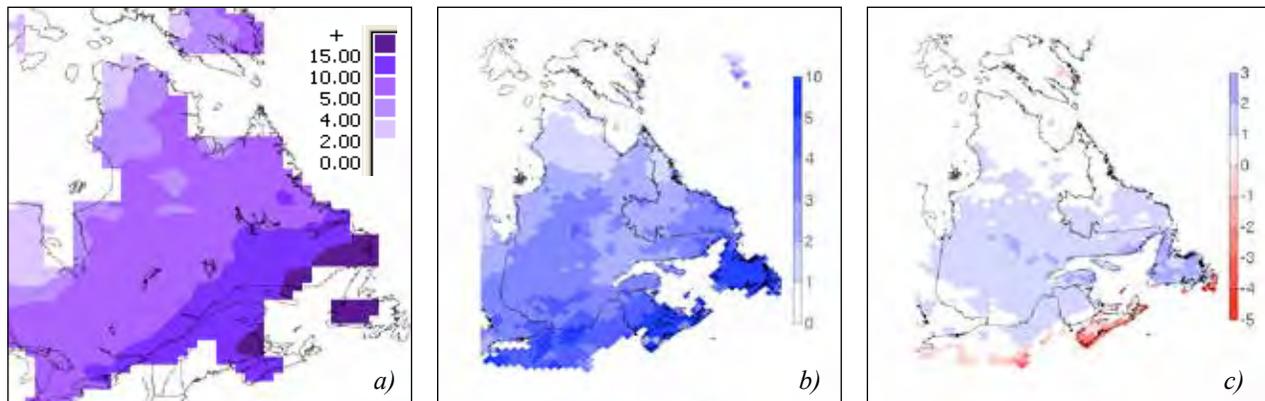


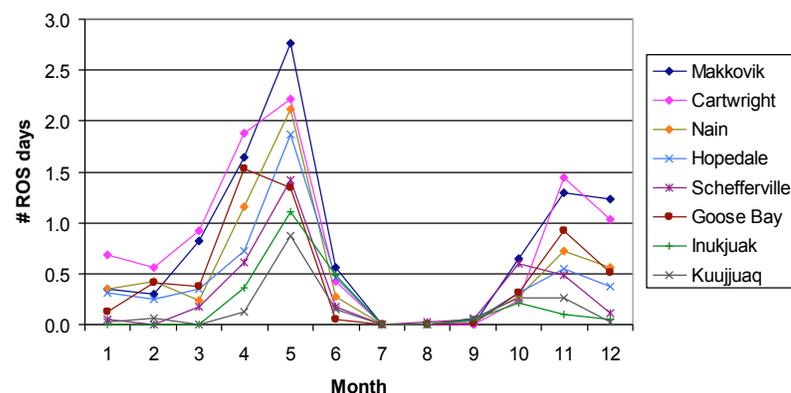
Figure A8. Comparison of CRCM simulated rain on snow (ROS) frequency (events per year) 1971-2000 (b) with estimates obtained from the Brown (2010) snow cover reconstruction (a). The panel at right (c) shows the average (from six runs) CRCM projected change in annual frequency of ROS events for 2050. The standard deviation of the projected ROS changes from the six CRCM runs (not shown) is less than 1 event per year over the IRIS region. ROS days were defined following Rennert et al. (2009) as the number of days with snow on the ground with a snow water equivalent > 3 mm and daily total rainfall > 3 mm.

as NAO that were seen in Section 2.3 to mostly affect the eastern part of the Nunavik-Nunatsiavut IRIS region. The seasonal character of projected changes in total precipitation (see chapter 2, Figure 16 right panel) shows larger projected increases in the first half of the calendar year but the results are noisier than air temperature (see chapter 2, Figure 16 left panel). This is expected as precipitation exhibits greater spatial and temporal variability than air temperature.

Projected change in the annual number of rain-on-snow (ROS) days (Figure A8) over the IRIS region indicates

small increases of 1-2 days per year with the increases mainly confined to the southern part of the region (Figure A8c). ROS days are relatively rare events in the IRIS region and analysis of daily snow depth and rainfall data from climate stations across the region (Figure A9) showed that the mean annual occurrence of these events ranged from less than 2 days/year at Kuujjuaq to around 10 days/year at Makkovik and Cartwright. The CRCM appears to capture the spatial variability and magnitude of these events reasonably well. The seasonal distribution of ROS days as defined by Rennert et al. (2009) has a pronounced peak in the spring period (Figure A9)

Figure A9. Observed average monthly frequency of ROS days from climate station observations of daily snow depth and rainfall at various locations in the Nunavik-Nunatsiavut IRIS region for differing lengths and periods of data. ROS days were defined as days with rainfall > 3 mm on a snow cover with estimated snow water equivalent > 3 mm (assuming a snow density of 250 kg.m⁻³).



when there is lower potential for the formation of ice layers that may hamper caribou grazing. This definition may therefore not be optimal for assessing ROS event risks for caribou.

IV.III Projected changes in snow cover

Projected changes in mean annual snow depth for Nunavik and Nunatsiavut (Fig. A10a) show slight increases of up to about 7% over the northwestern part of Nunavik

with decreases over the rest of the Nunavik-Nunatsiavut IRIS region. The largest decreases in snow depth (-10 to -15%) are projected over coastal regions of Nunatsiavut. The southern and eastern parts of the Ungava Peninsula (Kuujuuaq to Kanjigsualujuaq) are expected to follow a similar trend with reductions between 0 and 5%. The STD results (Fig. A10b) indicate larger values and greater uncertainty in coastal regions, particularly in the Hudson Bay coast area around Kuujuuarapik.

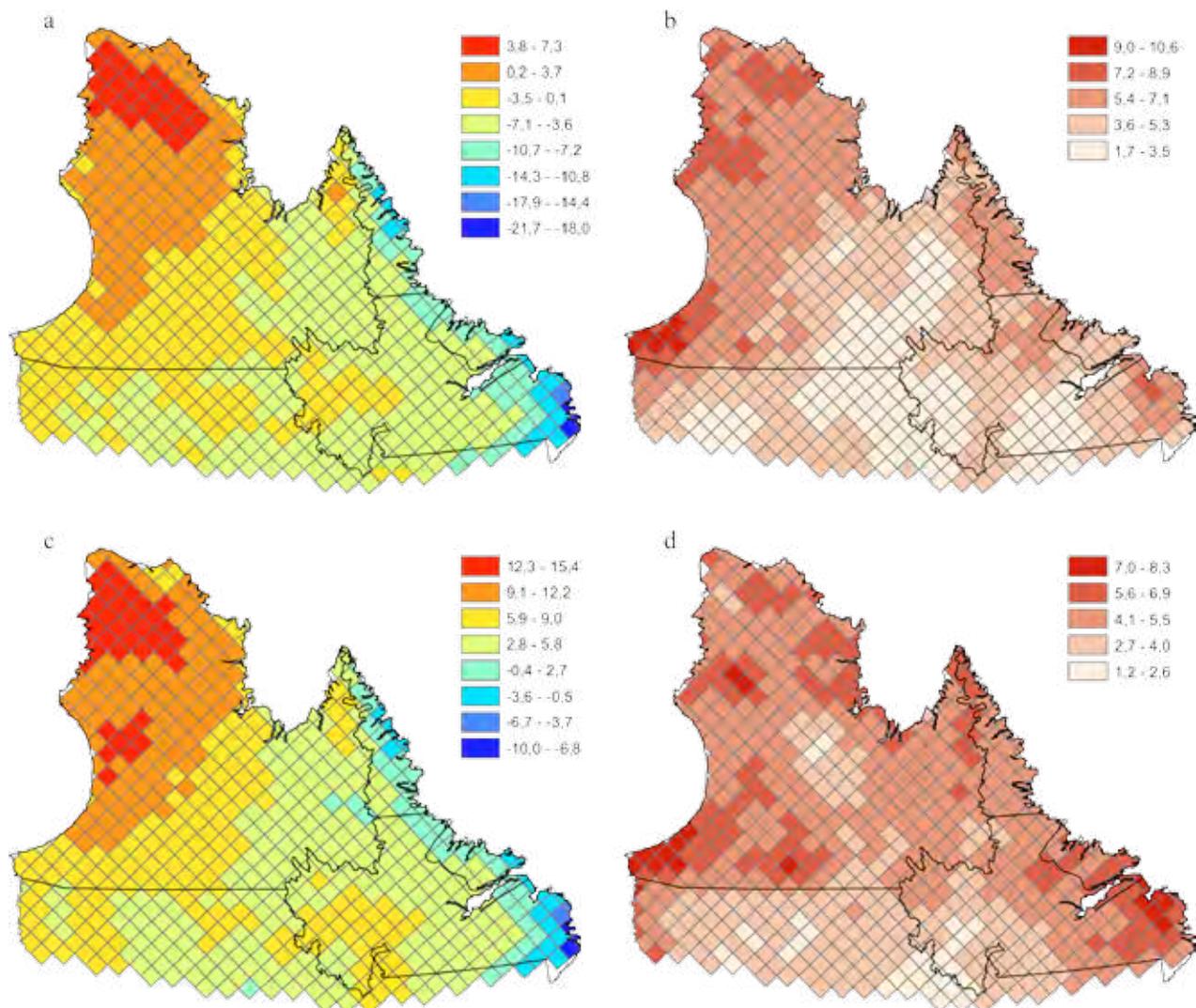


Figure A10. Projected % change in (a) mean annual and (c) annual maximum snow depth and (b, d) the standard deviation from six CRCM runs for 2050.

The projected changes in annual maximum snow depth (Fig. A10c) show a similar pattern but are shifted upward by about 10% resulting in a general increase in Maxzn over most of the region. The largest changes projected by models (increases of between 9 and 15%) are in the northern part of Nunavik. The Central region of Nunavik could experience changes in maximum snow depth in the range of around 3 to 9%. For the coastal regions of Nunatsiavut, changes projected by the CRCM show a

reduction in maximum snow accumulation between 0 and 5%. The relatively small changes in Maxzn seen over the IRIS region agree with results from 14 GCMs analysed by Brown and Mote (2009) that showed no consensus for significant changes in annual maximum monthly snow depth over northern Québec by 2050.

According to the 2050 projections, the average length of snow season could be reduced by about 10-25 days from

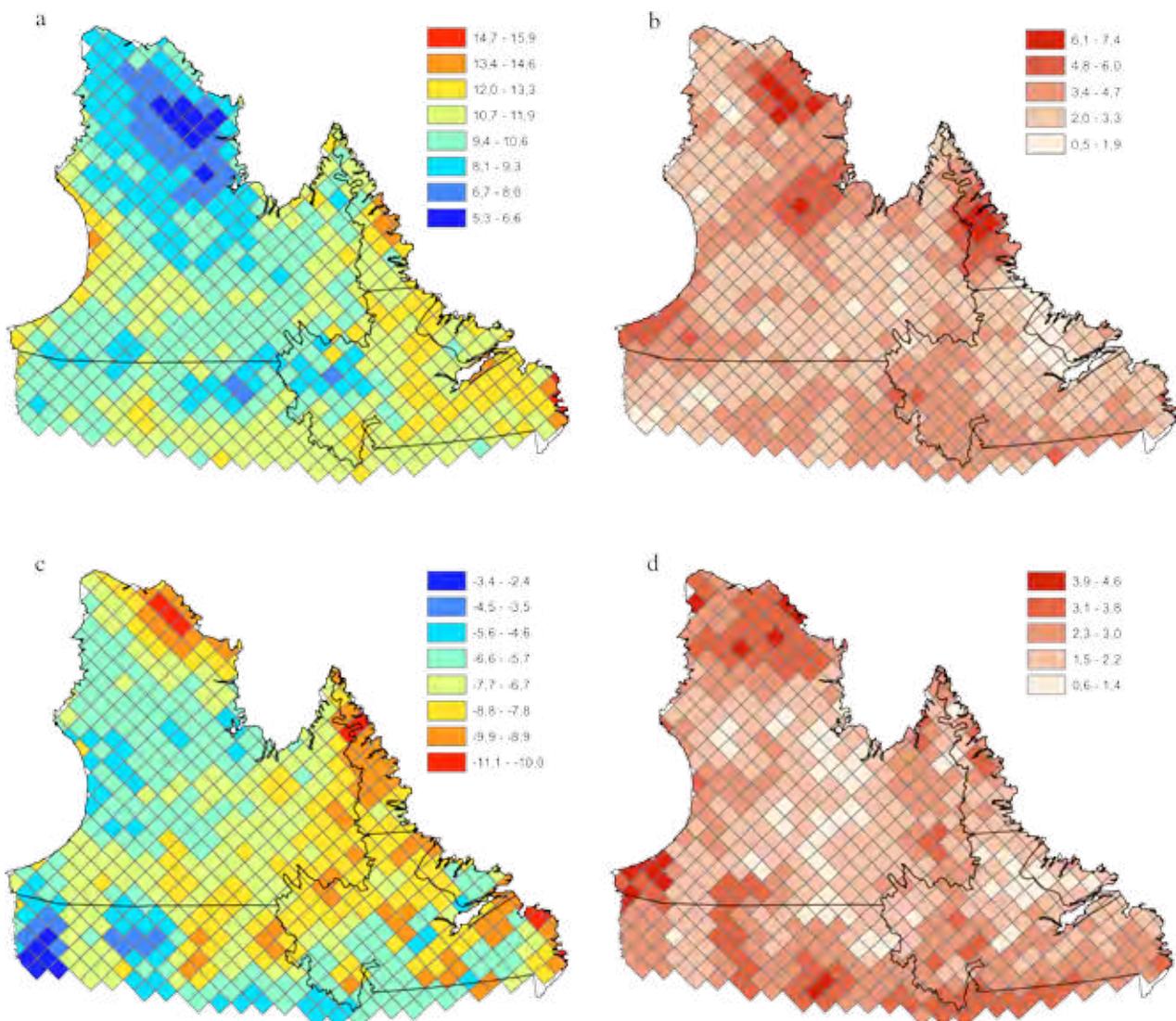


Figure A11. Projected change (days) in the start and end dates of snow cover from six CRCM runs for 2050: a) start-date of continuous snow cover c) end-date of continuous snow cover; b and d are the corresponding STD for the six runs. Negative (positive) values indicate changes to earlier (later) dates.

a 6-15 day later snow cover onset date (Figure A11a), and a 2-10 day earlier snow-off date in the spring (Figure A11c). The largest decreases in the snow cover season (> 20 days) are projected over coastal regions of Nunatsiavut near the Torngat mountain range and the northern part of Nunavik between Kangiqsujuaq and Quaqtaq. These results are consistent with analysis of annual snow cover duration (SCD) change projections from 8 GCMs by Brown and Mote (2009) that showed a clear model consensus for significant reductions in annual SCD over most of northern Québec by 2050.

IV.IV Projected changes in ice cover

Dumas et al. (2006) looked at the response of the Canadian landfast ice regime to climate warming with a simple downscaling technique that used a one-dimensional sea ice model driven by observationally based forcing and

superimposed projected future climate change from the Canadian Centre for Climate Modelling and Analysis global climate model (CGCM2). The method indicated decreases in maximum ice thickness of 30 cm and 50 cm, and a reduction in ice cover duration of 1 and 2 months by 2041-60 and 2081-2100, respectively for several Arctic sites. However, it projected slight increases in ice thickness and duration at Cartwright due to snow-ice formation (or white ice) from increased snowfall and a projected slight cooling over the NW Atlantic (note that this cooling is not present in the CGCM3 runs used here). Dibike et al. (2011a) examined the 2050 response of the lake ice regime over North America to projected climate change with the MyLake model (Saloranta and Andersen 2007) forced with output from CRCM4.2 driven by one CGCM3 run assuming the A2 emission scenario. The Dibike et al. (2011a) results for projected change in lake ice freeze-up and break-up (Figure A12 a,b) show later

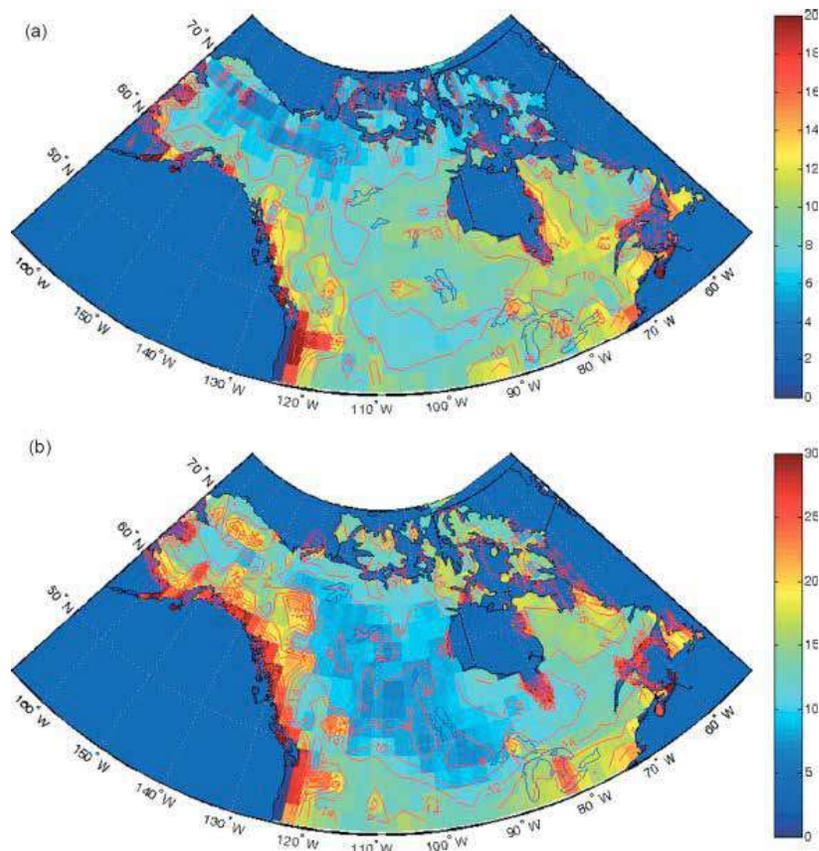


Figure A12. Projected change in mean date of a) freeze-up, and b) break-up (both in days) between the current (1961–1990) and future (2041–2070) climatic periods for a hypothetical lake of 20 m depth based on the MyLake model using CRCM4.2 output driven by CGCM3 for the SRES A2 emission scenario. Please note that the color legend in b) should show negative numbers to match the contour lines on the plot. Source: Dibike et al. (2011a).

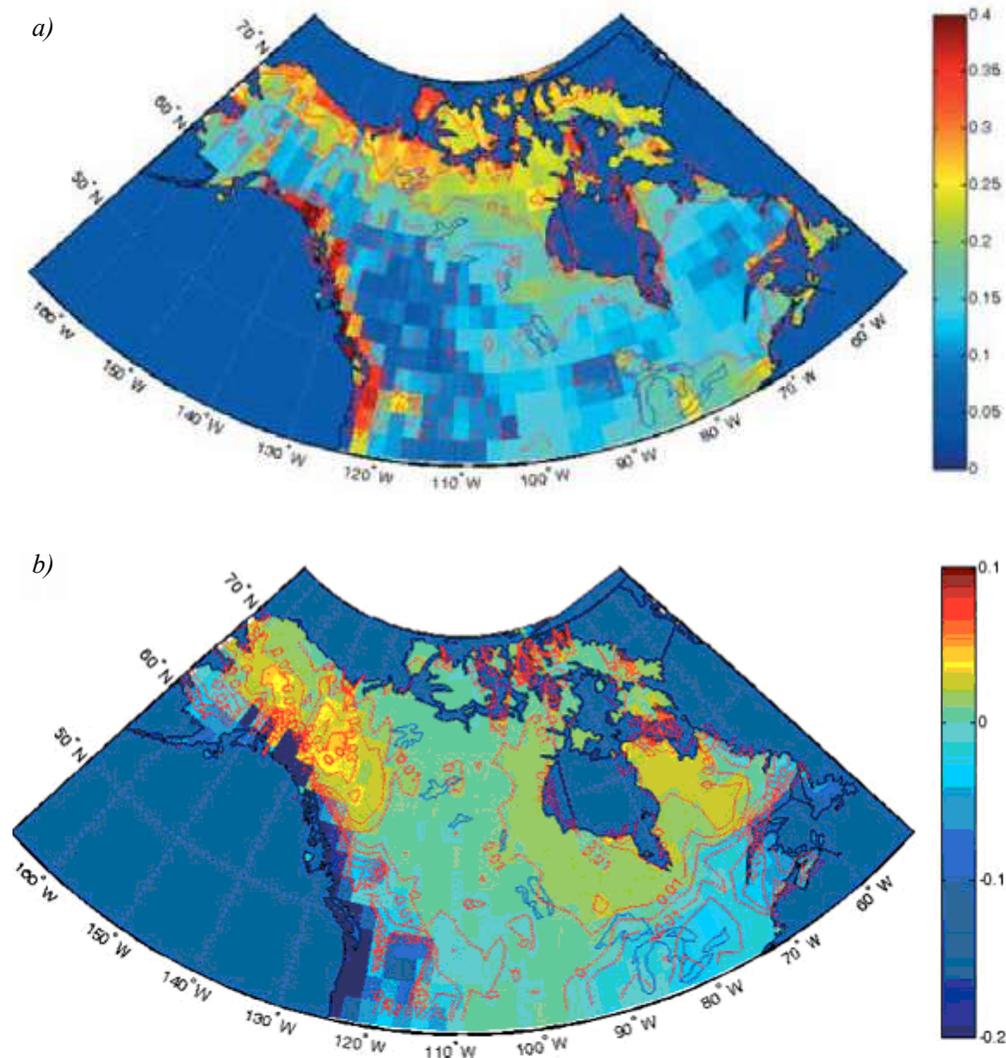


Figure A13. (a) Projected decreases in mean annual maximum ice thickness (meters) and (b), projected change in white-ice thickness (meters) between the current (1961–1990) and future (2041–2070) climatic periods for a hypothetical lake of 20 m depth based on the MyLake model using CRCM output driven by CGCM3 for the SRES A2 emission scenario. Source: Dibike et al. (2011a).

freeze-up of 8–12 days and earlier break-up of 14–20 days over the Nunavik–Nunatsiavut IRIS region. However, the spatial patterns are quite different with the largest changes in freeze-up concentrated along the east coast of Hudson Bay, while the largest changes in break-up are centred over northern Nunatsiavut (this pattern follows the results for change in start/end of summer season shown in Figure A5). The MYLAKE simulation of projected change in

maximum ice thickness (Figure A13a) shows that the largest decreases are located in northern coastal areas of the IRIS region. The simulated changes in white ice formation (Figure A13b) suggest slight increases over most of Nunavik with the largest increases over the northern Ungava Peninsula. Joly et al. (2010) examined the climate warming response of sea ice in Hudson Bay with a high-resolution regional oceanic model developed by Saucier

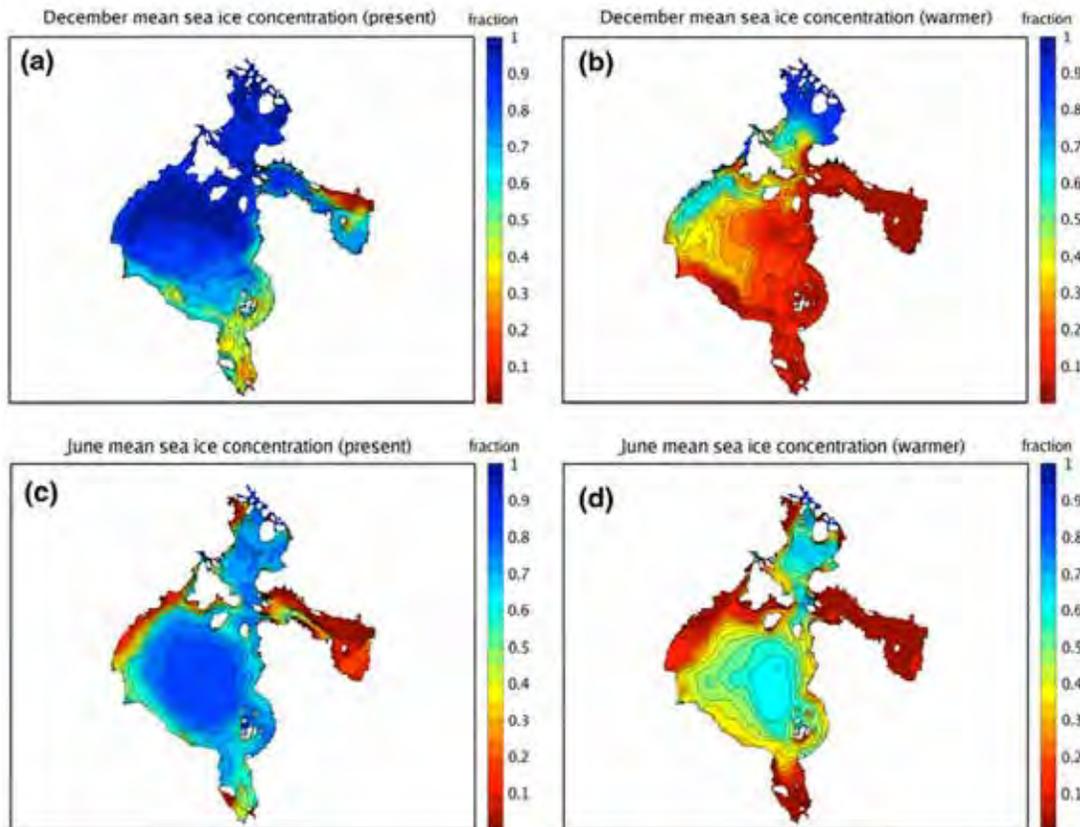


Figure A14. Simulated current mean sea ice concentration for December (a) and June (c) with the corresponding mean sea ice concentration for 2050 (b) and (d) based on CGCM3 downscaled temperature change with CRCM assuming the SRES A2 emission scenario. Source: Joly et al. (2010).

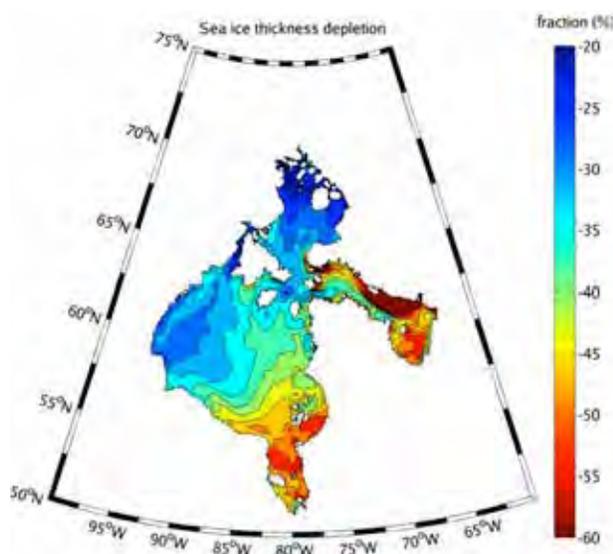


Figure A15. Relative change (%) in winter-averaged (JFMA) sea ice thickness for 2050 based on CGCM3 downscaled temperature change with CRCM assuming the SRES A2 emission scenario. Source: Joly et al. (2010).

et al. (2004) using temperature change projections from CGCM3 for the SRES A2 scenario downscaled with the Canadian Regional Climate Model. The results for change in sea ice concentration (Figure A14) and sea ice thickness (Figure A15) suggest extensive reductions in early winter ice amount in all coastal regions of Nunavik, with the largest relative decreases in ice thickness over eastern Hudson Bay north of James Bay (in the vicinity of the community of Kuujjuarapik and also in Ungava Bay, Kuujuaq).

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Chapter 3. Health Surveys and Beyond: Nunavik and Nunatsiavut

Lead authors

Éric Dewailly and Sandra Owens

Centre de Recherche du Centre Hospitalier Universitaire de Québec, Québec, QC

Abstract

The context of cultural transition, exacerbated by climate change requires adaptation on many levels on the part of circumpolar Inuit. By definition, adaptation capacity is influenced by health status. This chapter draws on results from health surveys carried out in 2004 (Nunavik) and 2007-08 (Nunatsiavut) and looks at selected health status indicators for these two populations. Health surveys take stock of many health endpoints as well as enable new understanding of key underlying factors contributing to health problems including food and nutrition, cardiovascular disease risk factors, contaminants, infectious disease from animals or drinking water, and injuries through travel.

Recent health indicator data paint an unfavourable picture for Nunavik's population, with that of Nunatsiavut fairing somewhat better. By these measures, the two regions together are among the least healthy in the country. In Inuit Nunangat (i.e. the whole of the four Inuit regions), young males and older females are particularly vulnerable to premature death. Mortality profiles differ by sex with intentional and non-intentional injuries weighing most heavily for males and chronic diseases weighing most heavily for women. Birth outcomes data indicate little positive change over time. Health inequity observed for these populations is of public health concern.

Obesity levels are high and rising (where data permit comparison), as is the incidence of associated cardiovascular disease. However, for the same level of risk factors, Inuit are in better health than Caucasian populations. The consumption of marine fatty acids, the beneficial effects of which appear to be multiplying, is one of perhaps several protective factors that seem to be at play. However, these factors may be at risk of disappearing, due to dietary transition, environmental changes and the availability of quality country food.

Significant declines in mean blood concentrations of mercury, lead and cadmium have been observed in Nunavik between 1992 and 2004. Nevertheless, a significant proportion of individuals, and of women of childbearing age in particular, continue to have concentrations exceeding the acceptable levels set by Health Canada. State-of-the-art research is identifying deleterious effects on the development of young Inuit with indications of long-lasting adverse effects of early contaminant exposure on cognitive function, as well as positive effects of fatty acids on sensory and memory function.

Survey results indicate a high level of infection by *Toxoplasma gondii* among women in Nunavik, which requires screening during pregnancy for the protection of the unborn. Levels in Nunatsiavut were found to be much lower. However, exposure to the bacteria *Helicobacter pylori* was found to be common in Nunatsiavut, and is the subject of investigation in the Inuvialuit Settlement Region (ISR) given concern over its association with stomach cancer.

Research driven interventions, such as the ban on *trans*-fats in Nunavik or the substantial decline in persistent organic pollutants found both in the environment and in people, have been successful in Inuit inhabited regions. Clearly, research and monitoring are critical for defining the complexities surrounding health determinants. Continuation of these efforts is necessary to address the significant health inequality that currently exists.

3.1 Introduction

The scenario of rapid transition experienced throughout Inuit regions means that the capacity to adapt is essential to the well-being of Inuit. However, their capacity to adapt is affected by their health status by definition whereby health is «the capacity of people to adapt to, respond to, or control life's challenges and changes». (Frankish et al. 1996). Health status is therefore an important measure of how a population may be developing sustainably and is an essential element of focus in terms of supporting the region, whether it be in terms of human rights, ecological or economic considerations, or sovereignty issues.

What do we know about the health status of Inuit people and of those living in Nunavik or Nunatsiavut in particular, and what direction does knowledge development need to take in order to address evident health inequities? Health status is determined by a host of factors, or determinants and our understanding of what these are is continually evolving. By influencing determinants, there is

an influence on health status. Climate change influences health in Inuit regions in many ways, for example through the availability, accessibility and quality of traditional foods; travel risks and injuries; the presence of infectious agents in water or food; and relationships with the land and therefore culture.

This chapter draws on the research initiatives undertaken in association with ArcticNet which have already contributed to a greater understanding of the health status and determinants of health for these two populations, for whom access to health services and public health surveillance is different than in the South and also for whom health surveys in particular may be particularly beneficial. In 2004, 2007 and 2008, the Canadian component of the International Inuit Cohort Study conducted its first “leg” of health surveys with the assistance of an ice-breaker from the Canadian Coast Guard fleet, retrofitted for ArcticNet’s research activities. In 2004, 929 participants from Nunavik’s 14 coastal villages became part of the “*Qanuipitaa? How are we?*” study, followed in 2007 and 2008 by



1902 participants from Nunavut and NWT and finally 310 participants from Nunatsiavut who joined the “Inuit Health Survey”. At the present time, results are available for Nunavik while those for Nunatsiavut are preliminary. In addition, the *Qanuippitaa? How are we?* survey represented a second wave of data collection for the Nunavik region, having adopted similar methods as were used in 1992 for the Santé Québec Health Survey, and thus allowing time trend analysis.

New knowledge and understanding continue to flow from these projects and the many interactions taking place among scientists from various disciplines. As data are analysed under different lenses, pooled and assessed in various ways, they shed light on questions of relevance to northern officials, Inuit organizations and residents. This chapter begins with an overview of health status for these two populations by examining classical measures or indicators. Subsequent sections highlight findings from the health surveys.

3.2 Population Health Status Indicators

Studies calculating life expectancy at birth for the populations within the four Inuit regions of Canada provide insight regarding one of the most revealing population health status indicators. In an analysis of the most recent mortality data available, the trend is positive showing that over the period spanning from 1989 to 2008, life expectancy within the four Inuit regions has increased from 69.0 to 70.8 years (Figure 1, Peters, in press). In terms of the difference in life expectancy between the populations of the Inuit regions and Canada, results provide a mixed message. Data show a reduction in the difference in life expectancy spanning the 1996 to 2006 study periods (or 1994 – 2008) decreasing from a difference of 13.6 years for both sexes to a difference of 9.8 years. However, all three of these most recent study periods show a greater difference in life expectancy than for the earliest study period which stands at 8.6 years – that from 1989-1993. In other words, while the recent trend shows progress has

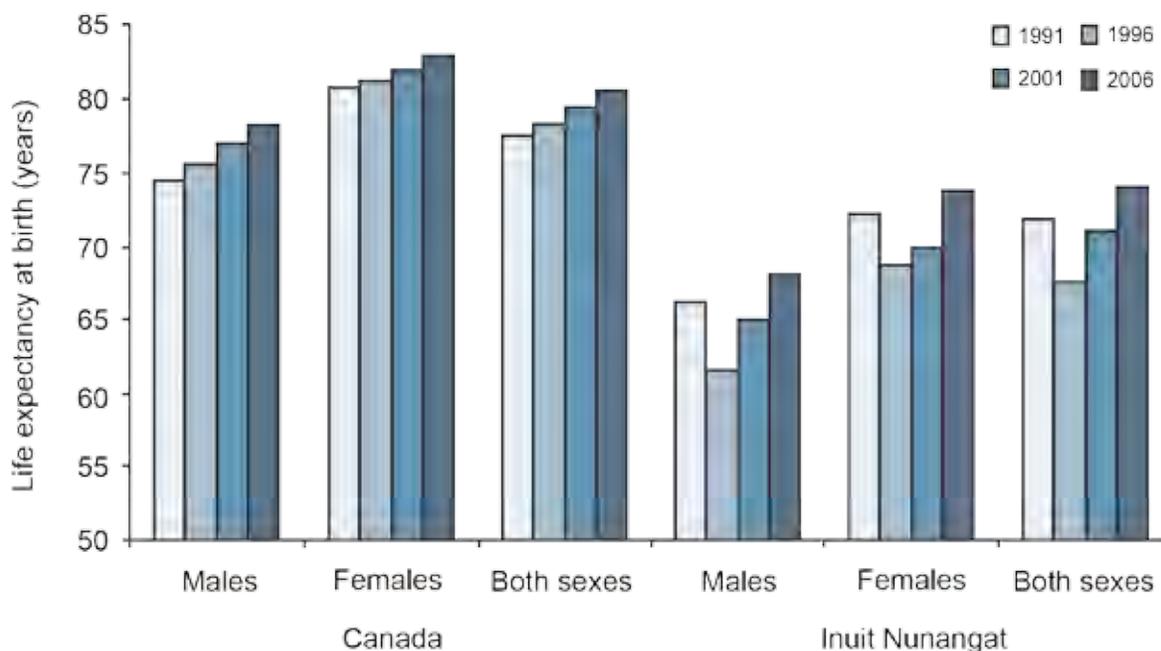


Figure 1. Life expectancy at birth (1991-2006) in Canada and Inuit Nunangat.

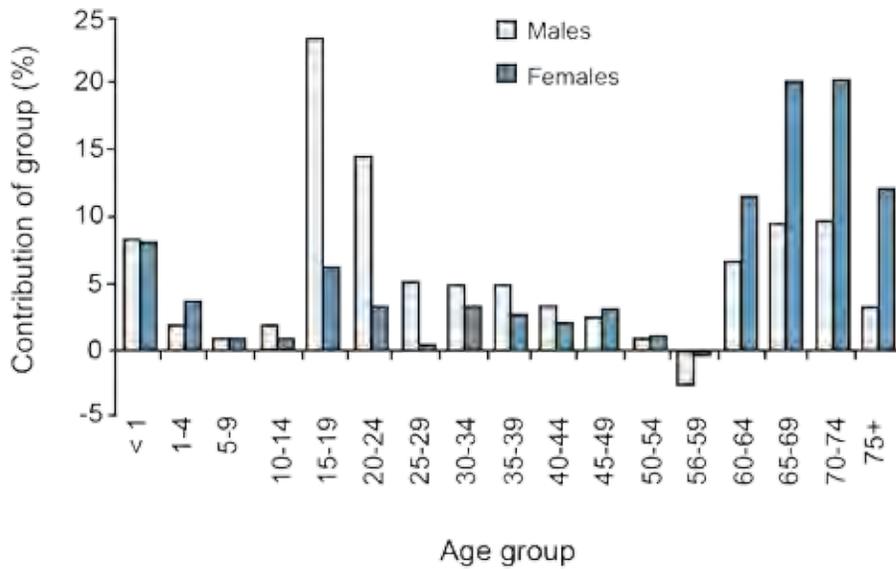


Figure 2. Age contributions to differences in life expectancy, 1999-2003 (Canada and Inuit Nunangat). From Peters (2010).

taken place in diminishing the health inequity within the regions where most Inuit live, there is no net progress in comparison to the late 1980s.

In terms of differences between the regions, Nunavik and Nunatsiavut have the shortest life expectancy at birth of the four Inuit regions (Wilkins et al. 2008). Nunavik males are the group that bears the greatest level of health inequity. Wilkins et al. (2008) calculated their life expectancy at birth to be below the 60 year threshold. In comparison, in 1926, men in Canada enjoyed a life expectancy of 60.5 years (note: life expectancy calculations for these two populations of males are based on different age structures and contexts).

In a subsequent study which attempted to account for the difference in life expectancy between Inuit inhabited regions and the rest of Canada, Peters (2010) found that deaths occurring in males between 15 and 24 years of age accounted for almost 40% of the difference in life expectancy between these two populations. Another bulge in the histogram of contributions to differences in life expectancy (Figure 2) is attributed to females over the age

of sixty where just over 64% of the difference in female life expectancy is due to what Peters (2010) refers to as “excess” mortality. Peters’ analysis suggests that addressing inequity requires a strategy that recognizes and understands how and why young men and older women from Inuit inhabited regions are experiencing excess mortality.

Figure 3 shows the top five primary cause of death categories for Inuit Nunangat (i.e. the whole of the four Inuit regions) for males and females based on vital statistics data from 1999 to 2003. These mortality rates, corrected for the different age distributions of the Inuit and Canadian populations, indicate that injuries are the leading cause of death for Inuit males. In particular, the category suicide and intentional injuries, was the leading cause of death for Inuit males. For females, the profile was somewhat different with chronic diseases playing a more important role in terms of identifying leading causes of death. Not surprisingly, for both sexes and for all categories, mortality rates were higher for Inuit Nunangat than those for Canada as a whole. Deaths caused by injury, accident or suicide were more common in Nunavik and Nunatsiavut than for Inuit Nunangat as a whole. (Statistics Canada, n.a.).

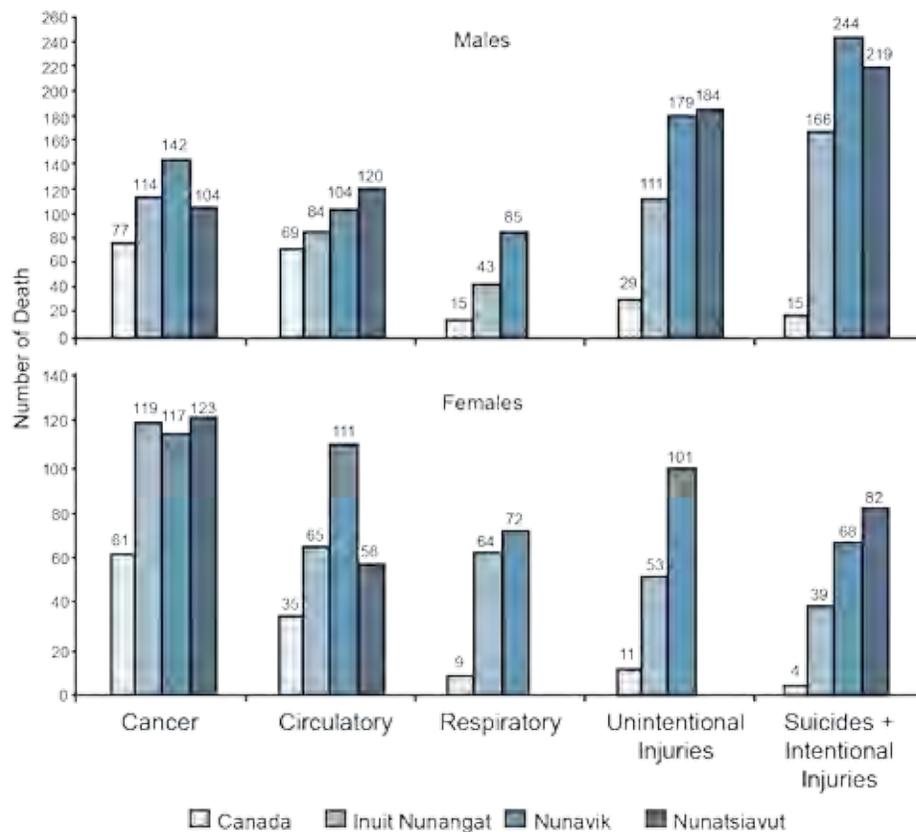


Figure 3. Primary causes of death between 1999 and 2003. Age-standardized mortality rates per 100 000 population. Source: Statistics Canada.

The infant mortality rate (IMR), measured as the number of deaths in children in the first year of life per 1000 live births per year is considered a robust indicator for the health of a population (Reidpath and Allotey 2003). Zhong-Cheng et al. (2010) undertook a cohort study of birth outcomes for Inuit inhabited areas over a period spanning a decade. The IMR for all Inuit inhabited areas combined was substantially higher than the rate for the rest of Canada (16.5 versus 4.6). Nunavik presented the highest IMR of the four Inuit regions at 18.1, with Nunatsiavut and Nunavut at 16.7 and 16.5 respectively and Inuvialuit at 13.4 (Figure 4). In terms of trends over time, the authors suspect that overall, little change in birth outcomes took place over the study period. They speculate that changes in registration practices adopted in the later study period

explain an apparent decrease in infant mortality in favour of an increase in stillbirths (not shown). In terms of population health, birth outcomes data indicate that the inequity between Inuit and the rest of Canada is stable.

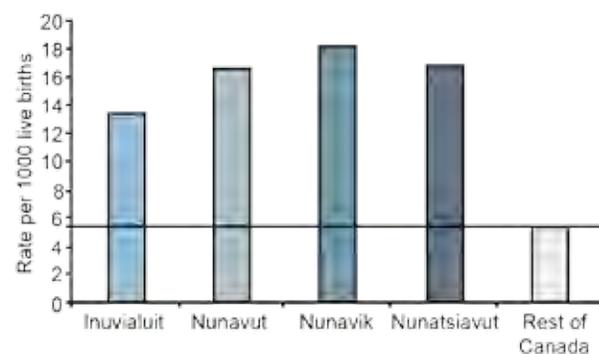


Figure 4. Infant mortality from 1990 to 2000. Adapted from Luo et al. (2010).



3.3 Findings from the Inuit Health Surveys

3.3.1 Nutrition and Cardiovascular Disease

The Inuit diet in Nunavik and Nunatsiavut is by some measures poor, as revealed by Inuit cohort surveys (Blanchet and Rochette 2008, Egeland 2010). High in sugar and salt, low in calcium, magnesium, vitamins A, C and D, and fibre, as well as deficient in iron, traditional clinical measures of body fat provide somewhat expected but disquieting information. Obesity rates in Nunavik in 2004 were high, especially among women who display abdominal obesity (Château-Degat et al. 2011). Moreover, the prevalence of obesity and severe obesity in Nunavik increased significantly between 1992 and 2004. Propor-

tionately more women and older adults had an at-risk waist circumference however, the greatest increases from 1992 to 2004 were observed among men and young adults (Dewailly et al. 2007b). In Nunatsiavut, 74% of women and 35% of men had a waist circumference that is considered “at-risk” for health problems (Egeland 2010).

Dietary fat intake is recognized for its important role in the development or prevention of chronic disease (Zhou et al., in press). Marine fat, such as that from whales, may be a very particular elixir in maintaining a healthy fat profile that is protective against cardiovascular disease (CVD), as well as other health outcomes. Lucas et al. (2010) found that marine mammal fat was the most significant contributor to the healthy fat profile of Inuit of Nunavik providing a rich source of n-3 long-chain polyunsaturated fatty acids. Its positive effects uncovered to date include significantly increasing the gestational age of unborn Nunavik infants (Lucas et al. 2004); having beneficial effects on visual system function of school aged Inuit children (Jacques et al. 2011); and possibly reducing psychological distress, particularly among Inuit women (Lucas et al. 2009). It is also suspected to be an important protective factor against prostate cancer along with selen-



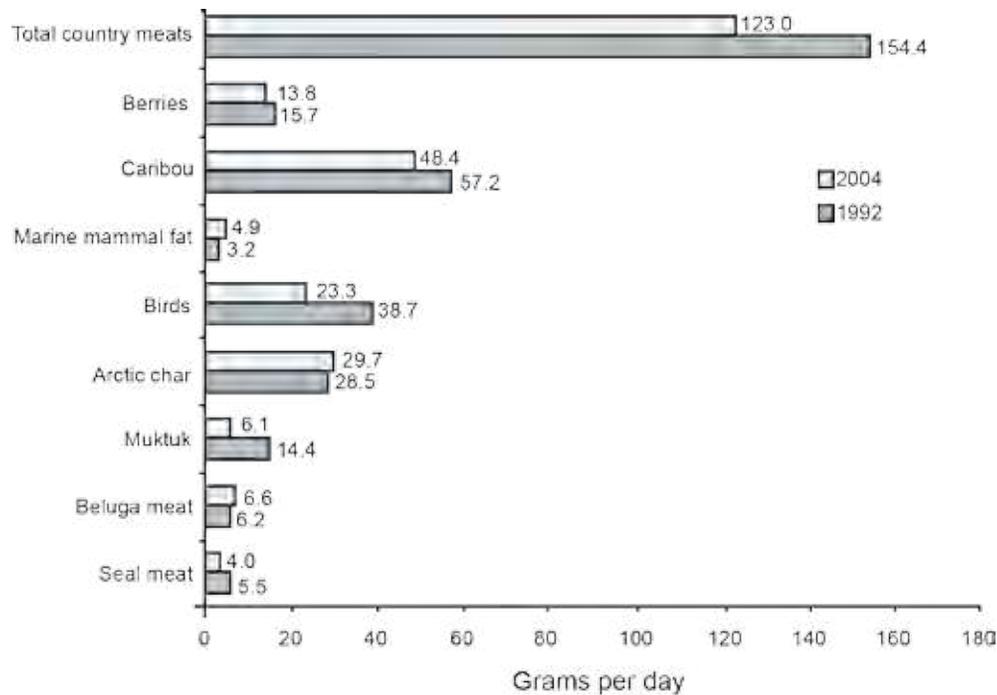


Figure 5. Comparison of daily traditional food consumption among Inuit women as estimated in 1992 and in 2004, Nunavik, 2004. From Blanchette and Rochette (2008).

ium (Dewailly et al. 2003). Researchers are attempting to understand what aspect specifically has been protecting Inuit, despite the fact that this protective agent seems to be eroding over time and with acculturation.

This erosion may be taking place in two ways – Inuit may be eating less marine fat and, its quality may be changing. For the former, eating less marine fat is associated with the transition towards a Western-type diet, with foods being transported north (note: The Federal Government has recently announced the replacement of its Food Mail Program with Nutrition North Canada, to ensure that more nutritious foods be available and subsidized for all Northern communities), as well as other factors interfering with traditional activities – such as employment and financial considerations. Comparison of results from the Nunavik health surveys administered in 1992 and 2004 provides information on time trends. Overall, total country meats consumed, expressed in

grams per day, decreased between the two study periods from an estimated 154 to 124 grams per day with a portion of this decrease attributed to shifts in marine mammal consumption (Figure 5, Blanchet and Rochette 2008). Indeed, in an analysis of fatty acid profiles among the Nunavik Inuit as measured in blood samples collected in 1992 and again in 2004, Proust (in preparation) found that n-3 PUFA went from about 10% in 1992 to about 7% of total fatty acids in 2004 (Table 1).

Many of the “replacement” foods are laden with saturated and *trans*-fats which offer stability and long shelf lives to foods. *Trans*-fats or *trans*-fatty acids (TFA) originate mainly from commercially hydrogenated vegetable oils, as well as from dairy and meat fats. They are associated with increased risk of cardiovascular disease and certain cancers. Given these risks, certain countries have imposed maximum content limits in industrially produced foods in order to limit exposure to these fats (Council et al,

Table 1. 1992-2004 comparisons between relative mean concentrations of fatty acids (% of total fatty acids) in plasma phospholipids in Inuit of Nunavik.

FATTY ACIDS	ALL AGES	
	1992 (N=424) MEAN ± SD	2004 (N=462) MEAN ± SD
EPA	3.34 ± 2.80	1.84 ± 2.06
DHA	5.23 ± 2.05	4.15 ± 1.94
EPA + DHA	8.57 ± 4.47	5.99 ± 3.71
DPA	1.36 ± 0.52	1.08 ± 0.45
ALA	0.16 ± 0.08	0.22 ± 0.16
LA	18.41 ± 4.42	22.08 ± 4.08
AA	6.22 ± 1.83	5.60 ± 1.67
EPA/AA	0.57 ± 0.51	0.33 ± 0.36
n-3 PUFA	10.40 ± 4.86	7.38 ± 4.02
n-6 PUFA	21.60 ± 4.80	30.83 ± 3.89
n6:n3	2.87 ± 2.06	5.78 ± 3.84
SFA	40.27 ± 2.83	43.84 ± 1.78

EPA, eicosapentanoic acid; DHA, docosahexanoic acid; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids.

in press). A study by Counil et al. (2008) comparing levels of both TFA and n-3 fatty acids among Inuit of Nunavik and Greenland revealed that levels among the Inuit of northern Québec are three times those of Greenlanders as depicted in Figure 6. Moreover, these levels were associated with problematic blood lipid profiles for Nunavik males (Counil et al. 2009). These findings led to an intervention strategy which resulted in the Nunavik Regional Board of Health and Social Services passing a resolution in January of 2009 to support an active campaign against the importation of food items containing TFA (Counil et al., in press).

In terms of the quality of the marine fat, research is needed to better understand the changes taking place in the Arctic and Subarctic ecosystems in response to climate change. Researchers have hypothesized that the Arctic marine food web will respond to climatic shifts by adjusting its species profile down to the smallest of organisms found at the base of the food chain. Specifically, sci-

entists predict the replacement of highly specialised flora and fauna by less specialised ones from the Atlantic and Pacific Oceans (e.g. Tynan and DeMaster 1997, Barber et al. 2006). This shift would likely entail a move towards less fat rich species – and herein lays the potential for adversely impacting the Inuit traditional diet.

In terms of chronic diseases and nutrition, Inuit health has been characterised in the literature by a paradox – on the one hand scientists warn of the risk of an oncoming epidemic caused primarily by a shift away from a traditional lifestyle and towards western foods (e.g. Blanchet and Rochette 2008), and on the other, many have invoked the presence of a protective factor staving off the expected onset of diseases (e.g. Bjerregaard and Young 1998). Studies of obesity levels, of markers of cardiovascular health such as blood pressure and lipid levels, and of disease levels, point in a similar direction. Inuit are as obese as North Americans (Young et al. 2007, Château-Degat et al. 2011) and their bodies respond to this obesity by increasing metabolic measurements such as blood pressure (Bjerregaard et al. 2003) and high density lipoprotein (HDL) levels, but this response is not as marked as for other populations (Young et al. 2007). Château-Degat et al. (2011) found that despite the high level of abdominal obesity, or central fat patterning, the participating Inuit of Nunavik rated well for known indicators of cardiovascular disease risk such as blood pressure or HDL - cholesterol. The authors go on to suggest that the study may indicate the presence of obese but healthy individuals, representing a “phenotype” that may be resistant to developing diabetes as well as cardiovascular disease, and that women in particular may be less affected by abdominal fat. Furthermore, it has been documented that n-3 fatty acids are clearly associated with this advantage (Dewailly et al. 2003a).

In other words, for the same level of obesity, Inuit are in better health than Caucasian populations - but they do however develop cardiovascular disease or diabetes, and these rates are reaching levels similar to those seen in Caucasian populations (Château-Degat et al. 2010).

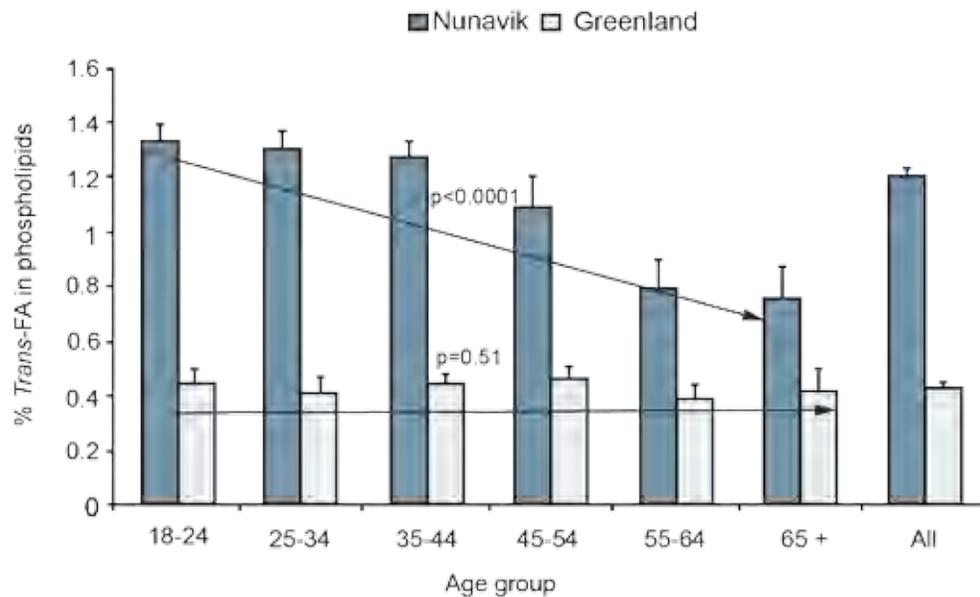


Figure 6. Relative proportion of trans-fatty acids in red blood cell membrane phospholipids according to age group in Inuit populations living in Nunavik (Canada) and Greenland (Denmark). Adapted from Counil et al. (2008).

Château-Degat et al. (2010) revealed through an analysis of survey results augmented by medical record information, that the prevalence of some cardiovascular diseases among Nunavik Inuit are reaching levels seen in the Canadian population. The authors drew on the fact that when the spectrum of cardiovascular diseases is considered, (age-adjusted) mortality rates from all cardiovascular diseases are highest in Nunavik compared with the other regions of the province of Québec (INSPQ). The high rate of tobacco use among Inuit is also a risk factor contributing to cardiovascular disease.

Studies have found many differences among Inuit populations in terms of fat lipid profiles (Counil et al. 2008, Zhou et al. 2010), obesity levels, and metabolic markers of cardiovascular health which further support that Inuit health is as susceptible as that of any other population to changes in response to diet, lifestyle factors and other determinants.

The Inuit diet in transition is particular in that its point of departure, or the historical Inuit diet, was rich in poly-

unsaturated fatty acids and minerals and its replacement diet, is rich in *trans*-fatty acids. The consumption of fats from both ends of the fat continuum – from particularly good to particularly bad – justifies the need to closely monitor the situation.

In addition to this complex set of issues to assimilate, the impact of methylmercury on the cardiovascular system must be considered. As well as its known effects on the central nervous system, recent investigations have documented its adverse impacts on cardiovascular health. Valera et al. (2009) found that mercury in the blood of Inuit of Nunavik is associated with increasing blood pressure and pulse pressure. As well, their study, as reported for the first time for an adult cohort, suggests that mercury may reduce Heart Rate Variability (HRV), an important indicator associated with many heart conditions and causes of mortality. Mercury levels among Inuit as measured by the *Qanuippitaa?* How are we? survey are in decline but are still higher than the recommended safe levels for a significant portion of the population (Dewailly et al. 2007), and moreover, these recommended safe levels do not take into account this emerging research.

Several studies have reported that younger Inuit eat less country food than their parents or Elders (e.g. Blanchet and Rochette 2008), opening the way for questions regarding the sustainability of traditional Inuit culture as well as for concern for consumption of protective fat. In Nunavik, two health surveys – one in 1992 and one in 2004 – show the same pattern, but also allow for the observation that the younger people in 1992 became an older age group for the 2004 survey – and reported eating more traditional foods than the following generation of Inuit. This observation indicates an apparent return or move towards adopting the cultural habits of parents and elders with age. Zhou et al. (in press) analysed fat samples from Inuit surveyed from across the Canadian North and found a strong association with age for healthy n-3 fatty acids for the Baffin and Kivalliq regions of Nunavut. The authors associate this age-consumption pattern with a state of dietary transition while for other communities where healthy fat levels were less associated with age, the authors suggest that the more stable dietary pattern may be reflective of the acculturation process that has run its course. So a stabilisation of country food consumption rates among Inuit in Canada may be expected, highlighting the importance of working to maintain the quality and quantity of such resources in locations where arable land is clearly lacking. Moreover, flying food northward is costly and contributes to the carbon footprint of the region.



3.3.2 Food insecurity

Significant levels of food insecurity are found in both the Nunavik and Nunatsiavut populations. In Nunavik in 2004, nearly one quarter of individuals (24%) stated they had lacked food during the month prior to the survey (Blanchet and Rochette 2008). In Nunatsiavut, the household results report that 46% of households with children were food insecure, with about 16% of households reporting severe food insecurity. This compares with 9% of Canadian households reporting moderate or severe food insecurity according to the Canadian Community Health Survey 2004 (Egeland 2010). Unemployment, low income, high food costs (Egeland 2010), unavailability of foods, the decrease in consumption of country foods and the lack of information on nutrition and food choices (Blanchet and Rochette 2008) are reasons for these high levels of food insecurity.

3.3.3 Environmental contaminants

Human exposure to environmental contaminants is a well known phenomenon in the Canadian Arctic. Inuit are exposed to a plethora of toxic substances that are carried from southern to northern latitudes by oceanic and atmospheric transport and biomagnified in Arctic and Subarctic food webs. As the Inuit traditional diet comprises large amounts of tissues from marine mammals, fish and terrestrial wild game, Inuit are more exposed to metals and persistent organic pollutants (POPs) than populations living in southern regions. Contaminants of concern include mercury (Hg), lead (Pb) and cadmium (Cd). Each of these metals is associated with a range of detrimental health effects at levels of exposure that are associated with environmental pollution.

Concentrations of cadmium, mercury and lead measured in blood samples taken as part of the *Qanuippitaa?* How are we? survey show a significant decline in 2004 levels as compared to data from the 1992 survey. Mean blood concentrations of mercury declined by 32%, lead by 55%, and cadmium by 22%, over that timeframe (Fon-

taine et al. 2008). Nevertheless, a significant proportion of individuals generally, and women of childbearing age in particular, continue to have concentrations exceeding the acceptable level set by Health Canada. In the overall population, 36%, 28% and 9% of individuals had blood concentrations exceeding the recommendations set by Health Canada for cadmium, mercury and lead, respectively. Among women of childbearing age, 35%, 72% and 2% had concentrations of cadmium, mercury and lead exceeding acceptable levels. The results also reveal that the blood concentrations of mercury observed increased significantly with consumption of marine mammals, whereas concentrations of cadmium were linked to tobacco smoking. (Dewailly et al. 2007a)

Persistent organic pollutants (POPs) such as polychlorinated dibenzo p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs) and chlorinated pesticides are industrial compounds which accumulate in fatty tissues, find their way into human breast milk and can travel across the placental barrier. They have been associated with a range of problems including detrimental effects on aspects of cognitive development; cancer; endocrine or hormonal processes and others. (Dewailly et al. 2007)

Blood (plasma) concentrations of all the classical persistent organic pollutants (POPs) among Inuit declined between 1992 and 2004. As certain studies on the subject suggest, this decrease is likely attributable to a reduction in contaminants in the Arctic environment, combined with changes in Inuit eating habits. Nevertheless, in 2004, 11% of the overall population and 14% of women of childbearing age had total PCB concentrations exceeding the acceptable levels set by Health Canada. The concentrations of new contaminants of concern, measured for the first time in 2004, did not prove to be high. Consumption of traditional foods did not prove to be a source of exposure to these contaminants, except in the case of PFOS (perfluorooctanesulfuric acid - a chemical substance used in water, soil and grease repellents, paper, packaging, rugs and carpets, fabrics, etc.). (Dewailly et al. 2007c)

In a study of contaminant trends as detected in the cord blood of Inuit infants born in Nunavik between 1994 and 2001, Dallaire et al. (2003) found results which emulate the general trends found in the adult population discussed above. Mercury and lead levels were found to have decreased significantly, likely attributable to a combination of lower levels of contamination in traditional foods as well as shifts in dietary habits (Figure 7). Trends for certain POPs were strongly decreasing: PCBs, dichlorodiphenyl trichloroethane (DDT), dichlorodiphenyl dichloroethylene (DDE), and hexachlorobenzene (HCB), while no significant trend was observed for chlordanes (Figure 8).

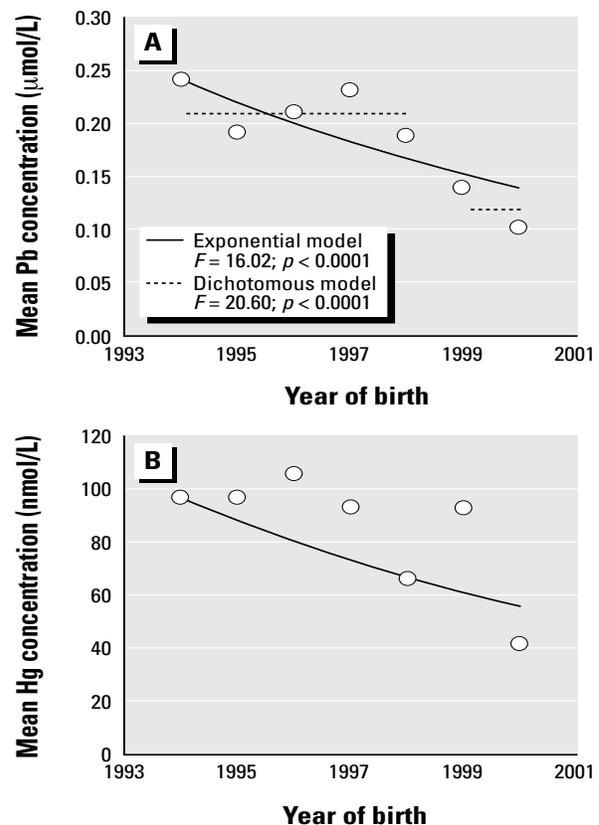


Figure 7. Adjusted mean heavy metal concentrations according to the year of birth for (A) lead and (B) mercury. From Dallaire et al. (2003).

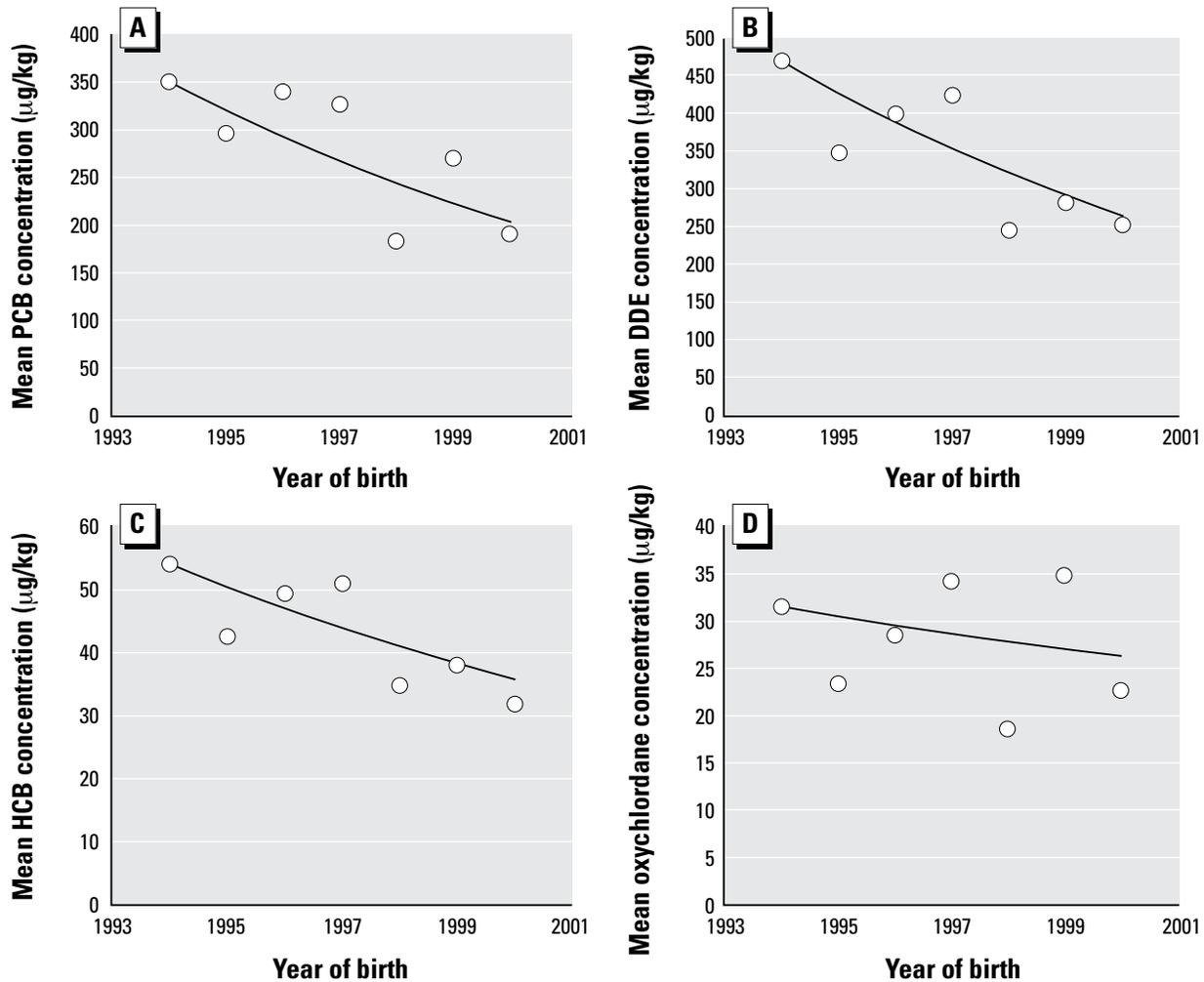


Figure 8. Adjusted mean OC concentrations according to year of birth: (A) PCBs; (B) DDE; (C) HCB; (D) oxychlordanes. From Dallaire et al. (2003).

Between 1993 and 2001, two birth-cohort studies were initiated in Nunavik to examine the effects of early-life exposure to environmental contaminants on child development (Muckle et al. 1998, 2001). Assessments conducted during infancy and at preschool age revealed impairments in attention and motor function as a function of Pb exposure (Després et al. 2005, Plusquellec et al. 2007, 2010) and subtle sensory alterations resulting from Hg and PCB exposure (Saint-Amour et al. 2006). By contrast, polyunsaturated fatty acids (PUFAs), also found in large quantities in marine species, were associated with beneficial effects on infant cognition and visual function (Jacobson et al. 2008). Both cohorts

were recently combined for an assessment involving nearly 300 school-age children. Although all of the data collected has not yet been analyzed, initial findings tend to indicate long-lasting adverse effects of early contaminant exposure on cognitive function, together with positive effects of PUFAs for sensory and memory function (Boucher et al. 2010, in press, Jacques et al. 2011). The effects of contaminant exposure on child behavior at school were also assessed from questionnaires given to teachers, and will provide key information about the repercussions of the cognitive impairments attributed to contaminants on daily functioning.

During the 2008 component of the Inuit Health Survey, data was collected from participants in the Nunatsiavut region. Results are still not available at this time. They represent an important contribution to describing the health status of the population as no other biomonitoring activities are ongoing in the region (Owens et al. 2009).

3.3.4 Infectious disease from animals or drinking water

Some common practices in Nunavik, such as the consumption of untreated water and raw fish, marine and land mammals may favour exposure to a variety of micro-organisms leading to disease. There is little documentation concerning zoonotic diseases – infections transmissible from animals to humans – among Inuit. For a number of these diseases, little is known about how they are transmitted in the Arctic environment. Additionally, their clinical presentation or symptoms are often unspecific and can make diagnosis extremely difficult. All of these factors make it difficult to determine the significance of these infections for Subarctic populations (Messier et al. 2007).

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 Nunavik and those prevailing elsewhere in Québec. In most Inuit communities, drinking water is obtained from unfiltered chlorinated surface water which is distributed daily by tanker truck and stored in reservoirs inside homes (Hodgins 1997). However, about 30% of Inuit still use untreated water (Martin et al. 2007). As well, sewage is generally dumped not far from the village in ponds reserved for this purpose, or sometimes spread directly on the ground (Martin et al. 2007). This scenario may favour exposure to water-borne diseases.

Almost 10% of respondents to the *Qanuipitaa?* How are we? Survey reported having suffered from gastroenteritis in the month prior to the survey, with the highest levels among the very youngest and the oldest age groups.

While the manner of preparing meats, living in close quarters, the main source of drinking water and the type of water treatment used in the household were not associated with episodes of gastroenteritis, frequent cleaning of the home water reservoir does appear to have a protective effect against the transmission of gastro-intestinal infections (Messier et al. 2007).

Seroprevalance is the number of persons in a population who test positive for having had a disease as measured through the detection in blood of antibodies to that specific infectious agent. Blood samples taken from adults aged 18 to 74 allowed for a verification of the presence of antibodies for eight zoonotic infections (*trichinellosis*, *toxocariasis*, *echinococcus*, *brucellosis*, *leptospirosis*, Q fever, *toxoplasmosis* and *tularemia*). While cases are rarely reported in Nunavik, this direct verification reveals that Inuit are indeed exposed to these micro-organisms which lead to infections, and to *Toxoplasma gondii* in particular (Table 2). Messier et al. (2009) reported that the incidence of *Toxoplasma gondii* infection in Nunavik at 59.8% is high in comparison to many parts of the world, very high in comparison with North America and unexpectedly high given an anticipated low level of environmental risk in Nunavik based on the near absence of “definitive reservoir hosts” in the region, raising questions regarding this latter assumption. The authors go on to report that the

Table 2. Seroprevalence (%) to various infectious agents in the Inuit population aged 18 to 74, Nunavik, 2004. Adapted from Messier et al. (2007).

INFECTIOUS AGENTS	POSITIVES	NEGATIVES
<i>Trichinella</i> sp.	F	98.9
<i>T. canis</i>	3.9	96.1
<i>E. granulosus</i>	8.3	91.7
<i>T. gondii</i> (%)	59.8	37.2
<i>Brucella</i> sp.	F	99.6
<i>C. burnetii</i>	F	99
<i>Leptospira</i> sp.	5.9	94.1
<i>F. talarensis</i>	18.9	81.1

F: Unreliable estimate

Table 3. Seroprevalence of *Toxoplasma gondii* among permanent residents of Nunavik stratified per village on a south-north gradient, weighted data, 2004 (n=917). Adapted from Messier et al. (2009).

VILLAGES	HOUSEHOLDS		INDIVIDUAL (N)	SEROPREVALENCE (%)	95 % CI
	COMMUNITY (N)	SAMPLE (N)			
Hudson Bay				65.6	61.5-69.7
Kuujuarapik	138	26	46	87.2 ^a	71.1-96.2
Umiujaq	77	19	33	82.2 ^a	66.5-92.6
Inukjuak	281	61	116	74.6 ^b	64.9-82.8
Puvirnituq	271	75	110	69.6	60.6-78.5
Akulivik	99	28	52	69.6 ^b	52.4-83.5
Salluit	210	47	109	37.9	30.6-45.1
Ivujivik	54	15	32	46.7 ^b	26.6-67.5
Ungava Bay				52.3	47.9-56.8
Kuujuuaq	441	104	158	44.3	36.5-52.0
Tasiujaq	53	13	19	71.3 ^a	45.4-89.8
Kangiqsualujjuaq	153	32	62	74.9 ^b	64.7-83.5
Aupaluk	36	10	19	57.1 ^b	33.4-78.6
Kangirsuk	93	28	48	58.0	44.8-71.2
Quaqtaq	70	16	24	34.1 ^b	18.1-53.1
Kangiqsujuaq	113	32	62	44.5	35.3-53.7

^a Coefficient of variation >33.3 % ; insufficient precision, unreliable estimate.

^b Coefficient of variation between 16.6 % and 33.3 % ; interpret with circumspection.

data indicate that seroprevalence increases with decreasing latitude, or as one moves southward (Table 3). One hypothesis suggests the possibility of a relationship with climate and the survival rate of the parasite, wherein a warmer and more humid climate may favour its proliferation. However, factors indirectly related to climate such as differing walrus feeding regimes across the north-south Nunavik gradient may also play a role in accounting for seroprevalence shifts with latitude.

Furthermore, seroprevalence was higher in women than in men (62.8 versus 57.9%, p-value 0.0476), perhaps given their proximity to raw flesh during food and hide preparation activities. Given that the main health impact of *Toxoplasma gondii* is as a significant cause of mortality and morbidity to the unborn foetus, women's exposure to the parasite remains a public health issue. Indeed, Nunavik is

the only jurisdiction in Canada with a *Toxoplasma gondii* screening program among pregnant women (Lavoie et al. 2008). In comparison, only 8% of participants in Nunatsiavut were found to have been infected by the parasite, with little difference observed between men and women (Egeland 2010).

For the other seven zoonotic infections Messier et al. (2011) reported seroprevalence levels in Nunavik that are lower to much lower, ranging from 8.3% of the population which are exposed to *Echinococcus granulosus* to rates that fall under 1% such as that for *Trichinella spiralis* (see Table 2). In the case of the latter zoonotic agent, the authors highlighted the importance of the trichinellosis prevention program which targets the consumption of walrus meat, traditionally eaten raw in Nunavik. Samples of harvested animals are tested at a regional laboratory

and results are quickly disseminated back to the community in question (Proulx et al. 2002). Since its implementation in 1992, outbreaks of *trichinosis* have been sporadic and small. In general, seropositivity for zoonotic infections was found to increase with age.

In Nunatsiavut, results for other parasites indicate that exposure within the population is rare, in line with what was found for Nunavik. In the Nunatsiavut survey blood samples were also tested for exposure to the bacteria *Helicobacter pylori* which was found to be a common infection with 71% of all participants testing positive for this bacteria. Because it is spread from person-to-person it is thought to be associated with household crowding (Egeland 2010).

3.3.5 Transportation injuries and safety

Modernization in Arctic and Subarctic communities has meant adopting modes of transport that are mechanical in nature and are adapted to the terrain and environmental conditions. While some traditional motorised vehicles such as trucks are used within village limits, much short and longer distance travel is accomplished with the aid of snowmobile or All Terrain Vehicle (ATV). Motorised boats are also an important means of transport for residents of coastal communities. Generally speaking, the accident profile for isolated northern regions is characterised by few traffic accidents, with an accident rate related to snowmobiling and boating that is higher than in more southern areas (Légaré and Rochette 2007). Climate change is recognized as contributing to increased travel risks in northern regions given the changes to snow, ice and weather (e.g. Climate changes in Northern Quebec see <http://climatechange.krg.ca/index.html>).

Rates for hospitalization due to non-intentional injury show Nunavik with the highest rate of all 18 health regions within the province and more than double the rate for the whole population (INSPQ, MSSSQ and ISQ; 2006). The *Qanuipitaa? How are we?* Survey gathered information on travel and safety practices that are

common place in isolated northern locations - travel by snowmobile, boat or all terrain vehicle (see chapter 5 for further details). By collecting information on the circumstances surrounding the reported injury related to the adoption of safety measures or behaviours at risk, results can inform initiatives seeking to prevent such injuries. The latter are essential to understanding non-intentional injury in Nunavik and for the development of injury prevention initiatives.

About 4% of residents of all ages from the region reported at least one injury which limited regular activities within the 12 months preceding the *Qanuipitaa? How are we?* Survey with no significant difference between the injury rates reported in the 1992 and the 2004 surveys. Men were more at risk for injury than women and young people aged 15 to 29 had higher rates of injury than other age groups. There was a significant difference in injury rates reported between the two coastal regions of Nunavik, with a higher prevalence among Ungava residents than those from the Hudson coast. Interestingly, a significant association was observed between the reported injury rate and relative education level, with the highest rate among residents who had completed secondary school or higher. There was also a higher injury rate observed among pre-school children and students.

Injuries occur, in descending order of frequency: in sports activities, on ATVs, on snowmobiles or from falls. Accidents involving transportation represent 40% of all reported injuries.

One quarter of snowmobile users (drivers and passengers) aged 15 and above are lone-travellers - they rarely or never travel in the company of another snowmobile, whether man or woman. This practice is more common among residents of the Hudson coast as opposed to the Ungava coast. Those who tend to travel by snowmobile unaccompanied are those with the lowest level of education, those having an income less than \$20 000 and those not having formal employment. A profile may be emerging of individuals who may be more active in trad-

itional activities in lieu of modern economic ones – and that these individuals are not those who are most likely to have suffered an injury.

In addition, three-quarters of Inuit aged 15 and over rarely or never wear a personal floatation device (PFD) when travelling in a motorized boat. This proportion is significantly higher among women than men although no significant difference was observed among age groups. Residents living along the Hudson coast wear a PDF less frequently than their counterparts from the Ungava coast. This preventive measure does not vary with educational level, income or main occupation.

Driving motorized vehicles under the influence of drugs or alcohol multiplies the risk of trauma. The following proportions relate only to individuals aged 15 and over who drive these vehicles. One car/truck driver in five (20%) reported having driven under the influence of drugs or alcohol on at least one occasion in the previous 12 months. This proportion reaches 32% in the case of ATVs and snowmobiles and is less frequent (10%) in the case of motorized boats. Among all motor vehicle drivers,

38% had driven a vehicle while under the influence of a substance in the 12 months preceding the survey (Figure 9, Légaré and Rochette 2007).

3.4 Conclusion

Like many aboriginal populations, Nunavik and Nunatsiavut inhabitants are expected to live a substantially shorter life span than the average Canadian. As well, their infant mortality rate is 3 – 4 times that of Canada's. These two key indicators of a population's health status speak volumes, and serve as motivation to the many Inuit and other stakeholders with an interest in improving the situation. Vital statistics data offer sobering but effective messages about how problems are manifesting within Inuit society. While not news, the continued seriousness of the suicide rate particularly among young men, raises a red flag. Clearly, there are critical determinants of Inuit health that are being missed. Indeed, an emphasis on the critical role of social determinants in contributing to health inequalities in aboriginal populations is reflected in recent literature (e.g. Postl et al. 2009).

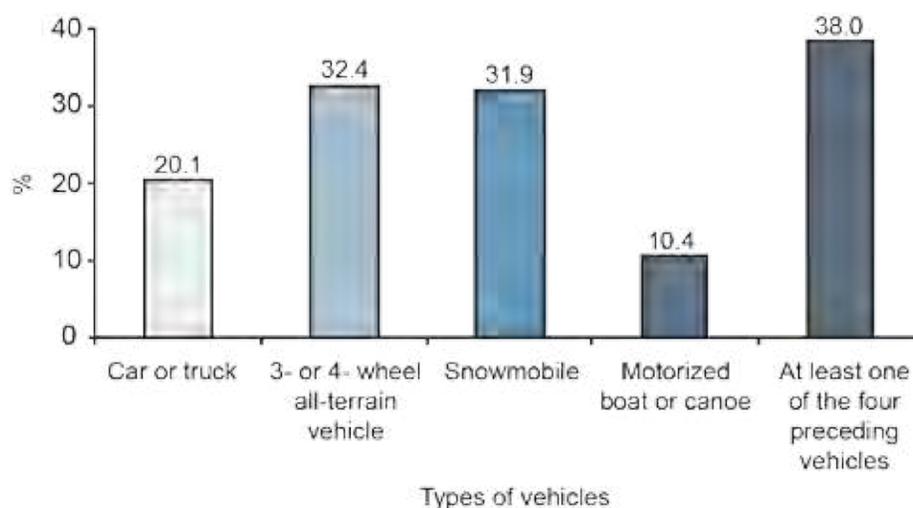


Figure 9. Proportion of drivers (%) who reported driving a motorized vehicle at least once while under the influence of alcohol in the 12 months preceding the survey by type of vehicle, population aged 15 and over, Nunavik, 2004. From Légaré and Rochette (2007).



But all is not bleak – Inuit may have an advantage in terms of certain serious chronic diseases, such as Ischemic heart disease and diabetes in particular. Not only is this extremely positive for them, but it also raises interesting questions from a scientific perspective, the exploration of which holds the potential to help Inuit continue to benefit from some protection from these diseases in the face of modernization and also to gain knowledge that may be transferable to other populations who are not so fortunate in this regard.

In retrospect, certain critical elements, or determinants, to maintaining or improving the health of Inuit whether in the Eastern Subarctic or elsewhere in the remote North can be identified thanks to health survey work. That their diet and lifestyle in general be ameliorated in terms of access to healthy foods, exercise and abstaining from tobacco use; that safe travel behaviours be widely adopted; that they continue to have access to country foods which provide them with high quality fats which may be the remaining stronghold in preventing an epidemic of cardiovascular disease and other very important benefits; that

global efforts to reduce environmental contamination that are transported into the Arctic food web continue; and that monitoring of climate related changes continue in order to support adaptation on many levels such as for hunting and fishing.

There are now several wonderful examples of interventions that are working well for Nunavik's population - from global scale work to reduce the production of highly deleterious contaminants that travel over long ranges, to specialized local initiatives to prevent zoonotic infection, and reduce, even eliminate *trans*-fatty acids from village food shops. Each of these initiatives was informed by science, which underscores the necessity to continue to understand the complex relationships between health determinants and health status for these unique remote groups. And while this research process may seem at times arduous, anyone who has travelled in the North knows that word travels fast, and therein may lie a certain economy to investing in interventions on the several remaining fronts that lie on the path away from inequity.

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Chapter 4. Freshwater resources in a changing environment

Lead authors

Warwick F. Vincent^{1,2}, Daniel Martin³, Reinhart Pienitz^{1,4}, Isabelle Laurion^{1,5}

¹Centre d'études nordiques (CEN), Université Laval, Québec, QC; ²Département de biologie, Université Laval, Québec, QC; ³Nasivvik and Unité de recherche en santé publique, Centre de recherche du CHUL-CHUQ, Québec, QC; ⁴Département de géographie, Université Laval, Québec, QC; ⁵Institut de la recherche scientifique – Centre Eau Terre Environnement (INRS-ETE), Québec, QC

Contributing authors

D.C.G. Muir, K. L. Young, Y. Bégin

Abstract

Northern lakes, rivers and wetlands provide many ecosystem services including drinking water supplies for northern residents, habitats for Arctic charr and other aquatic wildlife, and water for industries such as hydroelectric power generation, recreational fishing, eco-tourism and mining. Nunavik and Nunatsiavut have a rich natural heritage of freshwater ecosystems ranging from shallow permafrost thaw ponds, which are expanding in size and abundance at some sites, to wild rivers and deep ancient lakes of outstanding scenic, cultural and ecological value. The impacts of climate change and economic development on the water quality and supply for these vital aquatic resources have been viewed with increasing concern by Inuit communities. The creation of northern parks provides an effective way to protect many of these environments in the face of climate change and rapid development of the North, as well as a way to stimulate eco-tourism and associated economic activity. A variety of drinking water problems, including those associated with the storage and use of untreated water, have been identified throughout Nunavik, and a set of recommendations are outlined to reduce these problems. The effects of local pollution, as well as the continuing rise in certain long range contaminants such as mercury require continuing surveillance. Two of the largest underground power stations in the world are located in northern Québec and Labrador, and there is further potential for hydroelectric development. Future projects will require close and timely consultation with all stakeholders, including analysis of the tradeoffs in ecosystem values. Future and current installations require ongoing research to project future water supply in the rapidly changing northern climate, and paleoclimate analyses will continue to help assess the magnitude of natural fluctuations in the past.

4.1 Introduction

Lakes, rivers and wetlands are major ecosystem features of the circumpolar Arctic. These vital resources provide many essential services including drinking water supplies for northern residents, habitats for Arctic charr (see Chapter 7) and other aquatic wildlife, transport routes by boat in summer and surface vehicles in winter (see Chapter 5, see also Prowse et al. 2011), and water for industries including hydroelectricity, recreational fishing, eco-tourism and mining. Subarctic freshwater ecosystems are intrinsically important as rich sites of biodiversity, and they also provide records of change in the past (e.g., Saulnier-Talbot et al. 2003, Pienitz et al. 2004, Saulnier-Talbot and Pienitz 2009) and present that will help guide environmental monitoring and management. These diverse aquatic resources are vulnerable to ongoing climate change, and changes in water supply and quality are increasingly observed with concern by Inuit and other indigenous peoples (Moquin 2005). This and other climate related issues are of special concern in the eastern Canadian Subarctic where climate warming is now proceeding at unprecedented rates after centuries or longer of prolonged environmental stability (Bhiry et al. 2011).

This chapter first describes the range of aquatic resources of Nunavik and Nunatsiavut, and their potential ecological responses to climate change. We then briefly summarize the work to date on contaminants in snowpack and freshwaters of this region, and examine specific issues concerning protected aquatic environments in parks, drinking water supplies, mining needs, and hydroelectric resources. We end this chapter with general conclusions and recommendations for the future.

4.2 Climate impacts on northern freshwater ecosystems

The effect of ongoing climate change on lakes and reservoirs has been identified as one of the most serious issues facing human society throughout the world, and northern

lake and river ecosystems may be especially prone to alteration given the greater magnitude of climate change at higher latitudes (ACIA 2005). The projected changes in regional water balance will alter the capacity of lakes and rivers to provide ecosystem goods and services such as inland fisheries and adequate supplies of safe drinking water, and result in modified discharge and erosion in rivers. The ongoing warming trend will affect the physical, chemical and biological properties of freshwater ecosystems (Figure 1), with implications for water quality; for example, through the likely increased abundance of noxious cyanobacteria, and for wildlife habitats; for example, through changes in runoff, productivity, oxygen and thermal regimes.

At the most basic physiological level, changes in water temperature and ice cover will affect the metabolic rates and life cycle of aquatic organisms, and for some species

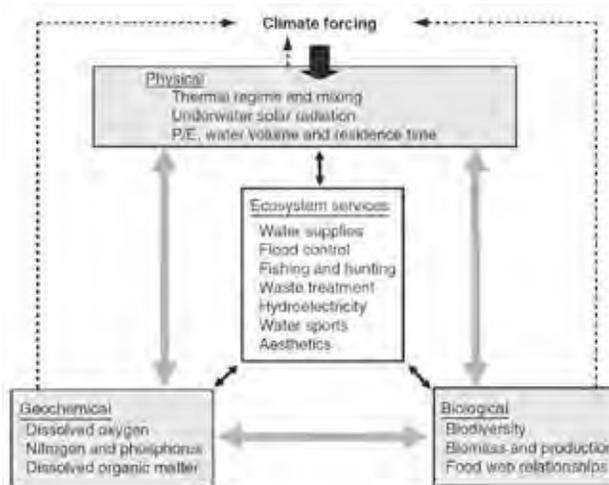


Figure 1. Changes in climate affect the physical environment of lake and river ecosystems and thereby alter their chemical and biological properties. These changes modify the capacity of freshwaters to provide ecosystem services. P/E refers to the Precipitation to Evaporation ratio. Dotted lines indicate positive feedback effects, e.g., via decreased ice cover or the release of greenhouse gases from lakes and rivers into the atmosphere. From Vincent 2009.

there may be shifts beyond their critical threshold for survival. Warming may also be accompanied by increased stratification, algal biomass production, and loss of oxygen, to the detriment of many aquatic communities. On the other hand, warmer temperatures will allow some newly invading species to survive and complete their life cycles, although this may come at the expense of any original species that are driven to extinction through predation or competition. In the North, this may result in an increase of biodiversity at a local scale while many native species disappear, causing shifts in biotic interactions, a decline in global biodiversity, and serious impairment of traditional hunting and fishing practices (Vincent et al. 2011). At the broader ecosystem level, climate change will have pervasive effects on the physical structure and connectivity of lake and river ecosystems, and on their food webs, biogeochemical characteristics and overall metabolic properties, including greenhouse gas emissions. This section examines different types of aquatic ecosystems in Nunavik-Nunatsiavut and their potential sensitivity to climate change, with emphasis on thaw lakes because of their significance in greenhouse gas emissions as well as abundant wildlife habitats.

4.2.1 Thaw lakes

Permafrost thaw lakes (thermokarst lakes, see Figure 2) are a key component of many northern landscapes, developing in depressions that result from the thawing of permafrost (Pienitz et al. 2008). They have attracted much attention with the realization that they are not only habitats for aquatic flora and fauna, but also for microbiological life. They act as microbial reaction sites for greenhouse gas production (Walter et al. 2006, Laurion et al. 2010) and have the potential to exert a strongly positive feedback on global climate in the future, as they appear to have done in the past (Walter et al. 2007).

In many parts of the Arctic, the permafrost has begun to warm and the active layer has deepened (see Chapter 6 for description of their geophysical dynamics). However, the extent of these changes is highly variable regionally, with



Figure 2. Examples of thaw lakes in Nunavik. The striking differences in colour are the result of underwater light absorption and scattering by different combinations of coloured dissolved organic matter (CDOM) and soil particles derived from the surrounding landscape. These colour differences can be quantified by radiometric sensors, which may provide a way to estimate ecosystem properties, including greenhouse gas emissions, by satellite remote sensing (details in Watanabe et al. 2011).

a deepening of the active layer by several metres at some sites and yet no detectable change at others. In parts of Nunavik, thermokarst lakes and wetlands are expanding as a result of permafrost thawing and erosion (e.g., Payette et al. 2006, Vincent et al. 2011), thereby producing more habitats for aquatic birds and other animals as well as greater areas of intense greenhouse gas production. Elsewhere in the circumpolar Arctic, however, the degradation of permafrost is causing a rapid draining of the landscape and loss of aquatic and semi-aquatic ecosystems (e.g., in Siberia, Smith et al. 2005; on Bylot Island, Arctic Canada, Laurion et al. unpublished). Such changes may result in a more homogeneous northern landscape, with reduced habitat and species diversity.

ArcticNet studies on thaw lakes in Nunavik have shown that, despite their shallow depths (typically 1-4 m) and exposure to the wind, they are poorly mixed and have striking gradients in their physical, chemical and biological

properties with depth throughout most of the year (Breton et al. 2009, Laurion et al. 2010, see Figure 3). In summer, and probably through much of winter, their bottom waters are depleted in oxygen as a result of the lack of mixing, and these anoxic (devoid of oxygen) conditions favour microbial processes that convert carbon coming in from tundra soils to the powerful greenhouse gas methane, which is ultimately released to the atmosphere by ebullition and other processes (Walter et al. 2006). CO₂ dynamics are influenced by the level of photosynthetic

activity, and observations show that thaw lakes colonized by microbial mats and aquatic plants can act as CO₂ sinks, at least during summer, however they all represent methane sources (Laurion et al. 2010).

Globally significant quantities of organic matter are stored in frozen northern soils (Tarnocai et al. 2009). Some of this tundra carbon is released into lakes, rivers and coastal seas as a result of thawing and erosion, and may be converted to CO₂ and methane by aquatic microbial processes

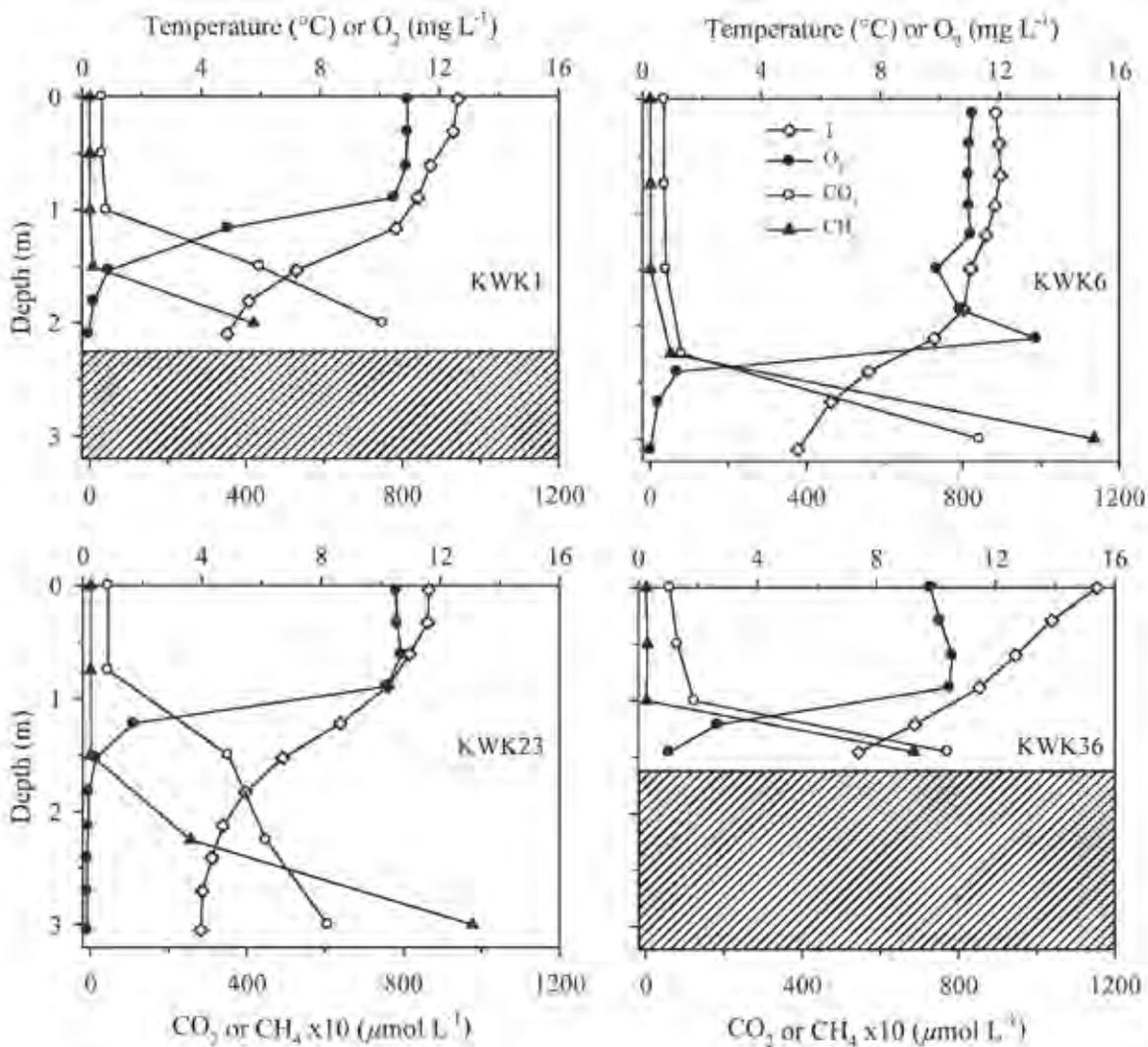


Figure 3. Profiles for thaw lakes near Kuujuarapik showing their strong stratification and high concentrations of greenhouse gases. From Laurion et al. 2010.

(Schuur et al. 2008). There are large temporal variations in thaw lake gas emissions, indicating the need for a better understanding of diurnal and seasonal changes in carbon fluxes, as well as the influence of physical processes on air-water exchanges. One of the main questions is the relative importance of old organic carbon stocks released from melting ice in peat as carbon sources for aquatic microbial processes, as compared to the newly fixed carbon in plants and algae, which is also likely to be increasing with climate warming. There is also considerable spatial variability in greenhouse gas emissions, with large differences between even nearby water bodies (Laurion et al. 2010). Promising satellite remote sensing methods have been developed in Nunavik that may help scale up local estimates to the landscape level (Watanabe et al. 2011). Understanding these biogeochemical processes and their spatial and temporal variability will be essential steps towards assessing the magnitude of positive feedback from these thaw lakes on the global carbon cycle and climate system.

4.2.2 Other shallow water lakes

The Subarctic region also contains many shallow lakes and ponds in rock basins that have been carved by glacial activity. Studies on these water bodies have shown that they are often rich in zooplankton (Swadling et al. 2001, Rautio and Vincent 2006, Rautio et al. 2011), with benthic algae and plants that favour other aquatic life including insects, ducks, loons and geese. Changes in the precipitation-evaporation balance associated with climate change could result in higher evaporation leading to dryness and the loss of some of these habitats, as has been observed in Nunavut (Smol and Douglas 2007, Vincent et al. 2009).

4.2.3 Deep lakes

Subarctic Québec and Labrador contain many large (>100 km²), deep lakes. The ecology of these freshwater ecosystems has been little explored to date, however they are important sites for northern outfitter operations and recreational fishing. Of particular interest are the deep

lakes derived from meteoritic impact events. Two such lakes have attracted particular attention in Nunavik: Pinguait Crater Lake, and Lac à l'Eau-Claire (Clearwater Lake – Box 1). The former contains an isolated population of Arctic charr (*Salvelinus alpinus*) that has attracted scientific interest for its survival strategies and low contaminant levels (Delisle and Roy 1989, Gantner et al. 2012) in one of the world's most dilute and transparent freshwater ecosystems, while the latter has been the site of detailed studies on periphyton (Maltais and Vincent 1997), phytoplankton production (Milot-Roy and Vincent 1994) and UV radiation effects (Laurion et al. 1997, Laurion and Vincent 1998). As in deep clear lakes elsewhere, the plankton is dominated by extremely small species, with most of the phytoplankton biomass in the size fraction less than 2 µm. The cold stratification regime of these deep lakes allows frequent mixing, however this could change in the future with increased warming and a shorter duration of ice cover, which in turn may influence plankton growth and fish habitats.

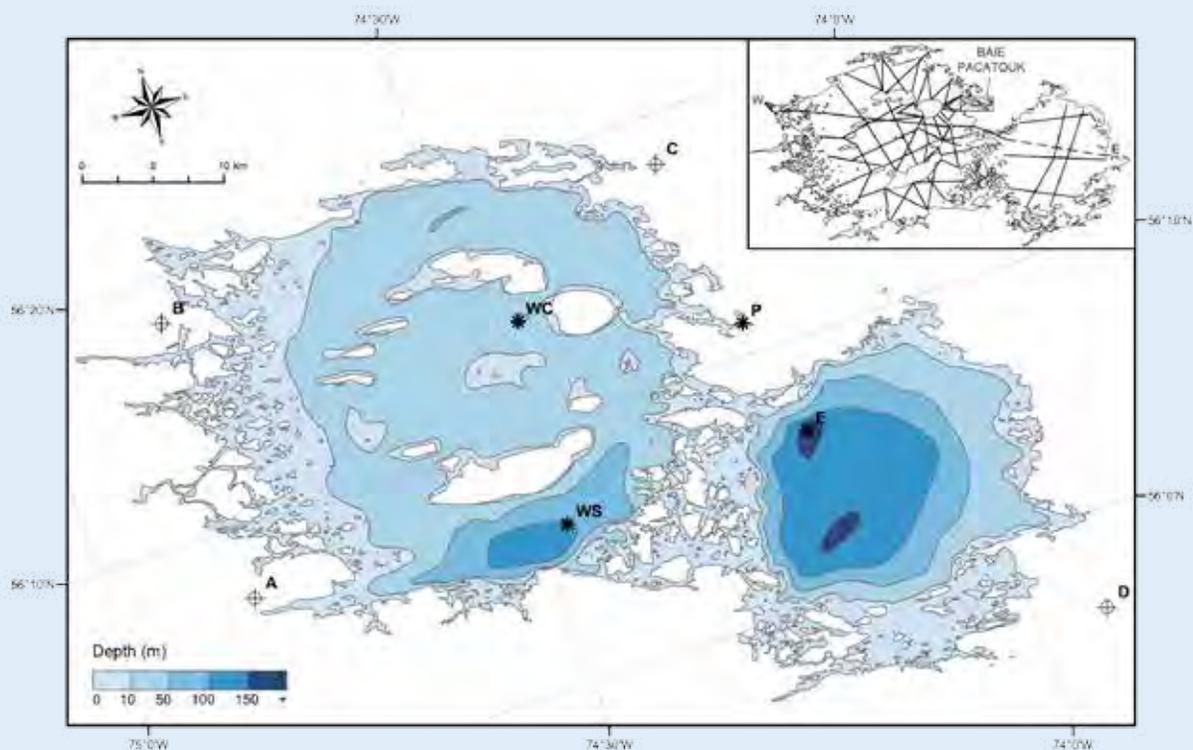
4.2.4 Rivers, streams and wetlands

Flowing water ecosystems are a critically important part of the freshwater resources of the Subarctic (Woo and Young 2010 and references therein). Apart from providing transport routes for northern communities, they are habitats for key wildlife species (notably Arctic charr), they discharge water, nutrients and organic carbon into the sea, thereby supporting the coastal marine ecosystem, and they are resources for drinking water supplies, hydroelectricity, mining and other industrial needs.

Accelerated thawing of permafrost may release increasing amounts of organic matter, gases, inorganic solutes and microbiota into rivers and the coastal ocean. Organic-rich particles that are transferred by erosion from the permafrost into rivers provide substrates for microbial communities, specifically *Bacteria* and *Archaea* (Garneau et al. 2008). Climate effects on these organisms combined with increased light limitation of phytoplankton may drive Arctic rivers and estuaries towards even greater heterotrophy

BOX 1. Lac à l'Eau-Claire (Clearwater Lake), Nunavik.

Clearwater Lake and its vast watershed lie within the proposed Tursujuq National Park, and will thereby benefit from long term environmental protection. The unique shape of the lake is the result of a double meteoritic impact crater that was formed 285 to 300 million years before the present (Plante 1990). The lake has a total estimated area of 1239 km², a maximum depth of 136 m (western basin) and 178 m (eastern basin), an average depth of 37 m and an estimated hydraulic residence time (the time an average drop of water resides in the lake) of 14 years (Arsenault 1993, Milot-Roy and Vincent 1993). The cold, transparent waters of the lake are oligotrophic (low nutrients and algal concentrations), and the lake supports a renowned traditional and recreational fishery for lake and brook trout.



This bathymetric map was derived from a total of 335 km of profiling transects across the lake (top right insert) using a Furuno BG-11 MARK 3 echo-sounder at a boat speed of 10 km h⁻¹, combined with additional transect data from Plante (1986). The asterisks mark the water column sampling stations as in Milot-Roy and Vincent (1993): WC, western basin central; WS, western basin south; P: Baie Pacatouk; E: eastern basin. A, B, C, and D are georeference sites; details in Arsenault (1993).

and net CO₂ efflux in the future (Vallières et al. 2008). In the boreal forest region, streams represent only 1% of the total freshwater area, but are disproportionately important as CO₂ emitters (25% of total aquatic carbon emissions), with gas efflux rates rising with increasing Dissolved Organic Carbon (DOC) concentrations (Teodoru et al. 2009). Further to the south, in the USA, changes in precipitation have recently been identified as a controlling factor for river CO₂ emissions (Butman and Raymond 2011), and this will require further attention in the North.

High latitude wetlands are important sites for plant biodiversity and wildlife, and are vulnerable to changes in precipitation, evaporation and lateral flow (Wolf et al. 2011). In the Arctic, late-lying snow banks are an important source of water for wetlands (Woo and Young 2003), which are therefore sensitive to the ongoing trend of decreasing duration of snow cover (Vincent et al. 2011). Wetlands are also biogeochemically active “hotspots” for carbon and nitrogen metabolism, and climate change will affect their exchanges with the atmosphere. Boreal wetlands are significant greenhouse gas (GHG) emitters, with evidence that the smaller and shallower pools (ombrotrophic raised bogs) have larger CO₂ and CH₄ emissions (McEnroe et al. 2009), and that winter contributes significantly to the annual CH₄ fluxes from this type of system (Pelletier et al. 2007). In Subarctic Sweden, recent changes in permafrost and vegetation have been shown to be responsible for 22-66% increases in CH₄ emissions between 1970 and 2000 (Christensen et al. 2004). A larger study covering wetland sites in Greenland, Iceland, Scandinavia and Siberia showed that temperature and the organic carbon substrates for the microbiota explained almost 100% of the variation in mean annual CH₄ emission (Christensen et al. 2003).

4.3 Protected environments – Parks

Conservation is emerging as a major priority for the North in the face of climate change, with the recognition that because high latitude ecosystems have less biodiversity,

and therefore less functional redundancy, they are inherently more sensitive to perturbation (Post et al. 2009). The new parks created in Nunavik and Nunatsiavut with their protected areas are therefore timely and extremely valuable investments for the future sustainable development and preservation of the northern landscapes. Lakes, rivers and wetlands are key elements of the natural heritage of these two territories, and the parks contain some excellent examples for protection. In Nunatsiavut, the largest park is Torngat Mountains National Park, which includes many pristine fjords, lakes and rivers, for example in the Komaktorvik-Chasm lakes area. In Northern Québec (Nunavik), the first of a series of parks, the Parc national des Pingualuit, has recently been created. Under the terms of the Sanarrutik Agreement, and noting that “Nunavik has an under-exploited tourism potential”, the Government of Québec committed to provide resources to develop a series of northern parks, specifically Monts-Torngat-et-de-la-Rivière-Koroc, Lac-Guillaume-Delisle-Lac-à-l’Eau-Claire (now known as Tursujuq – see Box 1), Mont Puvurnituk and Cap Wolstenholme parks. The government also committed 9.6M\$ to the creation, capital expenses and initial 5-year operational costs of Parc national des Pingualuit.

Research and monitoring are central activities conducted by Parks Canada throughout the country, with regular status reports provided to the public. Such an approach should also be integral to the management of these northern parks. Some of the lakes contain remarkable resources of great public and scientific interest. For example, Pingualuit Crater Lake (Figure 4) contains a remarkable paleoclimate record in its sediments potentially going back 1.4 million years, more than eight glacial cycles. Lac à l’Eau-Claire (Box 1) is another intriguing ancient crater lake of great geological as well as ecological interest, and nearby, Lacs des Loups Marins contain a landlocked freshwater seal population with a total size estimated at 500 individuals (Ministère du Développement Durable, de l’Environnement et des Parcs 2008).



Figure 4. *Pingualuit Crater Lake, Nunavik. Photo by Denis Sarrazin, CEN/ArcticNet.*

4.4 Chemical pollution

Given the remote, pristine nature of the Subarctic and the lack of large cities and heavy industry, chemical pollution of waters from local sources is generally not a major issue in Nunavik and Nunatsiavut at present. However, abandoned mines, current mining wastes and waters in the vicinity of municipal waste disposal sites may pose environmental concerns at some sites. Furthermore, the impacts of chemical pollution are likely to rise with industrial development, increased shipping, and the rapid expansion of populations in northern townships in the past and present. Analysis of sediments from Lac Dauriat by Laperrière et al. (2009) at Schefferville showed that there was a major deterioration of water quality associated with the discharge of municipal and mining wastes during the mining boom development of this town. The

sediments received maximum metal pollution during the 1930-1970 period, however even 20 years after the closure of the mine and the population exodus, the lake has still not returned to its original ecological state.

Long-range pollution continues to be of great concern throughout the North, including within this IRIS region. Mercury has been detected in the snowpack (Steffen et al. 2005, 2006) and perfluorocontaminants have been detected even in the most pristine lakes of the region, albeit in extremely low concentrations (Gantner et al. 2012). Analysis of mercury in lake sediments, including from lakes in Nunavik and Nunatsiavut (examples in Figure 5) show that the input of this toxic metal is continuing to increase (Muir et al. 2009). Further analysis has shown that these increased mercury fluxes were primarily due to long range transport and deposition of anthropogenic Hg rather

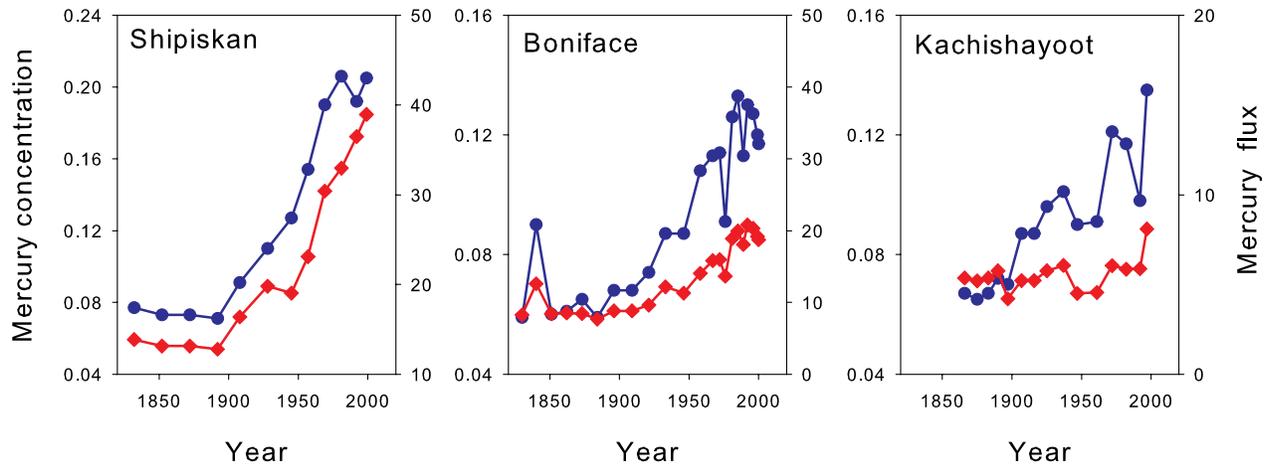


Figure 5. Trends in mercury concentrations in lake sediments ($\mu\text{g Hg per g dry weight of sediment}$; blue circles; left-hand Y-axes) and mercury deposition fluxes ($\mu\text{g Hg per m}^2 \text{ per y}$; red diamonds; right-hand Y-axes) in Shipiskan Lake, Labrador (54.5°N , 62.2°W); Lake B2 at Boniface, northern Québec (57.5°N , 76.1°W); and Lake Kachishayoot (55.2°N , 77.4°W), northern Québec. Derived from Muir et al. 2009.

than remobilization of natural background sources. This and other contaminants will require ongoing monitoring, particularly in local water supplies and fish that are routinely harvested for food.

4.5 Drinking water supplies

The following excerpt is from the report prepared by ArcticNet and Nasivvik that was presented to Nunavik mayors (Martin et al. 2005), and Martin et al. (2009).

Most Nunavik communities are now equipped with a water plant, but houses do not benefit from aqueduct systems because of permafrost. As throughout many parts of the North, water is delivered daily by truck to houses where it is kept in large tanks (Figure 6). A large portion of Nunavimmiut use untreated water. This water is drawn from lakes, creeks and rivers during the summer months or is obtained by melting ice or snow in winter and spring months. In Nunavik, one person out of five is under five years of age, representing an at-risk group for gastroenteritis due to that group's fragile immune system. During the

Qanuippitaa? Health Survey (Fall 2004), onboard the CCGS *Amundsen* icebreaker, ArcticNet researchers visited 232 houses and 19 external sites (creeks, rivers and lakes used for raw water supply), in 14 Nunavik communities. Water samples were analyzed in the microbiological



Figure 6. Delivery of drinking water by truck at Kangiqsujaq, Nunavik (Photo: R. Pienitz, CEN/ArcticNet).

laboratory onboard the ship, except for DNA tests where samples were obtained and treated on the ship, but analysed at the Infectious Diseases Research Center (CRI), in Quebec City.

The main goal of the study was to evaluate water consumption habits that could place Nunavik residents at an increased risk of disease, in a climate change context. The first objective was to evaluate if water coming from household tanks, raw water sources and raw water stored in individual plastic containers had low microbiological contamination and was safe to drink. Secondly, the study aimed to compare the water quality of household tanks in a community with municipal regulation for tank cleaning (Puvirnitug) to other Nunavik communities without regulations regarding tank cleaning, with the objective of making recommendations for water tank cleaning (frequency of cleaning and cleaning procedures). This project also had an educational component: four Inuit trainees from the Nunavik, Nunavut, Inuvialuit and Labrador region were involved in water sampling and analytical methods for testing drinking water quality.

Total coliforms (TC), *Escherichia coli* (EC) and *enterococci* (EI) were selected as indicators of water quality and were assayed using Colilert™ and Enterolert™ techniques. These techniques are similar to those used in Nunavik communities to check water quality at the water plant and water tank outlet. The water was considered unsafe for human consumption if contamination was equal to or exceeded the following thresholds:

- * 10 total coliforms/100 ml
- * 1 *Escherichia coli* /100 ml
- * 1 *enterococcus* /100 ml

The presence and levels of *Escherichia coli* and *enterococci* bacteria, obtained by DNA and membrane filtration methods were compared to results obtained by Colilert™ and Enterolert™ methods. Additionally, *Cryptosporidium parvum/hominis* and *Giardia duodenalis* presence/absence tests were carried out by DNA methods.

In the samples, 71% of the consumed water came from household tanks and 29% was raw water (water directly from creeks, rivers, lakes). In this study, it was determined that water coming from household tanks (disinfected or partly disinfected) was of good microbiological quality and safe to drink. Raw water was often stored in plastic containers (jugs), and most of the time, this water was not refrigerated in the house. Plastic containers were more contaminated (TC, EC, EI) than household tanks, and contrary to expectation, the percentage of contaminated household tanks was lower among households having cleaned their tank more than 6 months ago. It appears that frequent but inadequate cleaning may contribute to the re-circulation of bacteria in the tank, indicating the need to improve cleaning protocols. The procedures established a few years ago in Puvirnitug seem to be adequate but further investigation of cleaning frequency is necessary.

The *Qanuippitaa?* Health Survey raised a lot of interest among Inuit trainees participating in sampling and testing operations. Upon completion of the analyses, abnormal results were communicated to community health centres. In April 2005, community mayors received a report on their community water results (Martin et al. 2005) and a summary for all Nunavik communities.

Results obtained from this survey can be used to make general recommendations to Nunavik residents and to initiate projects pertinent to drinking water quality. If water quality was good in household tanks during the study, it does not mean that it is safe to drink all the time. Residents should follow the boiling advisories when announced. Raw water from rivers, lakes and creeks could be at risk and should always be boiled before drinking (1 minute). As raw water stored in plastic containers is frequently contaminated, containers should be cleaned on a regular basis and water should always be boiled before drinking (1 minute).

In February 2005, following the *Qanuippitaa?* Health Survey, a workshop gathering drinking water managers

and people involved in public health (scientists and medical practitioners), was held in Kuujuaq. The workshop began with presentations of microbiological results obtained during the campaign. During the second part of the workshop, participants were invited to put forward priorities and to share ideas about projects related to drinking water quality. Priorities were: 1) Encouraging water consumption, instead of pop and juice, especially among children; 2) implementation of small disinfection systems (UV) at specific locations to avoid parasite contamination; 3) training for tank cleaning and evaluation of water quality (microbiological) before/after cleaning, in different situations (type of tanks, type of cleaning, frequency); 4) information on cleaning plastic containers (used to store raw water); 5) projects on gastroenteritis surveillance (public health) and; 6) projects on environmental surveillance.

There are cultural factors that must also be considered in the implementation of improved protocols for water security. In many communities there is a long tradition of using specific springs, lakes and rivers for drinking water purposes, and the idea of shifting to hygienic, treated supplies may be treated with suspicion. For example, a survey of the aboriginal community of Rigolet showed that only 4% of the population considered water from the land to be unsafe, while 37% considered tap water to be unsafe (Goldhar 2011).

4.6 Hydroelectricity

Hydroelectricity is a major ecosystem service (Figure 1) that harnesses water resources in northern Québec and Labrador. Two of the largest underground power stations in the world are located in this region: the Robert-Bourassa generating station at 53.8°N, 77.4°W (5616 megawatts (MW)), and the adjacent La Grande-2-A that can generate 2106 MW (collectively these are referred to as the La Grande complex) and the Churchill Falls station at 53.6°N, 64.3°W (5428 MW installed, expandable to about 6300 MW). These are at somewhat lower latitudes

than the southern limit of Nunavik (55°N) and Nunatsiavut (about 54°N), but there has been considerable interest in extending this exploitation of hydro-resources northwards, including via small-scale schemes (Box 2).

In the 1970s, Hydro-Québec initiated planning of a project located along the Great Whale River, east of the village of Whapmagoostui-Kuujuaapik, with an installed capacity of 3200 MW and requiring 575 km of access roads to be constructed. This project was subject to considerable debate concerning its economic viability and environmental impacts, and was shelved in 1982, reactivated in 1989, and re-suspended by the Government of Québec in 1994. However, there is growing need for energy as well as sustainable industries in the North, and the Nunavik Environment Commission (2009) notes that *“It would be imprudent to assume that the coastal waters, rivers, and lakes of Nunavik will remain unharnessed as sources of energy and interest”*.

In 2002, the Sanarrutik Agreement was signed between the Makivik Corporation, the Kativik Regional Government and the Government of Québec (details available online at: [http://www.saa.gouv.qc.ca/relations_autochtones/ententes/inuits/sanarrutik-consolidee_en.pdf](http://www.saa.gouv.qc.ca/rerelations_autochtones/ententes/inuits/sanarrutik-consolidee_en.pdf)). This agreement estimated the total hydro-potential of Nunavik as within the range 6300 to 7200 MW, and identified several northern rivers with high hydroelectric power potential (Nastapoka; Whale, George, Aux Mélézes Caniapiscau, Leaf) and others with low power potential (Kovik, Decoumte, Buet). The agreement explicitly states that *“there will be full and timely disclosure by Québec to Makivik and the concerned Nunavik Inuit communities with respect to all proposed new hydroelectric projects”* and that *“Makivik and communities that may be affected will be involved and consulted in the technical description of potential projects in order to reduce environmental and social impacts on the communities”*. As in each of the water resource issues discussed in this chapter, this consultation process is critically important given that hydro-development has a variety of potential ecological and social impacts, including a trade-off in wilderness

Box 2. The Innavik hydro project.**An example of sustainable socio-economic development.**

This information is derived from the website www.innavik.com/

Innavik started in 2007 as a project to construct an 8 MW hydroelectricity generating plant (near the village of Inukjuaq in Nunavik). Despite its small size, the plant could substantially reduce diesel fuel consumption and dependency while lowering greenhouse gas emissions of the community by an expected average of 15 thousand tonnes of CO₂ per year. A priority of the Innavik project is to ensure environmental protection of the Inukjuak River and surroundings. The supervision by local Pituvik Landholding Corporation (PLC) ensures that community and regional interests are at the very centre at all stages of the project. One of the main objectives is to provide reliable cost-effective power, in tune with long term sustainable economic development of the community. The plant is majority-owned by PLC and will therefore economically aid all beneficiaries and Inukjuakmiut.



values. For example, development of the Nastapoka River as a hydroelectric resource could have implications for the quality of habitat of the freshwater seals in its headwater Seal Lakes (Lacs des Loups Marins), and protecting this unique biodiversity feature would be an issue of international concern. Such features are also of considerable local concern. For example, as a result of the consultation process with northern communities for the creation of Tursujuq National Park, the Kativik Environmental Advisory Committee (KEAC) recommended in its position paper that “Given the exceptional scenery of the Nastapoka River and the wildlife resources of this

river and its drainage basin, specifically the fresh-water seal population of Upper Seal Lake which is unique in North America, as well as the eastern Hudson Bay stock of beluga and the landlocked salmon population, which are considered vulnerable, the KEAC recommends that the Nastapoka River and its entire drainage basin be included in the future park” (Kativik Environmental Advisory Committee 2008). These considerations may have been viewed as secondary to mineral resource claims and hydroelectricity resources as outlined in the Sanarrutik Agreement, since the provisional park management plan excluded the Seal Lakes and Nastapoka River from the



proposed park (Carte 4 La limite proposée; in: Ministère du Développement Durable, de l'Environnement et des Parcs 2008). The limits of the park are currently under review to include these unique features (Service des parcs MDDEP, communication, 2 May 2012). Additional considerations concerning land use management are given in Chapter 1 of this volume.

Hydroelectricity developments will also need to carefully assess the implications of climate change for shifts in water supply, specifically the current and future magnitude of precipitation gains (likely to increase with climate change, see Chapter 2), the extent of evaporation losses (likely to increase with warmer water temperatures, and longer ice free conditions), and changes in water plant species and density that may influence storage volume and operating protocols. Future shifts in lake and river ice conditions may also affect hydroelectric operations (Prowse et al. 2011). Additionally, close attention will need to be given to the magnitude of natural variability in hydroclimate. Assessments based on tree-ring analysis

in northern Québec suggest that this variability in the past has yielded fluctuations of the order of 25% (Lemay and Bégin 2008). The research project ARCHIVES (*Analyse Rétrospective des Conditions Hydro-climatiques à l'aide des Indicateurs et de leur Variabilité à l'Échelle Séculaire*) is currently underway in partnership with ArcticNet to analyse sediment and tree ring records, the latter from 120 chronologies of 200 years at 20 to 30 trees per site. The past variations in hydro-regional climate are being reconstructed from these multiple indicators by the extraction of common signals, for example by neural network analysis (details at: <http://archives.ete.inrs.ca>).

4.7 Conclusions and recommendations

The most successful strategies for long-term sustainable management of aquatic ecosystems are those combining global perspectives and scientific knowledge with a local understanding of cultural, environmental and economic factors (Kumagai and Vincent 2003). Although this inte-

grative 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 human needs (Wrona et al. 2007, Vincent and Laybourn-Parry 2008). As described in this chapter, this combination of approaches is especially pertinent in Nunavik, where the success of water resource development hinges not only on the best scientific insight and advice, but also on full consultation with northern communities, and on respect for, understanding and inclusion of cultural perspectives. This central theme of global science plus local community integration is at the heart of the following key recommendations:

- * Nunavik and Nunatsiavut have a rich natural heritage of lakes, rivers and wetlands that require ongoing stewardship and protection. Northern communities and authorities should continue to develop their leadership

and managerial roles in monitoring and protecting these vulnerable ecosystems.

- * Permafrost thaw lakes (thermokarst lakes) are a major category of northern freshwater ecosystems, and they appear to be increasing in abundance and total surface area in parts of the circumpolar North, including Nunavik, as the permafrost continues to warm and degrade. Given their very active production of greenhouse gases as well as their importance for aquatic plants and wildlife, they will require close ongoing monitoring and research.
- * The creation and management of parks is an effective way to achieve the best possible protection in the face of climate change and ongoing development of the North, as well as a way to stimulate eco-tourism and the associated economic activity. Research and monitoring should be essential parts of the strategic management plan for these northern parks.



- * The avoidance and mitigation of chemical pollution of northern aquatic ecosystems requires ongoing vigilance. The continuing rise in some long range contaminants such as mercury requires surveillance, in collaboration with northern communities and global partners.
- * A variety of drinking water problems have been identified throughout Nunavik, and a set of recommendations has been communicated to reduce these problems. Raw water from rivers, lakes and creeks could be at risk and should always be boiled before drinking. Raw water stored in plastic containers is frequently contaminated, hence containers should be cleaned on a regular basis and water should always be boiled before drinking.
- * The North continues to offer considerable potential for hydroelectric development at both small and large scales. Such projects will require close and timely consultation with all stakeholders, especially local communities, to assess the environmental and social impacts, including effects on wilderness values. Potential and currently operating hydroelectricity complexes will also require ongoing research to project future water supply. These needs include downscaled, local projections of future precipitation and ice cover, evaluation of evaporation scenarios in the changing northern climate, and analyses of interannual and other natural fluctuations. Paleoclimate research approaches will continue to play a valuable role in these assessments.

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Chapter 5. Impacts of climate change on food security in Nunavik and Nunatsiavut

Lead authors

Christopher Furgal¹, Laurie Chan², Martin Tremblay³, V Rajdev¹, Michael Barrett⁴, Tom Sheldon⁵

¹Indigenous Environmental Studies Program, Trent University, Peterborough, ON; ²University of Ottawa, Ottawa, ON; ³Aboriginal Affairs and Northern Development Canada, Ottawa, ON; ⁴Renewable Resources Department, Kativik Regional Government, Kuujuaq, Nunavik; ⁵Environment Division, Nunatsiavut Government, Nain, Nunatsiavut

Abstract

Food security status in all Inuit regions, including Nunavik and Nunatsiavut, is significantly lower than the national average and individuals are reporting challenges in being able to access enough food as well as their preferred foods. As the Inuit diet is comprised of foods from both the store and local environment, food security is influenced by environmental, political, social and economic factors. The specific impacts of climate change and variability on market food transport, storage and distribution or country/wild food availability, accessibility and quality are difficult to predict. However, the relationship between weather variability and other changes in environmental conditions and their influence on country/wild food access in these two regions has been studied under several ArcticNet projects in recent years. Despite the recognized importance of country/wild foods to health and well-being, a decrease in their consumption is being observed over time. Yet, many residents still maintain a strong connection to the land through participation in hunting, fishing and collecting activities. While many residents are reporting that changes in local weather conditions and climatic norms are influencing the distribution or accessibility of key species, experienced hunters have developed certain coping mechanisms that have provided some protection, thus far, from the impacts of these changes on their ability to locate and acquire adequate country food resources. However, the limits of these adaptive strategies are not well understood. Local food support programs may be critical in assisting communities with adaptation to the many pressures on their changing food systems over time.



5.1 Introduction to Food Systems in Nunavik and Nunatsiavut

In many northern communities the diet of residents is made up of a combination of imported food items from outside of the region that are sold in local stores, and local foods harvested from the environment. Items from outside of Nunavik and Nunatsiavut are transported by air, boat, or a combination of these mechanisms into the communities. Foods from the land, sea and freshwater of the region include a diversity of species specific to the community or region.

The current consumption of market and country foods (as they are commonly referred to in Nunavik) or wild foods (as they are commonly referred to in Nunatsiavut) (foods from the local environment) varies between and within regions, communities and households. For example,



in Nunavik, the proportion of the total diet consisting of country foods is higher among Inuit residents, older aged residents, and those residents living further from a regional centre, such as Kuujjuaq (Kuhnlein et al. 2000, Blanchet et al. 2000, Blanchet and Rochette 2008, AMAP 2009). According to surveys done in Nunatsiavut communities, residents consume the largest diversity of wild food compared to other regions (Kuhnlein et al. 2000). The consumption of recommended levels of such market items as fruits and vegetables is considerably lower among northern residents than the national average in Canada and is lowest among Nunavut residents within the Inuit regions (Statistics Canada 2005). According to survey work done in Kuujjuaq, Nunavik (Bernier et al. 2003) and Nain, Nunatsiavut (Furgal et al. 2001) access (physical and economic), preference and ease of preparation are key determinants influencing peoples' food choices of both country foods and store foods in these two regions.

5.2 Harvesting still an important part of life in Nunavik and Nunatsiavut

Hunting, fishing and gathering of wild food resources and the subsequent sharing of these items with others in the community are social activities that bring together individuals, families and generations, and are often the focus of celebrations and festivities (Searles 2002). They form and maintain an important social fabric among individuals which supports community health and well-being. For example, not only is muktuk nutritionally and psychologically beneficial, but its widespread sharing among relatives and between communities creates and sustains the bonds that remain the basis of Inuit social, cultural and economic relationships today (Freeman et al. 1996). Further, such activities are opportunities for the transfer of knowledge between generations and the maintenance of language, as they necessitate and encourage the use of traditional Inuit knowledge and components of local language, and therefore support the exchange of information about hunting techniques, places and local history while

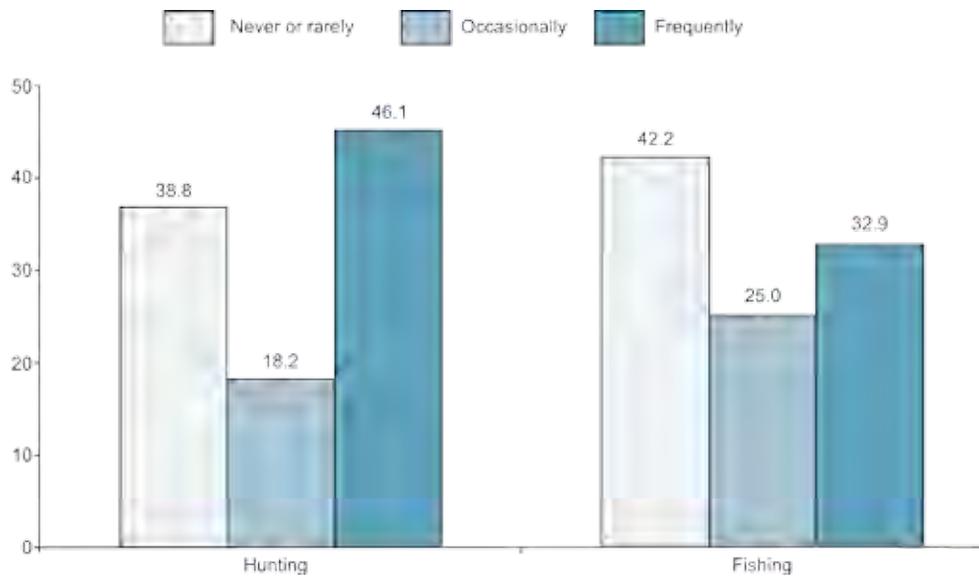


Figure 1. Percentage of participants reporting frequency of hunting and fishing activities (%), population aged 15 and over, Nunavik, 2004. Modified from Furgal and Rochette (2007).

on the land. Despite all of the social, cultural, economic and political changes taking place in Nunavik and Nunatsiavut over recent decades, hunting, fishing and gathering resources from the land and sea continue to be important activities for many residents (Furgal and Rochette 2007, ITK 2008).

As identified through the *Qanuippitaa* Inuit Health Survey study results gathered as part of ArcticNet’s research in Nunavik, nearly half (45%) of the Nunavik population classify themselves as “frequent” hunters throughout the year, hunting regularly once a week or more in at least two seasons (Figure 1). Nearly half of the population goes hunting more than once a week in the spring and summer seasons, which are the most active times of year. The level of hunting activity reported by residents varies with age with more men and individuals 50 years of age and older being more active hunters, on average, than others. Similarly, more individuals that are married or living in a couple and those with a higher individual income (61% for people earning more than 40 000\$ / year, $p = 0.001$) reported being more actively involved in hunting throughout the year (Furgal and Rochette 2007). Similar patterns

exist among residents in Nunatsiavut (Statistics Canada 2008; Table 1). As reported by Duhaime et al. (2002), consumption of country foods in Nunavik was highest among those individuals living in a household with a male head of household and a higher total household income. This is indicative of two main determinants in the collection of country food resources; access to an experienced male hunter as well as financial resources to purchase and maintain equipment and supplies for hunting and fishing.

Table 1. Inuit harvesting country food in 2005 by age group and sex, Inuit Nunaat, 2006. Source: Statistics Canada, Aboriginal Peoples Survey 2006.

AGE GROUPS	TOTAL BOTH SEXES	MEN	WOMEN
	PERCENT (%)		
Total (age 15 and over)	68	74	62
15 to 24	60	67	53
25 to 34	72	78	66
35 to 44	73	81	67
45 to 54	74	77	70
55 and over	71	79	61

Further, sharing of country foods or wild foods is still very much alive in Inuit communities today. More than half of all Nunavimmiut (57%) reported sharing their catch “often” with other members of their community. Sharing “often” was more commonly reported by men, individuals aged 50 years and over, those having completed secondary school or higher, those who were married or living with a partner, those employed at the time of the survey, and those with a higher personal income (>40 000\$ / year). Not surprisingly, sharing a catch more often was more regularly reported among those that hunted and fished more frequently.

Fewer Nunavimmiut are regular participants in fishing activities than in hunting activities, but fishing is still widely practiced throughout the region today. One-third of residents (33%) fish frequently, or more than once a week during at least two seasons throughout the year (Figure 1). Approximately half (48%) of the Nunavik population participates in berry collecting at least once a month at some time during the year. As was the case traditionally, this activity is still practiced much more by women than men. Participation in berry collecting also varies with age, marital status, education and personal income. Individuals 50 years of age and older, those who are married or living in a couple, those who have completed elementary school, and those who earn more than 40 000\$ / year report berry picking more frequently than others (Furgal and Rochette 2007). Similar data for sharing and participation in hunting and fishing activities in Nunatsiavut communities is currently being collected under various projects in that region.

Because of their importance in terms of physical activity, contribution to the preservation of tradition and culture, and their role in the provision of healthy and nutritious foods, hunting, fishing and collecting activities continue to play an important role in the health and well-being of Nunavik and Nunatsiavut residents today (see Chapter 3 – *Human Health*). However, despite this importance, both Nunavimmiut and Nunatsiavimmiut have reported changes in environmental conditions and quality of wildlife

which have influenced, at times, consumption of some species (Nickels et al. 2006). According to participants in the 2004 Inuit Health Survey, concern for contaminants in wildlife species was not a factor leading to the rejection of any catch. Rather, rejection of species caught was more closely associated with the presence of visible anomalies such as parasites in wildlife tissue. These events appear to be more common in Hudson Bay coastal communities than elsewhere in the region (Furgal and Rochette 2007).

5.3 Health contributions of country/wild foods

While hunting, fishing, and gathering of country foods provide the basis for local food production in the North, they also figure prominently in the social fabric and economy of local households and communities. As well, these food items, collected from the land, sea, lakes, and rivers continue to contribute significant amounts of protein to the total diet, and help individuals to meet or exceed daily requirements for several vitamins and essential elements and protect individuals from some forms of cardiovascular disease and contaminant toxicity (see Chapter 3).

Despite the significant importance of these foods, as in so many other Aboriginal populations, residents in Nunavik and Nunatsiavut are increasing the amount of market or store foods consumed in their total diet with time (see Chapter 3). This is especially the case among younger ages and in those communities with greater access to store foods. This shift is resulting in an increased intake of carbohydrates and saturated fats and is projected to change the incidence of ‘western type’ or lifestyle related chronic diseases such as diabetes, cardiovascular disease and some forms of cancers among this population in the future. This shift in diet balance between country/wild foods and market or store foods is influenced by a variety of factors including, but not limited to, increased access to market foods, ease of preparation of processed market items, changes in personal desires and preferences, changes in social norms regarding country/wild

foods, increased time spent in wage economy jobs and less individual time spent on the land and available for food preparation (in some communities), costs associated with hunting equipment purchase and maintenance, and environmental change imposing challenges on country/wild food availability and accessibility (Furgal and Sequin 2006, Alain 2008).

5.4 Food security in Nunavik and Nunatsiavut

Food security is a recognized determinant of health for both Aboriginal and non-Aboriginal populations (McIntyre 2003). The Food and Agriculture Organization (FAO) states that food security exists “*when all people, at all times, have access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life*” (FAO 1999). Additionally, as argued by Power (2008), “*Food insecurity is not only an issue of insufficient amounts of food but also challenges in access to quality food that meets cultural and social desires*”.

In Canada, food insecurity is more commonly reported among younger generations, women, single mothers, Northerners and Aboriginal residents (McIntyre et al. 2003, Ledrou and Gervais 2005, Willows et al. 2009, 2011). People who are food insecure are at an increased risk of being overweight, and having poorer nutritional status, chronic health conditions, mental health challenges and a lower learning capacity (McIntyre 2003, Willows et al. 2011). Residents in northern regions of the country are the most likely to report food insecurity at the household level, with Nunavut, for example, having a rate 4 times higher than the national average (Statistics Canada 2005) and the worst reported food security status among an Aboriginal population outside of the developing world (Egeland et al. 2011).

Significant levels of food insecurity have been identified in Nunavik and Nunatsiavut, most recently under com-

ponents of the Inuit Health Survey. ArcticNet-funded research within the Inuit Regional Health Surveys found that in Nunavik, in 2004, nearly one quarter of individuals (24%) stated that they had lacked food during the month prior to the survey. In Nunatsiavut, 46% of households with children were food insecure, with about 16% of households reporting severe food insecurity (Egeland et al. 2010). Unemployment, low income, high food costs, unavailability of foods, the decrease in consumption of country foods and the lack of nutrition and food choices are reasons for these high levels of food insecurity. The following sections will focus on describing the impacts of environmental change on country/wild food access and quality. Issues of availability and trends in availability of species are discussed in more detail in Chapters 7, 8 and 9 of this report.

5.5 Climate change impacts on food security

Climate change, variability and weather extremes all have implications for the security of availability and access to safe, nutritious and desired foods for Nunavik and Nunatsiavut households (Figures 2, 3). Warming temperatures and warming of permafrost have negative implications for road and airstrip security and accessibility in northern communities. Changes in these critical transportation infrastructures may influence store food transport and therefore, physical and economic access to food stuffs in small remote communities where many items are already prohibitively expensive for some residents. Work funded under ArcticNet and presented in Chapter 6 of this assessment reports instability of airstrips as a result of current permafrost warming in Nunavik. Conversely, a longer open water season with decreasing sea ice coverage and extent, as is projected for Ungava and James Bay (Chapter 2), and is occurring along the Nunatsiavut Coast (Statistics Canada 2011) will provide greater access to coastal communities throughout the year and make ship transportation more viable. However, the current data on both sides of the equation is insufficient to assess the specific



Figure 2. Overview of impacts of climate change and variability on aspects of country/wild food security in Inuit communities.

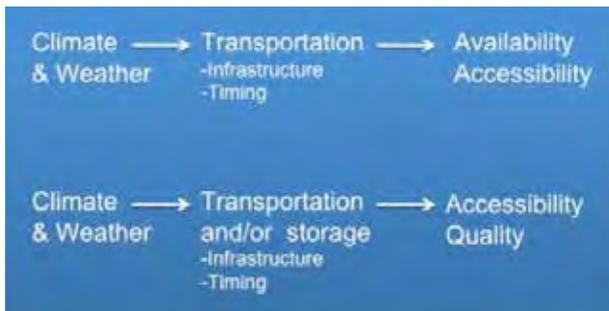


Figure 3. Overview of impacts of climate change and variability on aspects of market food security in Inuit communities.

implications in terms of changes in transport costs per region and associated adjustments in food prices as a result of climate warming or variability.

Through changes in animal distributions related to habitat shifts with warming temperatures or shifts in local community ecology (Chapters 7, 8 and 9), and changes in residents' access to these species as a result of lengthened ice free seasons and increases in uncharacteristic and extreme

weather events (Chapter 2), climate change and variability have significant implications for country food security in the two regions (Ford et al. 2006, Ford et al. 2008, Furgal et al. 2002).

In workshops discussed in Nickels et al. (2006), the majority of Inuit communities reported experiencing impacts on country food security related to changes in environmental conditions in Nunavik and Nunatsiavut. Higher winds in Nunavut and Nunavik communities were reported to make travel and hunting more dangerous by boat in the summer and therefore impact access to seals in open water and whales (Nickels et al. 2006, Ford et al. 2006). In the Inuvialuit Settlement Region, Nunavut and Nunavik, the increased length of the ice free season and decreased ice thickness resulting from warming temperatures was reported to reduce, and make more dangerous, access to ice dependant wildlife species and species that were hunted specifically from the ice (e.g. Ringed seal – *Pusa hispida*, Narwhal – *Monodon monoceros*, in Arctic Bay) (Nickels et al. 2006, Ford et al. 2006). Lower water levels in rivers and ponds in Labrador were reported to negatively impact access to and health of fish species (Furgal et al. 2002, Communities of Labrador et al. 2005).

As part of the 2004 Inuit Health Survey in Nunavik, participants were asked about influences on their access to country or wild foods. Half of the participants (51%) asked in the survey reported that some animals have become harder to find and hunt during the same season over the past 4 years. The reporting of these difficulties was more common among older age groups, men, and individuals with an income under \$20 000. The majority of people who reported that some species were harder to find and catch, specifically identified that caribou (60%) and beluga (53%) were more difficult to find and hunt today. The main reason mentioned for changes in caribou accessibility was related to the fact that they were seen to be further away from the community than they used to be (47%) (see Chapter 9). A small number (14%) said the increased difficulties were related to changes in the land, sea or weather conditions. The main reason mentioned for

difficulties in locating beluga was that there are fewer of them today (22%) and they have moved away from where they are usually found (18%) (Furgal and Rochette 2007).

In research conducted by Alain and Furgal in Kangiqsua-lujjuaq, Nunavik with hunters in the community, similar observations were reported (Alain 2008). However, despite changes having taken place, some hunters reported still being able to locate and access the wildlife they always had for subsistence purposes, but some form of adaptation was needed. Key factors influencing an individual's ability to continue to locate and hunt species despite the changes in environmental conditions noted above, included the individual's access to economic resources, their age, the length of time they had been hunting in the community, their access to hunting and fishing equipment and the strategies they stated were being used to continue to adapt to the changing circumstances. Those taking a more proactive approach to adaptation, shifting species hunted or changing routes to access species, were more successful in continuing to harvest species in their typical times of the year (Alain 2008). However, no evidence existed to support the argument that these pressures on country food access were impacting overall household food security for these individuals (Alain 2008).

5.6 Storms, travel and safety: Implications for food accessibility

Residents of many Arctic communities across the North have reported that the weather has become more “uncharacteristic” or less predictable and, in some cases, that storm events progress more quickly today than in previous memory (e.g. Nickles et al. 2006, Ford et al. 2006, Huntington and Fox 2005). Residents involved in these studies report that this unpredictability limits current participation in harvesting activities and travel as well as increases the risks of being stranded or involved in accidents outside of the community (Nickles et al. 2006, Ford et al. 2006, Fur-

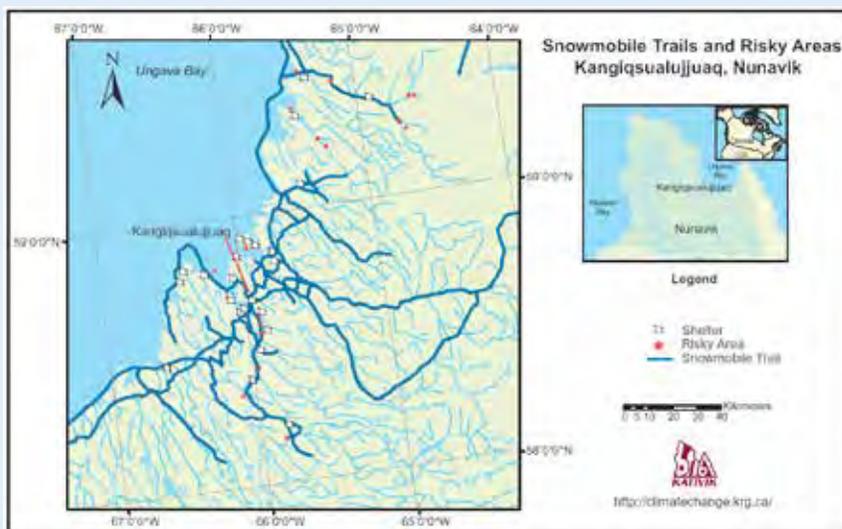
gal et al. 2002, Ford and Smit 2004). Residents of Nunavik and Nunatsiavut have reported this same observation in previous workshops in the two regions (Furgal et al. 2002, Nickles et al. 2006). As well, there is some qualitative evidence to suggest that the incidence of injuries associated with land-based travel and other activities is increasing in coastal communities, however no study to date has looked specifically at this issue.

As reported in the Inuit Health Survey in Nunavik and Chapter 3 of this assessment, the injury and trauma profile for isolated northern regions is characterised by few traffic accidents, but an incident rate related to snowmobiling, boating and ATV use that is significantly higher than in more southern areas (Légaré and Rochette 2007). Rates for hospitalization due to non-intentional injury show Nunavik with the highest rate of all 18 health regions within the Province of Québec and more than double the rate for the whole population (INSPQ, MSSQ and ISQ, 2006). Despite the qualitative reports of increasing injury and incidents occurring in association with changing weather conditions, the Qanuippitaa survey reported no increase in injury and trauma between 1992 and 2004 in Nunavik. Among those injured more in the 12 months prior to the survey were men, Ungava Bay community residents, and individuals with more formal education. Injuries were associated with, in order of decreasing importance, sports activities, ATV travel, snowmobiles travel or falls. Thus, while incidents involving transportation represent 40% of all reported injuries there is no clear pattern emerging that environmental variables have a major influence on injuries nor that those participating in more traditional activities (hunting and fishing) and spending more time on the land or at sea are the individuals suffering the most injuries in the region (Légaré and Rochette 2007). This issue requires further research to investigate community reports of increased injury as a result of storminess and weather variability. No comparable data is yet available for the Nunatsiavut region on this topic.

Box 1. Climate Change in Nunavik: Access to Territory and Resources

The project “*Access to Territory and Resources*” was initiated by the Kativik Regional Government (KRG) in collaboration with ArcticNet investigators at Trent University in response to concerns expressed by Nunavik communities about climate change influences on hunting and fishing activities in the region (Nickels and al. 2006). Its principal objective was to enhance the capacity of local residents to adapt to climate change through their participation in community-based activities. The project took place in five communities: Umiujaq, Akulivik, Ivujivik, Kangiqsujuaq, and Kangiqsualujjuaq (Tremblay et al. 2006, 2008).

During the first stage of the project, semi-structured interviews with elders and locally recognized expert harvesters were conducted to document current use of trail networks around each participating community. A mapping and interview process was developed with local researchers to identify trails used by community members, their specific use, the mode of transportation used for the trail and also to identify areas of increasing risk (environmental hazards) on the land and sea ice associated with changes in environmental conditions. The second phase of data collection involved conducting semi-structured in-depth interviews with elders and experienced hunters in each community to document knowledge on the processes of ice formation, melting and break-up and to identify qualitative information/observation used by local experts to determine when the ice was safe for travel (Tremblay and Furgal 2008). Over the course of the same period, an ice monitoring pilot project was initiated in each of the participating communities to collect both qualitative and quantitative data on changes in ice conditions at locations along key trails. This information was used with meteorological data to identify key indicators (qualitative and quantitative) of ‘safe’ ice conditions at the community level.



Winter trail networks, risky areas and shelters in the Kangiqsualujjuaq area (from Tremblay et al. 2008).

The results were made available in several forms for community members on the KRG web site (<http://climatechange.krg.ca/>) and include traditional and new winter trail maps, common areas of dangerous ice conditions, the location of shelters, traditional knowledge on ice dynamics, key (environmental and climate) indicators of ice safety and Inuit knowledge on climate change observations in the region.

5.7 Climate change and country/wild food quality

In addition to providing significant health benefits, country/wild food species are the most significant source of exposure to environmental contaminants such as PCBs, mercury and lead for northern residents (AMAP 2009, Donaldson et al. 2010, Chapter 3). The behaviour of these contaminants in the environment is influenced by temperature, and therefore climate warming may indirectly influence peoples' exposure to these chemicals which are known to adversely affect the immune system and neuro-motor development and functioning in children (AMAP 2009, Muckle et al. 2006). Some modeling studies have shown that projected climate warming in the North Atlantic (0.4-1.0°C) over the current century will increase rates of Hg transformation (methylation) and therefore increase the concentrations of mercury in marine species between 1.7-4.4% and therefore likely have implications for levels of human exposure via consumption of some fish and marine mammals in these regions. Further, evidence exists to suggest that degrading permafrost and melting multi-year sea ice are sources of contaminants for Arctic marine systems as well. Currently, Inuit regions including Nunavik and Nunatsiavut are involved in the monitoring of levels of several contaminants in marine and terrestrial species. This occurs in Nunatsiavut through such studies as the ArcticNet-funded Nunatsiavut Nuluak project (Chapter 10) and in Nunavik through several projects funded under ArcticNet and the Northern Contaminants Program (see Chapters 3,4,7 for more information on contaminant issues). In addition to impacts on contaminant levels in wildlife species that may be important food species for residents in the two regions, reports of more frequent extreme summer temperatures in combination with improper preparation techniques have put at risk the safety of traditional fermentation processes in the preparation of *igunaq* (Furgal et al. 2002, Furgal and Seguin 2006). At this time, the role of climate in influencing this and other aspects of food safety (e.g. parasite introduction, growth and transmission) is uncertain and requires further investigation in these regions.

5.8 Conclusion

The combined effects of climatic changes and environmental variability on food security and health in Nunavik and Nunatsiavut are difficult to predict. They are influenced by local availability and access factors including economic, technological and political forces and presuppose a strong understanding of what the local environment can provide and sustain in the way of natural food resources. Further, they have potential implications for store or market food supply and storage networks throughout the year that have not yet been explored in any detail. What has been documented is the relationship between weather variability and other changes in environmental conditions and their influence on country/wild food access for Inuit in these two, as well as other, regions. Further, a basic understanding of the ways in which individuals have begun to adapt to environmental change pressures on country/wild food access and availability is developing, however, more research is needed.

Status of Adaptation to Threats to Food Security

Individual behavioural changes have included shifting times of hunting activities to match times of safer access or shifts in migration times and locations, and purchase and use of different forms of transportation (e.g. faster or more powerful transportation vehicles, different vehicles) to access hard to reach locations for hunting and gathering because of decreased water levels, increased storms, or changes in route conditions (e.g. using ATV more than skidoo now because of increased snow free season) (e.g. Ford et al. 2008, Furgal 2008, Furgal and Seguin 2006). Changes in the availability and accessibility of animals in many regions have been reported (see Chapters 7 and 9) and some community members (e.g. elderly people, those without the technological or financial means) have not been able to adapt, continuing to hunt as much as they have in the past. Some communities (e.g. Ivujivik, Nunavik as in Nickels et al. 2006) have reported a greater need for support mechanisms such as community freezer programs to ensure access for all members of the com-

munity throughout the year, and for the development and use of inter-community trade programs to ensure food access at the regional level (e.g. Communities of Nunavik et al. 2005). A review of community and regional food support mechanisms conducted by Rajdev and Furgal (*in review*) in Nunavik identified a number of important programs that support access to healthy foods for community residents. Among them, the Hunter Support Program supported by the Kativik Regional Government (including the community freezer country food distribution), and the Nain community freezer program, are prime examples of support mechanisms that aid in adaptation to stresses on country/wild food access throughout the year caused by climate change and environmental variability. However, it is important to note that some of the responses being adopted at the individual level in response to climate and environmental change have potential indirect impacts as well (e.g. increased costs associated with more powerful means of transportation). In response to changes in accessibility, experienced hunters in Nunavik communities have been able to cope, reporting that they have not yet felt impacts that have changed the amount they harvest, rather simply how, when, where and how much they invest to access, harvest and store the same species (Alain 2008, Tremblay et al. 2008, Lafortune et al. 2004).

Recommendations

The information presented in this chapter represents work conducted in many regions, but highlights, the work conducted in Nunavik and Nunatsiavut on this topic. As a result, some extrapolations have been made from work being conducted in Nunavut and the Inuvialuit Settlement Region that were deemed applicable or relevant for Nunavik and Nunatsiavut. Given the current status of food insecurity in the two regions, the health outcomes associated with poor food security and nutrition, and the transition taking place today in many Inuit communities towards greater consumption of many market food items of poorer nutrient quality, a much greater understanding of food security and nutrient status and the factors influencing these issues, including climate change and variabil-

ity, is needed in these two regions, and elsewhere. Further, important investments in environmental and public health surveillance and monitoring for key issues, including those influenced by environmental change, are encouraged (e.g. Owens et al. 2009). Food security is threatened from the perspective of availability of healthy and nutritious foods and those of high cultural desire and value, safe and secure year round access to country/wild food species, and changing food quality. There are associations with climate and environmental change for each of these components of food security in the two regions (Figures 2,3). As a result, greater focus is required on this topic and the adaptations taking place and needed to support sustained food security and healthy diet behaviour in the future.

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Chapter 6. Permafrost and climate change in Nunavik and Nunatsiavut: Importance for municipal and transportation infrastructures

Lead authors

Michel Allard, Mickaël Lemay, Carl Barrette, Emmanuel L'Hérault, Denis Sarrazin
Centre d'études nordiques (CEN), ArcticNet, Université Laval, Québec, QC

Contributing authors

T. Bell, and G. Doré

Abstract

Permafrost degradation is seriously affecting the natural environment. The landscape is changing through thermokarst that takes place mostly in the discontinuous permafrost zone and through thicker active layer depth and more frequent slope processes in the continuous zone. Northern residents are affected as vegetation, water bodies and soil drainage are greatly modified, which has an impact on resources traditionally available for humans. The modern built environment is also affected. Transportation infrastructure is being studied and adaptive solutions are sought, applied and tested. To protect and optimize the major investments required for extensive housing and construction, the urban planning of communities calls upon better permafrost maps and prediction of permafrost behavior. Final permafrost degradation around 0°C appears to be primarily under the influence of unfrozen water content and heat brought to the thawing interface by groundwater. This process is also effective in accelerating localized thawing under man-made infrastructures. Collection and organization of permafrost information in geographic information systems (GIS) allows for the integration of essential knowledge and provides a very useful tool for establishing situation diagnostics, sharing information with stakeholders and communities, and supporting multidisciplinary decision making for land use planning. The principal adaptive measures lie in adapting foundation types to mapped permafrost conditions to ensure a prolonged service life of buildings.



6.1 Introduction

Permafrost, soil or rock that has remained at temperatures below 0°C for long periods of time, is the key factor that makes Arctic lands particularly sensitive to climate changes (ACIA 2005). This is in large part because the ice-bearing frozen ground is the physical support for terrestrial ecosystems. Under the influence of larger heat transfer in the ground from the warming atmosphere, permafrost thaws and may become unstable: the terrain often settles, soil drainage conditions are altered (either becoming dryer when water percolates deeper in coarse soils or wetter when the fine-grained ice-rich substrate remains impervious), various slope processes are triggered (such as active layer slides), hollows and ponds are created, and so on. Inevitably, the ecosystem structure changes; and its functioning also changes as increased ground and surface temperatures drive environmental biochemical processes at higher energy levels. Similarly, frozen ground used to provide a solid base for supporting man-made infrastructures. But permafrost thawing now threatens the integrity of municipal, transportation and industrial infrastructures. Engineering methods designed to either preserve permafrost or to adapt infrastructures to loss of frozen ground support have to be applied with increased care and meticulous planning. Understanding the impact of climate change on the natural environment and dealing with maintenance and development of infrastructures call for a better appraisal of permafrost conditions over the territory.

In the Canadian Eastern Subarctic region, recent applied research has already provided some important knowledge regarding the direct impacts of permafrost degradation associated with the accelerated warming recorded in the last decades (Allard et al. 2007, 2009, ACIA 2005, Calmels et al. 2008, Smith et al., 2010). Climate model projections indicate that this trend will continue to prevail, or even accelerate over the coming decades (Sushama et al. 2007, IPCC 2007; see chapter 2). Climate change comes at a time when intense industrial development - particularly linked to mining - and fast growing Inuit populations call

for new facilities such as roads, airstrips and railways, hundreds of new housing units in communities along with related service buildings and urban expansion. Huge investments are being made by both governments and the private sector for long-lasting infrastructures. Particularly, the pace of community expansion highlights the need for the establishment of sustainable community development plans to ensure healthy communities.

Urban planning in northern communities needs to reflect the importance and influence that the extreme climate and the highly sensitive nature of the landscape have on development (Forbes et al. 2007, Irvine et al. 2009, Ford et al. 2010). From a sustainable development perspective, it is critical that northern communities adopt specific adaptation techniques and strategies to deal with warming permafrost in order to preserve or expand their current residential, commercial, municipal, and transportation infrastructures. This chapter summarizes recently updated knowledge on permafrost properties and thermal conditions over the territories of Nunavik and Nunatsiavut. It provides a short review of research done in collaboration with governments and local communities to map and characterize permafrost conditions and to forecast expected impacts of climate change in support of regional and community land planning. An example of engineering solutions currently being applied in an adaptation strategy is also illustrated.

6.2 Permafrost: scientific background

Permafrost is a phenomenon directly related to climate. It is soil (or rock) that remains at or below the normal freezing point of water (<0°C) for two or more consecutive years (Harris 1988, Davis 2001, French 2007). Its presence depends mainly on the mean annual temperature at the soil surface, which has to be equal or less than 0°C (with rare exceptions). Permafrost covers 23% to 25% of the northern hemisphere (Zhang et al. 2008) and much of it is thousands of years old (Davis 2001).

As in other cold regions, the geographic distribution of permafrost over the Québec-Labrador peninsula is associated with basic factors that define regional and local surface climate conditions (Figure 1): air temperature, precipitation, topography, types of vegetation cover, soil organic layers and, particularly, snow cover thickness and

duration. The zone of sporadic permafrost in Nunavik and Nunatsiavut extends roughly between latitudes 51°N and 56°N where permafrost is mainly confined in peatlands because of the thermal offset effect related to peat's thermal properties (i.e. peat cools easily when frozen in winter and is a good insulator that prevents warming in

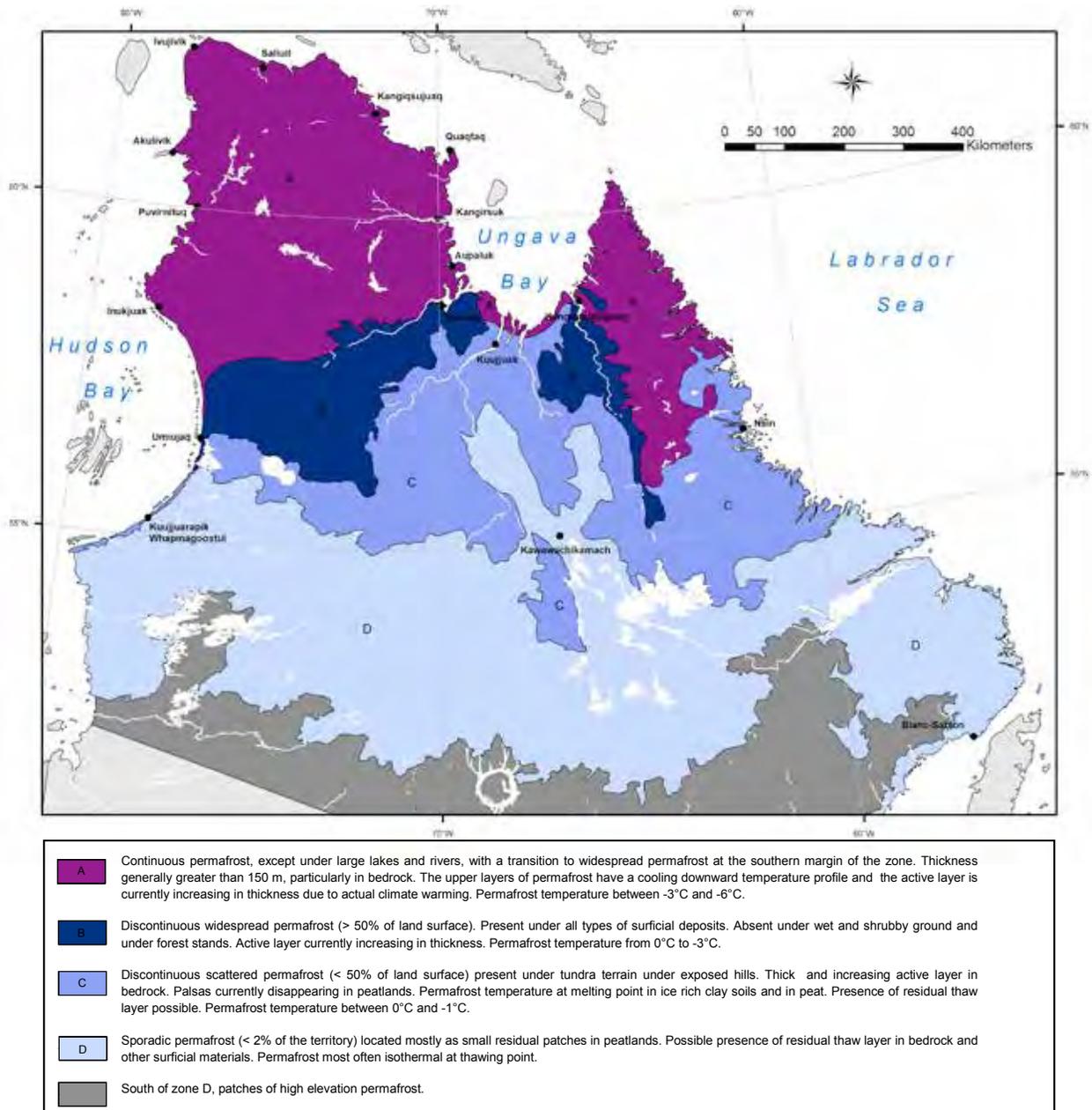


Figure 1. Permafrost distribution in Québec-Labrador peninsula.

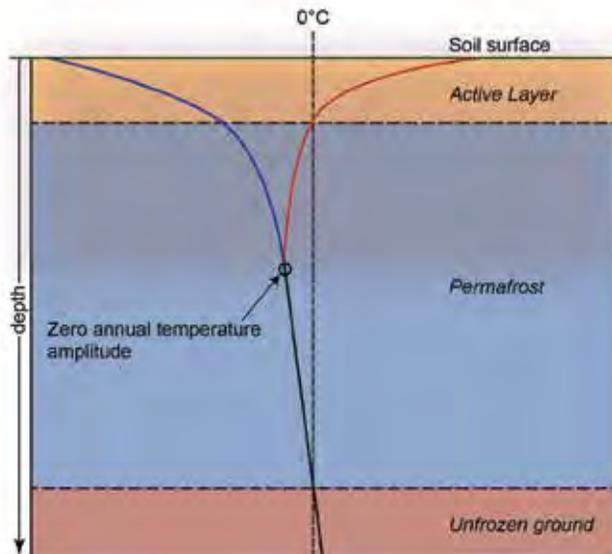


Figure 2. Profile of the permafrost thermal regime. Adapted from Brown 1970.

summer) (Brown 1970; Burn 1988). Hilltops devoid of snow cover due to blowing winds are also sites likely to be underlain by permafrost in the discontinuous zone. The zone of discontinuous permafrost is broadly contained between latitudes 56° and 58°N while the zone of continuous permafrost extends northward of latitude 58°N where annual temperatures prevailing since deglaciation allowed permafrost to reach depths over 150 meters (e.g. Tasiujaq) and even as deep as 590 m at the Raglan mine (Allard and Seguin 1987, Chouinard et al. 2007).

In permafrost regions, the ground is characterised by two main layers: the active layer that thaws every summer and the underlying permafrost that remains below 0°C year round (French 2007, Williams and Smith 1989). Both the active layer and the permafrost are affected by seasonal temperature variations (Figure 2), but only the active layer undergoes seasonal thawing (Washburn 1979, Williams and Smith 1989). It is also recognized that the stratigraphic unconformity between the active layer and the permafrost (termed the permafrost table) shifts up-

wards or downwards over periods of several years following climate variations. One exceptionally warm summer may lead to a thicker active layer. Consequently, the amount of ice near the permafrost table can vary within only a short period encompassing only a few years (Shur and Jorgenson, 2007). Deeper in the permafrost, the maximum depth affected by the annual temperature variations is called the depth of zero annual amplitude (Figure 2); it varies with air temperature and the type of soil (Pissart 1987, French 2007). In Nunavik it is about 22 m deep in bedrock, somewhat less in sands, and 5-6 m deep in clays (Lévesque et al. 1990).

6.3 Impacts of climate warming on permafrost

A warmer climate results over time in a warmer vertical temperature profile in the permafrost and a greater depth of summer thaw, i.e. a thicker active layer. Both an increase in mean annual air temperature and a thicker snow cover result in more heat absorption in the ground. In Alaska, an increase of 0.3°C to 4°C was observed in soil temperatures since 1980 depending on the environmental conditions (Osterkamp 2005). The increase of active layer thickness was observed and monitored in many sites in Subarctic Sweden (Åkerman and Johansson 2008), in Nunavut (Smith et al. 2010, 2005), in Alaska (Osterkamp and Romanovsky 1999, Osterkamp 2003) as well as in the Canadian Eastern Subarctic (Smith et al. 2010). In the Canadian Eastern Subarctic, this warming in fact began in 1993 and a general rise of 2°C in ground temperatures took place until about 2005 (Allard et al. 2007). Temperatures are now warmer than in the past. In eight Nunavik communities spread over the territory, permafrost monitoring data in different surficial materials showed significant changes in active layer thickness and soil temperature, here reported at the 4 m and the 20 m depths since the mid 1990s (Table 1).

When the active layer thickness increases over the years because of climate warming, the thaw of the underlying

Table 1. Ground temperature and active layer depth variations at different sites in Nunavik. Derived from Smith et al. 2010.

SITE (CABLE NO)	MATERIAL	AL 93 (CM)	AL 07 (CM)	Δ AL (CM)	Δ T°C 4M	ΔT°C 20M
Salluit (Sal-154)	Gneiss	279	374	95	1.8	1.0
Salluit (Sal-155)	Till	168	295	182	2.7	1.3
Akulivik (Aku-162)	Till	138	222	84	1.7	-
Akulivik (Aku-232)	Sand / clay	135	143	8	1.6	0.9
Quaqtaq (Quaq-156)	Sand / gravel	151	170	19	1.5	1.5
Quaqtaq (Quaq-158)	Gneiss	416	519 ³	103	1.6	1.2
Puvurnituq (Puv-303)	Gneiss	339	469 ²	130	3.3	1.1
Aupaluk (Aupa-299)	Sand / gravel	155	210	55	1.7	1.0
Tasiujaq (Tas-304)	Sand	113	207	94	1.7	-
Tasiujaq (Tas-roc)	Schist	509	552	43	2.0	1.2
Kangiqsualujuaq (Kan-231)	Gneiss	607 ¹	1100	493	3.4	1.2
Kangiqsualujuaq (Coastal mound)	Clay	252 ⁴	332 ⁵	80	1.5	0.05
Umiujaq (Umi-roc)	Basalt	1008 ⁶	1556 ²	548	1.5	1.2*

¹1995, ²2005, ³2004, ⁴1994, ⁵2007, ⁶1997, *permafrost now at -0.01°C

permafrost provokes terrain subsidence as the expulsion of ground ice melt water from the thawed soil leads to some soil compaction. This process is called thaw settlement. On sloping terrain, landslides may be triggered due to the release of melt water at the thawing front, which increases pore water pressure at the thawed/frozen interface. Thawing of the permafrost in the natural environment leads to the formation of hollows and ponds, which are end results of a process called thermokarst. As thickness of the active layer increases and thermokarst occurs, the terrain is disturbed and the ecosystems it supports are totally modified. Similarly, in built environments, under buildings and infrastructures such as roads and runways, the thawing of permafrost results in an important loss of bearing capacity because the frozen icy ground that used to be as hard as concrete turns into soft ground or even

into mud. As a result of climate warming, an intensification in permafrost degradation is observed at the circum-polar scale and human infrastructures are more at risk than before (Allard 1996, Nelson et al. 2002, Fortier et al. 2007, L'Hérault 2009, Smith et Riseborough 2010).

For instance, destructive slope processes such as active layer detachment failures (a shallow type of landslide; see Lewkowicz and Harris 2005a and b) are more frequently observed. In Salluit (Nunavik), active layer detachments that occurred in 1998 and 2005 have been directly associated with a yearly increase of the active layer thickness more than 9% over the previous summer, which was favoured by an increase in the number of thawing degree-days (i.e. warmer summers) (Figure 3; L'Hérault 2009).



Figure 3. *This active layer detachment failure in the village of Salluit occurred in 2005.*



Figure 4. *Palsamire field and thermokarst lakes in the region of Umiujaq, Nunavik.*

In Subarctic Québec, the number and areal coverage of thermokarst ponds have increased rapidly over the past 50 years (Marchildon 2007, Vallée and Payette 2007, Thibault and Payette 2009). Results of Vallée and Payette (2007) showed an increase of 76% of the thermokarst areas and a decrease of 23% of the permafrost mounds at a studied site along the Boniface River. Marchildon (2007) also observed the degradation of 43% of the permafrost cover and an increase of 65% of the thermokarst areas since 1957 near the Nastapoka and Sheldrake rivers, a region dominated by palsas, lithalsas and permafrost pla-

teaus in discontinuous permafrost (Box 1). This trend was also observed in a monitored palsa field close to Umiujaq (Nunavik) (Figure 4) (Calmels et al. 2008).

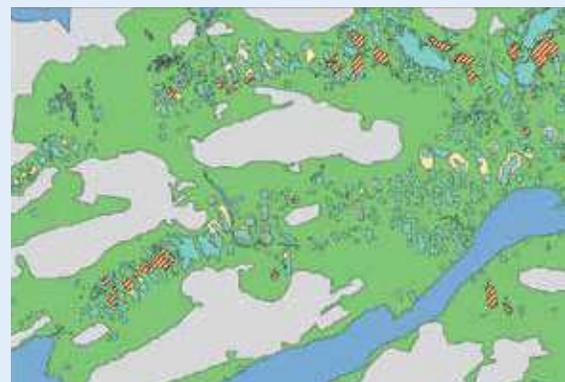
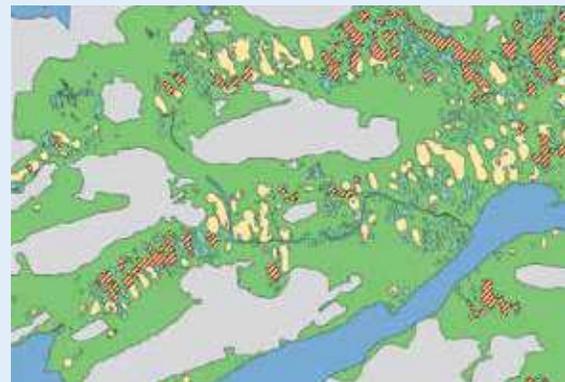
Finally, permafrost thawing amplifies the rate of occurrence of geomorphological processes that were up to the present only slightly active in the frozen environment (McKenzie et al. 2007). For instance, creeks and stream watersheds that were poorly developed on impervious permafrost terrain are now structuring themselves and expanding to allow surface water to flow through unfrozen

Box 1. Drastic increase in thermokarst lakes is observed in the Eastern Subarctic region

A thermokarst lake forms when the thawing of ice-rich fine-grained permafrost results in subsidence, creating a depression filled with water. When ponding is first initiated in a depression, more heat is stored in the water; this increases the thawing rate of the permafrost beneath and around the pond, inducing more subsidence. This process feedback accelerates the degradation of the permafrost once it has started (Larouche, 2010). Thousands of such small lakes occur in lowland regions, especially where palsas and lithalsas dominate the landscape. In Nunavik, a major zone of active thermokarst extends east of Hudson Bay, in fine-grained ice-rich soils, between 55° and 58°N. Thermokarst lakes can also be found in other types of soils where the soil contains excess ice.

Periods of past decreases in permafrost areas and increases in active layer depth were also interpreted from stratigraphic reconstructions and radiocarbon dating over the last thousand years in relation to Late Holocene climate changes. However, thermokarst since the end of the Little Ice Age (around 1880 AD), appears to have occurred on an unprecedented scale, with a still faster permafrost degradation rate in recent years (Allard and Seguin 1987, Kasper and Allard 2001).

Sheldrake River area



terrain; ponds are becoming interconnected and soil permeability generally increases (Mc Namara et al. 1999). In both cases, this new liquid water in the environment induces additional heat in the remaining permafrost underneath lake beds and around the lakes, which contributes to further intensify permafrost thawing and subsidence and modify the landscape (Mackay 1974, Larouche 2010).

6.4 Impacts of permafrost degradation on infrastructures

Permafrost thawing threatens the integrity of residential, municipal and transportation infrastructures. Infrastructures are affected in two ways: 1- through thaw settlement and, 2- through terrain destabilization by landslides and thermal erosion. Infrastructure foundations settle and lose their compaction when the permafrost starts thawing underneath. This affects buildings which then settle unevenly with resulting damage such as cracks in walls and warped floors. In large constructions on slabs, such as garages, the floor usually collapses in the central portion of the building and the overall structure deforms inwards. Often, costly corrective measures are necessary. So far, most observed cases of infrastructure settlement can be explained by factors that are not due to climate warming but rather to poor original foundation designs related to a lack of knowledge of local permafrost conditions, particularly the ground ice content. When runways were first built (from 1984 to 1992 in Nunavik), the permafrost table moved upward into the embankment or into the former active layer beneath. Currently, with climate warming the active layer below these embankments still remains in the former ice-poor, but frozen, active layer. Settlement is therefore minimal or negligible; however it will increase and become more damaging in the future as thaw depth reaches deeper into the permafrost in response to the expected continued climate warming.

Two major site factors were observed to generate heat in the ground that leads to permafrost thawing: snow bank accumulation and water ponding along the foot of em-

bankments. The snow banks that accumulate by wind drifting against the flanks of embankments insulate the ground surface and therefore prevent the soil from cooling back to colder temperatures in winter. During the following summers, thaw then progresses deeper and increases the thickness of the active layer, thus provoking ground settlement and leading to collapse of roads and runways. The local snow cover accumulated against an embankment side may even be thick enough to totally prevent the active layer from freezing again. For instance, measurements made with micro-dataloggers in Salluit revealed that a maximum snow thickness (measured at the end of March) of about 1.1 m is enough to keep the ground surface above 0°C, therefore leading to localized permafrost degradation. Similar measurements in Tasiujaq, where the climate is warmer, yielded a threshold snow thickness of 0.8 m to keep the ground surface above 0°C and prevent active layer freeze-back. Drilling and temperature measurements in collapsed ground alongside runway embankments indicated that in 2008, after a period of 10-15 years, the soil was thawed to depths as much as 6-7 m (Allard et al. 2010). For an airstrip, the impact is felt for a distance of several meters inwards of the margins of the runway. For a narrow road, the thermal effect of snow banks on both sides is sufficient to affect the road over its whole width (Fortier et al. 2011).

The influence of seasonal snow accumulation along embankments on permafrost thawing is thereafter further enhanced by the ponding of water in the depressions. In summer this water retains heat from solar radiation which is further transferred into the ground. The increase in water content of the thawed soil under the embankment side thereafter delays freeze-back of the soil due to latent heat effect (the amount of heat that must be extracted to freeze water into ice). The warm bulb extends underneath the embankment and the collapsing spreads inward in the infrastructure. A good example of this is the degradation observed along the Tasiujaq runway (Figure 5).

Water tracks are shallow depressions in the surface of sloping terrain without a definite creek and where water

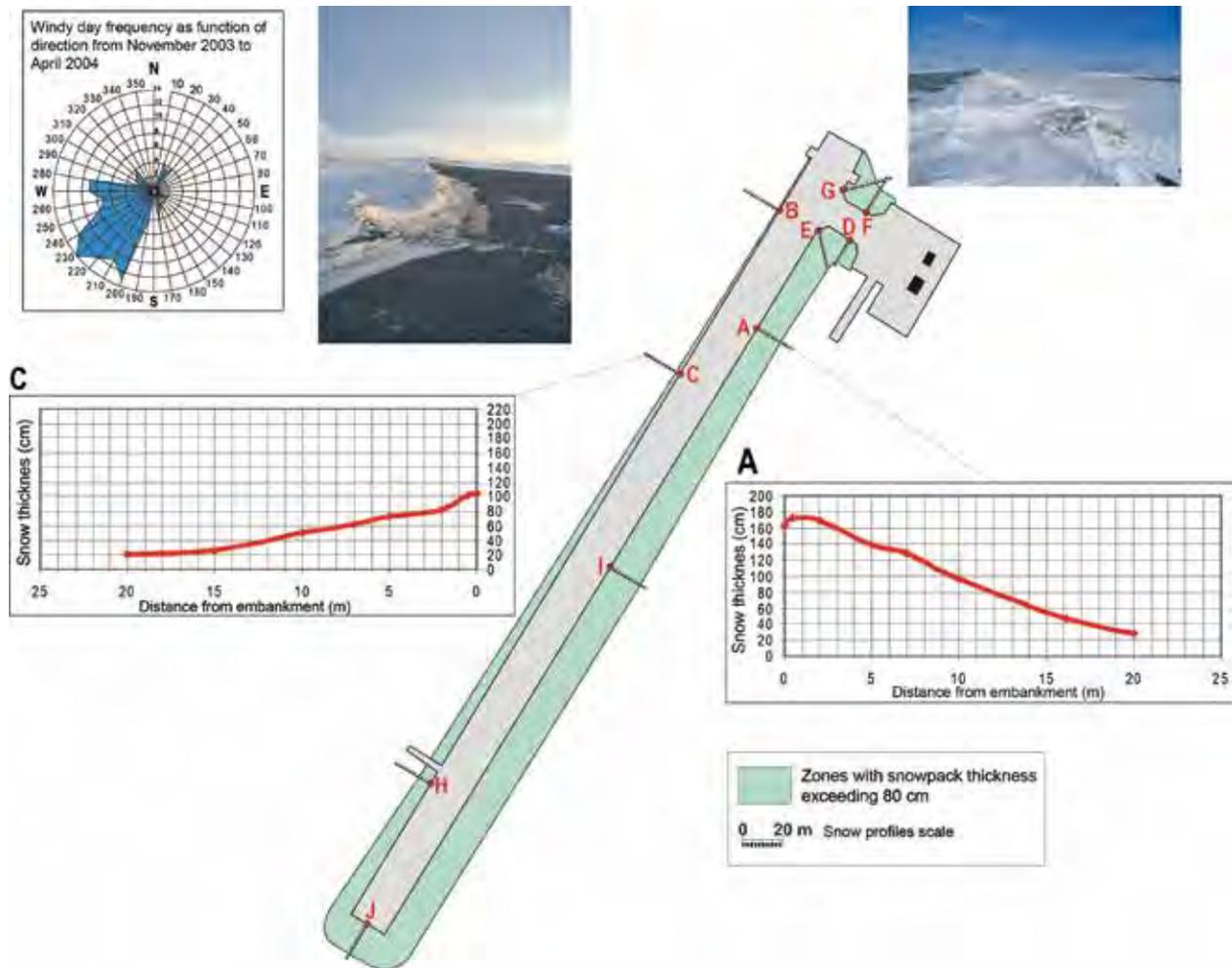


Figure 5. Tasiujaq airstrip with two transects showing clear difference in the snow accumulation profiles (A and C) for both sides of the runway. Snow accumulation is directly affected by the dominant winds coming from the Southwest. Letters represent other transects of snow accumulation profiles.

flows in thin sheets over the tundra and seeps through the active layer (McNamara et al. 1999). This near surface groundwater flow carries heat by advection, which adds to the heat that warms up the ground in summer through conduction from the surface. When such water tracks flow across a road or a runway embankment, localized transversal depressions are formed by settlement. (de Grandpré et al. 2010).

Ultimately, snow accumulation, water ponding and advected heat from seepage water contribute to warming

permafrost and generating thaw settlement, which damages infrastructures. A good example is provided by the multiple, repeated, settlement depressions that affect the road to the airport in Salluit (Figure 6).

At the present time, interventions to restore runways and roads and to extend their lifespan consist firstly, of reshaping side slopes at lower angles to make them more aerodynamic in order to prevent accumulation of snow banks by wind drifting and, secondly, of correcting surface drainage to divert it away from the infrastructures.



Figure 6. Access road to Salluit airport showing important deformations with a succession of thaw settlements.

When necessary, culverts and ditches are redesigned. More proactive engineering solutions such as convective embankments, berms and heat drains can be applied in specific cases to prevent further permafrost degradation after restoration. The solutions adopted for the maintenance of the Puvirnituk runway provide an example of a comprehensive intervention designed to stop the impact of both advective heat transfer by water seepage under the runway and snow accumulation on the sides (see Box 2).

In the Eastern Canadian Subarctic Region, active layer failures are a type of landslide commonly observed that have impacts on urban areas (Lewkowicz and Harris 2005a and 2005b). Such landslides may occur in any year; however they have been shown to happen particularly at the end of warmer summers (from mid-August onwards) when the thaw depth is deeper than in the previous years, therefore melting ground ice at the active layer/permafrost transition, which frees water in an otherwise impervious



Figure 7. This active layer detachment failure in Salluit occurred in 1998 and prompted the abandonment of the development project in this sector as well as the removal of 20 houses already built.



Figure 8. *Thermal erosion process initiated by the passage of a heavy vehicle, Salluit.*

soil, thus creating excess pore pressures just over a perfect slipping plane, i.e. the icy permafrost. A landslide such as this took place on 5 September 1998 in Salluit (Figure 7) near a new urban construction sector, prompting the abandonment of the development project and the removal of 20 new houses (L'Hérault 2009). As for thermal erosion, it occurs when water happens to flow directly along the icy permafrost. Often this occurs at specific places such as at the outlet of culverts and in tracks made by vehicles and machinery in the tundra (Figure 8). Thermal erosion may also take place in the cavities formed by landslides if a creek happens to flow into them or along riverbanks during high flow stages.

Building on permafrost in the context of a changing climate requires looking for innovative solutions designed to pre-

vent gradual deterioration of buildings and infrastructures. Planning for community expansion or for industrial facility construction over permafrost terrain with variable characteristics, ground ice contents and ground thermal regimes, while considering future climate, is a challenging multi-disciplinary technical undertaking, which must be pursued for sustainable and economical development. Without planning supported by sufficient local knowledge of permafrost, the risks of expensive management and repair costs are getting higher and higher. Recent climate change and the socio-economic situation in the Eastern Subarctic has compelled governments and researchers to work together to identify major knowledge gaps, produce maps of permafrost conditions for land management, search for applicable engineering solutions and use predictive models of the permafrost thermal regime to set up adaptation strategies.

6.4.1 Methodological approach for mapping and characterizing permafrost for urban and infrastructure management

Since 2002, an integrated, multi-technique and multi-disciplinary, approach has been developed to map permafrost conditions and geotechnical properties for projects pertaining to airports, roads and villages. As the amount of ground ice and structure (e.g. ice lenses, massive ice bodies, network of ice-wedges, etc.) are closely associated with the type of geological surficial material (Table 2), the first methodological step consists of mapping the Quaternary geology using air photographs and high resolution satellite images. This mapped interpretation is then validated with field checks such as terrain observations, test pits and drill holes with recovery. Most shield bedrock types in Nunavik and Nunatsiavut are massive and contain a small amount of ice confined in their structural elements such as joints and bedding planes. The thickening of the active layer therefore has negligible impacts on the stability of rocky terrain (although exceptions exist). Clays contain abundant ice segregation lenses with volumetric ice contents sometimes close to 100%. Till, a mixture of boulders, sand, gravel and silt, is very abundant in Nunavik and Nunatsiavut and often contains large amount of ice making it subject to thaw settlement. In gravel and coarse sand, the ice content is, most of the time, very low. Nevertheless, saturated gravel can experience significant consolidation upon thawing. Geomorphological features on the surface are also indicators of ground ice content and structure. The ones most often observed are frost boils in fine grained, or fine-matrix, ice rich soils, tundra polygons over networks of ice-wedges, and gelifluxion sheets and soil stripes on ice rich sloping soils. Other characteristic indicators of ground ice content and terrain sensitivity are: landslide scars, wetland patterns, stream bank erosion scars and thermokarst features.

For some projects, e.g. eight airport sites, frozen cores of permafrost were extracted by a contractor who used a diamond drill-bit with refrigerated drilling mud. The drilling

sites were selected in order to obtain representative samples of all the major surficial deposits and permafrost condition units encountered in the given study area. The ground ice volumetric content is measured by classification of tomographic scans made on the frozen cores (Calmels and Allard 2004). Other laboratory treatments such as grain-size analyses, salt content, and Atterberg's limits (i.e. plastic and liquid limits) are performed as well. Thaw consolidation tests are also performed on selected samples. Knowledge of the spatial extent of these deposits, their stratigraphy and regional ground ice conditions is further improved with the help of shallow geophysical surveys, particularly Ground Penetrating Radar (GPR) and electrical resistivity (e.g. Ohm-Mapper™). Finally, the information from all these sources is integrated and collated in a Geographic Information System (GIS) application. The information layers encompass the infrastructure, topography, drainage, surface geology, periglacial features and field surveys (i.e. test pits, drill holes, GPR and electrical resistivity).

The high precision maps and DEM are superposed over recently acquired high resolution satellite images (e.g. Quickbird, Ikonos or GeoEye) so that actual towns and infrastructures are visualized in their environmental context. All of this organized information is then used in multidisciplinary meetings (involving geomorphologists, engineers, geophysicists, land planners, administrators) with stakeholders (staff of responsible government agencies, community members and managers, staff of regional governments, consultants, etc.) to analyze situations, evaluate risks and make decisions for adaptations.

Projections of active layer changes and ground thermal regime are thereafter produced by numerical modeling in order to simulate the potential future impacts on permafrost and infrastructures. These simulations make use of Ouranos's high spatial resolution CRCM outputs (see chapter 2, this volume). Existing thermistor cables from the SILA network, that have been operational in most communities for two decades (Table 1), are used to calibrate numerical thermal analysis and simulations (Barrette 2010). New cables are installed in drill holes either to fill gaps in the network or to obtain specific measure-

Table 2. *Morphologic features of permafrost, geological features and type of ground ice for surficial deposits.*

MORPHOLOGY AND CRYOSOLS	SURFICIAL GEOLOGY TYPES	TEXTURE	PERMAFROST ZONATION	GROUND ICE TYPES	POSSIBLE PRESENCE OF EXCESS ICE
Frost mounds	Silts and marine clays Sands (low mounds)	Silty clays Fine to medium sands	Discontinuous and widespread Discontinuous and dispersed	Segregation	Yes
Palsas	Peat Peat/silts and clays Peat/sand or till (rare)	Fibric or hemic peat over fine grained deposits	Discontinuous and widespread Discontinuous and dispersed	Segregation	Yes, in mineral sediments under peat
Thermokarst lakes (associated with palsas and frost mounds)	All possible deposits; mostly fine grain and peaty sediments	Peat Silty-clay Sands	All zones	NA	NA
Ice-wedge polygons	Tills Fluvial terrace sands Carex sands	Peat Fine to coarse sands	Continuous	Ice wedge polygons with pore ice	Yes, in polygon networks
Soil wedge polygons	Tills (on drumlin ridges) Glacifluvial deposits (outwash and deltas), beach sands	Heterometric coarse sands and gravel deposits	Continuous Discontinuous and widespread	Pore ice	No
Low center mudboils	Tills, diamictons (uplifted tidal flat), often associated with soil wedge polygons and solifluction lobes.	Heterometric coarse sands and gravel deposits with very fine sands or silts	Continuous Discontinuous and widespread	Pore ice Small amounts of segregation ice	No
High center mudboils	Marine and lacustrine deposits. Abundant on top of cryogenic mounds	Fine sands and silty clays	Continuous, discontinuous and widespread Discontinuous and dispersed	Segregation	Yes
Striped soils	Tills Slope deposits	Blocky diamictons in fine matrix	Continuous	Pore ice	No
Solifluction lobes	Tills Marine sands Slope deposits	Heterometric deposits in fine sandy or silty matrix	All zones	Pore ice, Small amounts of segregation ice	No
Hummocks	Tills and diamictons over poorly drained low land	Heterometric deposits in fine sandy or silty matrix	Continuous Discontinuous and widespread	Pore ice	No
Seasonal frost mounds with ice-cores and icing	All deposit types	All grain size deposits and organic soils, near streams and spring run-offs	Continuous Discontinuous and widespread	Intrusive (significant and fast up-lift in winter and subsidence in summer)	Yes
Ejection mounds or blocs	Rocks (fractionated)		Continuous Discontinuous and widespread Discontinuous and dispersed	Intrusive ice? Segregation ice?	?

ments of particular situations (for instance the thermal regime under an embankment or under a restored site to monitor the recovery of the thermal regime).

6.4.2 Urban expansion and management

Historically, most of the communities of Nunavik and Nunatsiavut were located in environments that were originally selected by Inuit for access to surrounding food resources, drinking water, camping grounds, protected shorelines, etc. Organizations such as churches and the Hudson's Bay Company joined them on these sites. Many town sites are in marine embayments or at river mouths where they provide a wind shelter and good access to the sea; their locations favour the traditional way of life organized around camping, hunting, fishing and gathering. The fast population growth and modernization of the late 20th Century was not entirely expected. Around the end of the 1960s, the development of a sedentary lifestyle emerged following the provision of health, social, education, administrative and economic services by governments. Community growth and socio-economic development led to the construction of new houses, schools, arenas, health centres, and municipal and service infrastructures. Communities have expanded their infrastructures over the years sometimes in less favourable geomorphological zones (e.g. on fluvial and marine ice rich sediments) or are now bounded by a restricting topography or by expanses of poorly drained terrain. Each community is located in a specific geomorphological and climatological setting, some being more favourable to adaptation to modern expansion than others.

Nowadays, the population growth of Inuit communities is amongst the highest in the world. In Nunavik, population growth rate ranges from 2.3% in Kuujjuarapik to 23.4% in Inukjuak, with a mean growth rate for the 14 communities of 10.46% between 2001 and 2006 (Table 3A). However, an opposite trend is observed in most communities in Nunatsiavut where the overall growth rate is negative (-6.0%), ranging from -15.1% in Rigolet to -5.2% in Hopedale between the years 2001 and 2006 (Table 3B).

Despite the recent negative demographic trend in Nunatsiavut, the need for houses remains significant due to the rapid deterioration of the existing housing stock and because of inadequate housing construction programs in past years. A project initiated in 2010 by the Environment

Table 3. Demographic context in Nunavik (A) and in Nunatsiavut (B) for 2001 and 2006.

TABLE A	POPULATION		
	MUNICIPALITIES *	2006	2001
Akulivik	507	472	7.4
Aupaluk	174	159	9.4
Inukjuak	1 597	1 294	23.4
Ivujivik	349	298	17.1
Kangiqsualujuaq	735	710	3.5
Kangiqsujuaq	605	536	12.9
Kangirsuk	466	436	6.9
Kuujuuaq	2 132	1 932	10.4
Kuujjuarapik	568	555	2.3
Puvirnituk	1 457	1 287	13.2
Quaqtaq	315	305	3.3
Salluit	1 241	1 072	15.8
Tasiujaq	248	228	8.8
Umiujaq	390	348	12.1
TOTAL	10784	9632	10.46

TABLE B	POPULATION		
	MUNICIPALITIES*	2006	2001
Nain	1 034	1 159	-10.8
Cartwright	552	629	-12.2
Happy Valley-Goose Bay	7 572	7 969	-5
Makkovik	362	384	-5.7
Rigolet	269	317	-15.1
Postville	219	215	1.9
Hopedale (division 11)	530	559	-5.2
TOTAL	10 538	11 232	-7.4

*Statistics Canada 2006; *Institut de la statistique du Québec 2006

Division of the Nunatsiavut Government and the Nain Inuit Community Government - in partnership with Memorial University - has among its main goals to map the nature and distribution of permafrost, to assess the impacts of changes in permafrost conditions and active layer thickness on present and planned community infrastructures, and to investigate how modifications to building design and practice may improve overall integrity and sustainability of infrastructures under a changing climate and environment. The current practice of laying some buildings directly on the surface of the gravel and sand pads has created a series of structural issues, including cracking and shifting of walls and disruption of water and sewer services, which has led to condemned houses and commercial buildings, disruption of community services and increased costs for maintenance and heating (Figure 9). An important outcome of the current project is the development of a composite landscape hazard risk map for Nain, which will be integrated into community planning to help ensure human safety and security associated with existing and future development. A longer term goal is to inform decision

making for more sustainable communities in Nunatsiavut, including construction practices, development strategies, and infrastructure design and energy efficiency.

In Nunavik, the rapid population growth has led to a severe housing crisis. Indeed, the Kativik Municipal Housing Bureau (KMHB) assesses that with the current population in Nunavik of over 12 000 residents (Statistics Canada, 2012) living in 2100 houses, there is a need for an additional 915 units. In a report published in 2007 by the Commission des droits de la personne et de la jeunesse, overcrowding of the houses was identified as one of the main factors responsible for the mistreatment of children and the loss in quality of life. Under its Plan Nord, the Québec Government has just launched a new major housing program to begin to address these concerns. Planning for expansion on permafrost terrain now becomes even more urgent to support the expansion of communities driven by this construction program and to protect major public investments. Due to the variability of permafrost conditions within each community and



Figure 9. Ground subsidence related to permafrost thaw causing structural damages and infrastructure maintenance issues in Nain, Nunatsiavut.

between communities as well as to the large variations in climate throughout the Eastern Subarctic region, the problems for management and expansion on permafrost are often specific from case to case. Some of them need only minor adaptation solutions while others are facing challenges requiring a significant involvement and capacity strengthening of the local managers and stakeholders. Each community is also a group of people sharing a common regional history and is largely autonomous in developing a vision for its future; therefore it has a major say in development planning. The choice of the appropriate construction techniques and foundation types directly depend on the local characteristics of the permafrost and the type of buildings the communities decide to request (ex. single vs multiple dwellings, community buildings, schools, etc.).

Some construction techniques specially adapted to permafrost are currently applied in the North. For instance, adjustable posts on pads is a foundation design broadly used in northern villages. Ground temperatures measured underneath these types of foundations showed that they are efficient construction techniques in the face of permafrost warming (Allard et al. 2004). Correctly designed piles is another technique that has proven to be efficient for bigger buildings such as schools and hospitals, as well as thermosyphons which are mostly used for garages built on slab-on-grade foundations. Another known technique rarely applied in Nunavik and Nunatsiavut is duct-ventilated compacted fill foundations (i.e. pads ventilated by metal pipe-ducts) (Andersland and Ladanyi 2004). The costs largely vary from one building type to another and the best construction method used. Consequently, to minimize the potential impacts of thawing permafrost under existing and future infrastructures and to adopt affordable solutions and management strategies, a good knowledge of the permafrost conditions in the northern communities is required.

A research project conducted in 11 Nunavik communities (i.e. where permafrost is present) by CEN's team (Centre d'études Nordiques, Allard et al. 2007) provided

preliminary maps of spatial variability of permafrost conditions in the communities and their surroundings and allowed the general identification of favourable zones for expansion as well as of problematic zones where thaw settlement and other difficulties are to be expected. This project developed a general mapping approach based on the correlation between geomorphological features and surficial geology perceptible on aerial photographs and high resolution satellite images and the type of ground ice found (summarized in Table 2). These maps (Figure 10) now constitute a management tool available to help communities to orient their management strategies. However, since this mapping method was mainly based on observation and interpretation of geomorphologic features, and because ice contents can vary greatly locally within the same geomorphological unit (as showed by L'Hérault 2009), these maps only represent a starting point and a more advanced characterization program is now underway under the Regional Adaptation Collaboratives (RAC) program of Natural Resources Canada administered in Québec by Ouranos, in partnership with the Kativik Regional Government and four communities. This program also involves knowledge transfer and training of Northerners on practical permafrost issues by the Kativik Regional Government.

Case Study : Salluit

Among all Nunavik and Nunatsiavut communities, Salluit is the most documented case in terms of permafrost. It exemplifies the complexity of the expansion and management of communities on sensitive permafrost. Salluit currently accommodates approximately 1300 inhabitants and its population is expected to grow to 1700-2000 individuals by 2025 (Institut de la statistique du Québec). In 2008, the housing numbers were already showing a shortage of 131 units (Allard et al. 2009). However, Salluit must expand in a difficult and restrictive geomorphological context (Pluritec 1974). Most of the community is confined to a deep valley limited by steep cliffs (L'Hérault 2009). Flat expanses of land are limited and are usually underlain by sensitive ice-rich sediments such as saline

marine clays or tills. Rocky terrain with gentle slopes is also limited in extent. On ice-rich permafrost, even gentle slopes are unstable. Facing this complex situation, provincial authorities decided in 2007 to bring together permafrost and climate specialists, economists, engineers, architects and managers from various government levels in order to explore possibilities and develop the best management and expansion strategies with a concern for integrating the expected effects of climate warming on the stability of permafrost and the frequency of geomorphological hazards associated with ground instability.

This project generated substantial as well as useful knowledge on climate and permafrost within and around Saluit. Climate and ground thermal profiles monitored since 2002 allowed for an understanding of climate conditions triggering permafrost processes such as thaw settlement, active layer failures and thermal erosion. This information helped in orienting the development and validating modeled projections of permafrost behaviour according to different climate scenarios. This project also generated technical and engineering solutions to maintain and/or restore permafrost conditions suitable for construction. For instance, an experimental pad was designed and installed in a former degraded terrain in attempt to restore the permafrost. Monitoring shows that the permafrost is returning to its near-natural state and that it shall aggrade further beneath this experimental pad, therefore providing stability for many years to come.

Expansion needs required the creation of a detailed map of permafrost conditions. In total, over 100 boreholes were drilled between 2002 and 2008. Maps of the surficial geology and depth of the bedrock, and maps of permafrost conditions were produced (i.e. ground ice contents and cryostructure for a deposit of given grain size soils and expected behaviour upon thawing). Ice content varies greatly at the local scale, and consequently, it is necessary to produce maps as precise as possible that will be essential management tools when the time comes to invest in new developments. A major outcome

of this project has been the development of risk management maps resulting from the integration of all the geographic information produced (Figure 11). These maps are based on a risk index integrating three layers of information: slopes, permafrost conditions and identified zones of severe constraints for construction (e.g. such as wetlands, ice wedge polygon networks, concentrations of frost boils and areas of active layer detachment scars). Afterwards, the risk index allowed for production of maps of construction potential where, for any given terrain category, the suitable foundation types according to the existing engineering solution guidelines are proposed (see map legend of Figure 11).

Maps of construction potential represent a powerful and useful tool intended for policy-makers and managers for generating regulated urban management plans that will ensure quality and sustainability of northern infrastructures.

6.4.3 Airports and roads: managing the costs of building on unstable ground

Northern communities are dispersed over a vast territory and transportation of both people and goods is carried out by sea and air. The heaviest goods are brought North by ship but air transportation provides flexibility, speed and year-round services that are crucial to northern communities. Air transportation is the main means of travel between northern communities and provides the principal link with southern regions. Most airports and access roads were built during the 1980s and early 1990s at a time when climate was considered stable and, indeed, was even cooling in the Eastern Subarctic (Wang and Allard 1995, Allard et al. 1995). As air temperatures increased during the 1990s and 2000s, permafrost degradation problems like ground instability and thaw settlement started to affect runways and access roads. In severe cases, depressions in runways due to thaw settlement have raised safety issues. Maintenance rates had to be intensified, which increased significantly the operating costs. Research involving scientists and governments

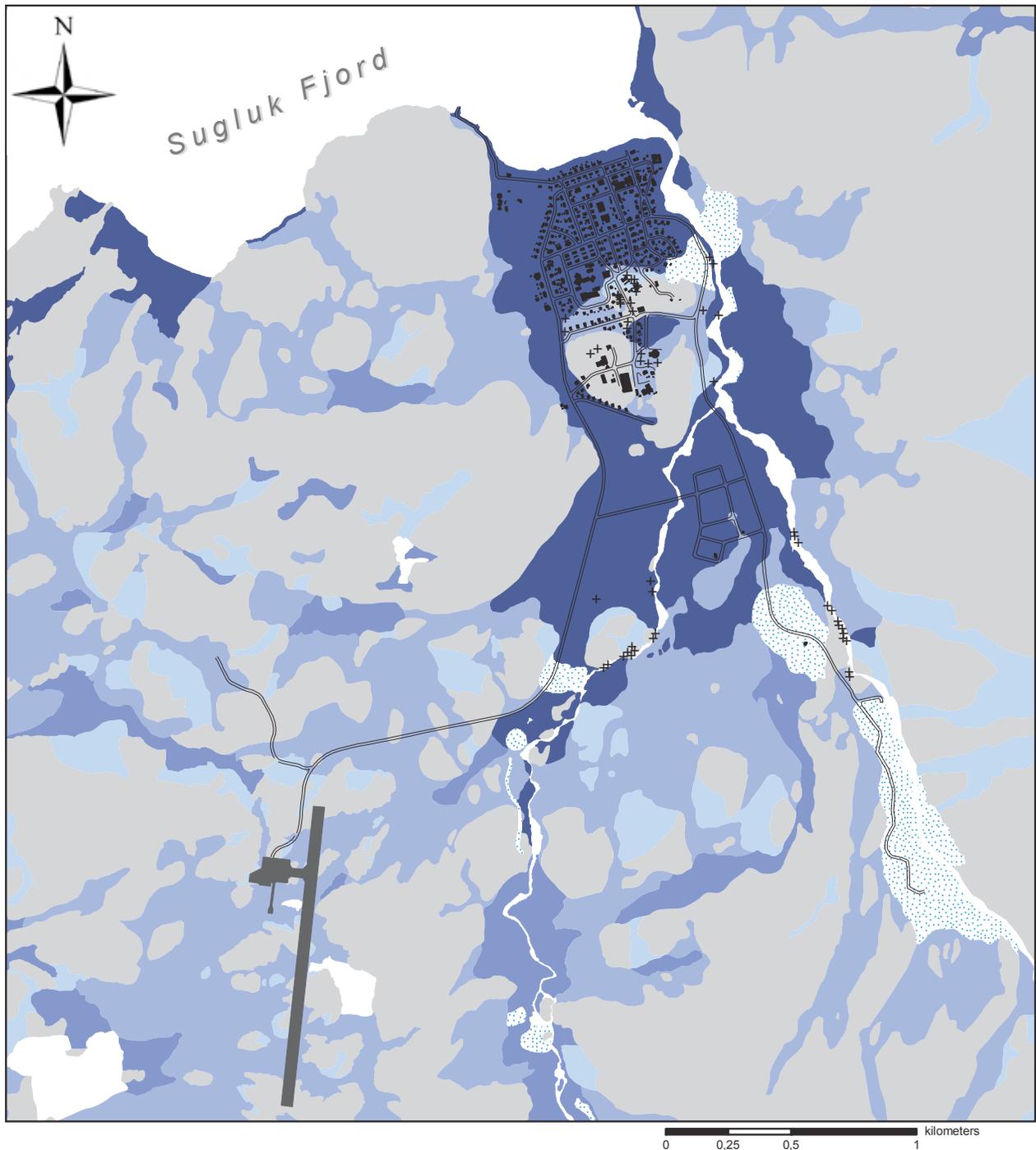


Figure 10. Map of permafrost conditions (ice content) in Salluit according to the spatial variability of surficial geology and geomorphologic features. Modified from Allard and L'Hérault 2010.

Permafrost conditions

Bedrock and superficial deposits with no or little ice content

- + Isolated rock outcrops

1a

Massive bedrock of Precambrian age with a very sparse thin and discontinuous cover of sand, gravel and boulders (till). Active layer depth varies across the terrain from 2.5 to 3.5 m.



Layered sand and gravel deposits. Contain pore ice and occasional ice lenses in fine sand and silty layers.

Ice-rich permafrost in superficial deposits

2a

Thin cover of sand, gravel and boulders over bedrock. The thickness of the deposits is generally less than 2 m. Topography is controlled by bedrock. Scattered rock outcrops. Active layer depth varies across terrain from 1.5 to 2.5 m. Thaw settlement of permafrost restricted to the superficial cover. Volumetric ice contents in the surface sediments vary from 15 to 70 %.

2b

Thick cover of sand, gravel and boulders (till) over bedrock. The thickness of the deposits is generally more than 2 m with occasional bedrock outcrops. Estimated maximum depth to bedrock is about 8 m. Frost boils are present and gelifluction lobes occur on slopes. Subject to thaw settlement. Active layer depth varies from 1.5 to 2.5 m across the terrain. Volumetric ice contents vary from 15 to 70 %.

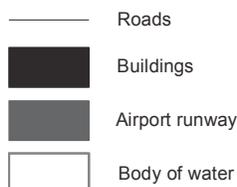
2c

Thick cover of Quaternary sediments, poorly drained with a peat cover. Thickness is more than 2 m and can be as much as 6 m. The deposits are ice rich and a polygonal network of ice wedges is present. Active layer depth varies from 50 cm to 2.5 m.

2d

Fine-grained sediments of marine origin. Occasionally covered by a thin layer of sand or gravel. Subject to differential thaw settlement and to active layer failures on slopes. Often surface is pitted with frost boils. Active layer thickness varies in the terrain from 50 cm to 1.2 m. Volumetric ice content in the permafrost is constantly above 30% and may be as high as close to 100%.

Infrastructures



Projection: MTM NAD 83 zone 9
Updates: Allard M. and L'Hérault E. (avril/april 2010)

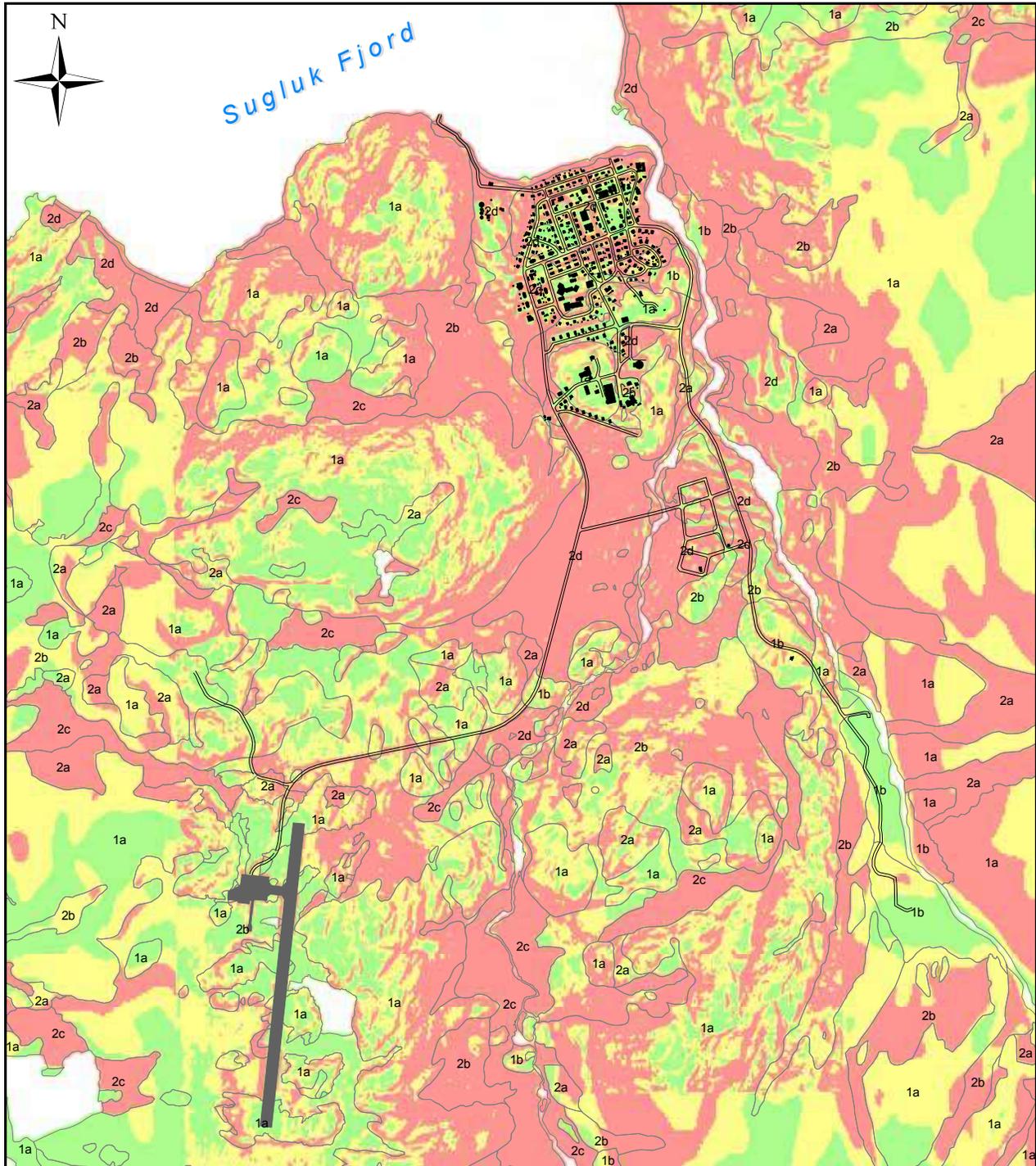


Figure 11. Risk management map for potential construction development in Salluit. Derived from Allard and L'Hérault 2010.

Construction potential and foundation design adapted to permafrost conditions and slopes

Bedrock and superficial deposits with no or little ice content

- 1a** - Massive bedrock of Precambrian age with a very sparse thin and discontinuous cover of sand, gravel and boulders (till). Active layer depth varies across the terrain from 2.5 to 3.5 m.
- All types of northern foundations. Adaptations to rugged topography are often necessary.
- Terrain manageable for construction (slope < 7.5°).
 - Terrain manageable for construction but may require significant earthwork (slope between 7.5 and 15°).
 - Terrain unsuitable for construction (slope > 15°).

- 1b** - Layered sand and gravel deposits. Contains pore ice and occasional ice lenses in fine sand and silty layers.
- Northern foundations on adjustable post and pad or on piles. Buildings with slab-on-grade foundations might need elaborated techniques to retain permafrost in its frozen state (ex.: thermosyphons).
- Terrain manageable for construction (slope < 5°).
 - Terrain manageable for construction but may require significant earthwork (slope between 5 and 10°).
 - Terrain unsuitable for construction (slope > 10°).

Ice-rich permafrost in superficial deposits

- 2a** - Thin cover of sand, gravel and boulders over bedrock. The thickness of the deposits is generally less than 2 m. Topography is controlled by bedrock. Scattered rock outcrops. Active layer depth varies across terrain from 1.5 to 2.5 m. Thaw settlement of permafrost restricted to the superficial cover. Volumetric ice contents in the surface sediments vary from 15 to 70 %.
- Deep northern foundations on the underlying bedrock applicable (ex.: Pile foundations). Adjustable post and pad foundations also feasible. Buildings with slab-on-grade foundations need elaborated techniques of terrain preparation (ex.: removal or pre-thaw of frozen sediments and consolidation).
- Terrain manageable for construction (slope < 4°).
 - Terrain manageable for construction but may require significant earthwork (slope between 4 and 8°).
 - Terrain unsuitable for construction (slope > 8°).

- 2b** - Thick cover of sand, gravel and boulders (till) over bedrock. The thickness of the deposits is generally more than 2 m with occasional bedrock outcrops. Estimated maximum depth to bedrock is about 8 m. Frost boils are present and gelifluction lobes occur on slopes. Subject to thaw settlement. Active layer depth varies from 1.5 to 2.5 m across the terrain. Volumetric ice contents vary from 15 to 70 %.
- Pile foundations feasible but require deeper drill-holes for pile driving. Adjustable post and pad foundations also feasible. Buildings with slab-on-grade foundations need elaborated techniques to retain permafrost in its frozen state (ex.: thermosyphons). Steeper slope sections may be affected by gelifluction and may require specific foundation design.
- Terrain manageable for construction (slope < 4°).
 - Terrain manageable for construction but may require significant earthwork (slope between 4 and 8°).
 - Terrain unsuitable for construction (slope > 8°).

- 2c** - Thick cover of Quaternary sediments, poorly drained with a peat cover. Thickness is more than 2 m and can be as much as 6 m. The deposits are ice rich and a polygonal network of ice wedges is present. Active layer depth varies from 0.5 to 2.5 m.
- Problematic terrain to be avoided.
- Problematic terrain unsuitable for construction.

- 2d** - Fine-grained sediments of marine origin. Occasionally covered by a thin layer of sand or gravel. Subject to differential thaw settlement and to active layer failures on slopes. Often surface is pitted with frost boils. Active layer thickness varies in the terrain from 0.5 to 1.2 m. Volumetric ice content in the permafrost is constantly above 30% and may be as high as 100%
- Adjustable post and pad foundations. Buildings with slab-on-grade foundations need elaborated techniques to retain permafrost in its frozen state (ex.: thermosyphons).
- Terrain manageable for construction (slope < 1°).
 - Terrain manageable for construction (slope between 1 and 2°).
 - Terrain unsuitable for construction (slope > 2°).

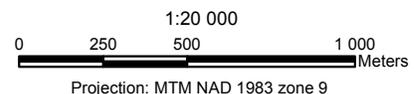
Infrastructures

Roads

Buildings

Airport

Water bodies



Box 2. Puvirnituk runway case study: an engineered adaptation design

Puvirnituk is located on the Hudson Bay coast of Nunavik. The airstrip construction ended in 1992. It was decided in 2008 to extend the runway in order to accommodate larger aircrafts, for instance Air Inuit's Boeing 737 and the Government of Québec's Challenger ambulance aircraft. Along most of its length, the runway embankment lies on bedrock with the exception of a 200 m long section that crosses a small valley floored by ice rich marine clay. By 2005 a depression of about 20 cm had appeared in the runway, near its south side, at this valley crossing (Beaulac and Doré 2005). The embankment in this section of the runway is 8 m thick. Wind drifting used to accumulate a deep snowbank against the embankment side, with the result that permafrost had locally thawed to a depth of 8-10 m beneath the toe of the embankment, which was generating the observed settlement. An additional heat source was water flowing through the runway from a little stream percolating into the embankment on the north side and seeping out at the toe of the embankment on the south side, thus locally enhancing permafrost thaw. The clay was sampled by drilling and coring to a depth of 15 m. Temperature measurements and a seismic refraction survey (MASW: Modal Analyses of Surface Waves) resolved the thawed zone at the foot of the embankment. As the elongation of the runway offered an opportunity to mobilize a contractor and as future runway safety was calling for corrective measures, a custom engineered berm and a specifically designed ground cooling system were put in place to stabilize the runway sides. The heavy berm is a counterweight that strengthens the thawed clay underneath and prevents it from liquefying and sliding. The berm is made of screened, decimeter-size, rock fragments that allow air to flow through in order to cool the underlying ground in winter and will, hopefully, favour the recovery of permafrost towards the surface. This set up is called a convection berm. Air ducts at the foot and at the top of the convection berm facilitate the convective effect of cold air flow through the stones to improve the cooling efficiency. The flow of water entering on the north side of the runway was diverted by digging a new ditch, and a new, albeit smaller, convective berm, was built on this side in order to help refreeze the ground and seal the embankment. The final installation has been equipped with slope movement and temperature sensors and its performance is currently being monitored (Boucher and Grondin 2010).



was conducted to provide geotechnical information and detailed information of processes affecting runways and roads as well as to organize maintenance practices.

The increasing air traffic and the larger aircrafts the airlifters now want to use require longer runways and larger parking aprons. Airport expansion calls for improved permafrost knowledge and inclusion of prediction of impacts of climate warming in the design of expansion projects. A recently terminated research program lead by Ministère des Transports du Québec applied a methodological approach similar to the one for villages; it aimed to provide adaptation strategies for eight airports deemed more sensitive because of specific permafrost conditions (Inukjuak, Puvirnituq (see inset box 2), Akulivik, Salluit, Quaqtaq, Kangirsuk and Tasiujaq, L'Hérault et al. 2012). A similar research project is supported by Transport Canada for the paved Kuujuaq runway, which is the region's hub.

Despite the technical, engineering and managerial advances, further research is still needed to better assess the expected thaw settlement rate and amplitude, as well as potential effects of increased ground wetness and seepage as the active layer deepens. This will help with planning longer term strategies for the airports built on sensitive permafrost areas.

6.5 Conclusion

Permafrost degradation is seriously affecting the natural environment. The landscape is changing through thermokarst formation that takes place primarily in the discontinuous permafrost zone and through thicker active layers and more frequent slope processes in the continuous zone. Northern residents are affected as vegetation, water bodies and soil drainage are changing, which has an impact on resources traditionally available such as berries that are shaded in the understory of shrubs that expand in thermokarst hollows (see chapter 4). These wide scale ecosystem changes affect animal populations as well,

such as caribou feeding habits and migration patterns (see chapter 9). Sediment and carbon release from thawing permafrost have the potential to affect water quality thereby affecting fish populations and water intakes for human consumption. The modern built environment is particularly affected. Transportation infrastructure is being studied and adaptive solutions are developed, applied and tested. Now necessary for the protection and optimization of the major investments in housing and infrastructures, the urban planning of communities calls upon better permafrost condition maps and improved prediction of permafrost behavior.

Collection and organization of permafrost/geoscience information in geographic information systems (GIS) allows for the integration of essential knowledge and provides a very useful tool for establishing situation diagnostics, for sharing information with stakeholders and communities, and for supporting multidisciplinary decision making for land use planning. New technologies such as high precision LIDAR imaging that provide more detailed and precise DEMs are now being used. Another forthcoming technology, is interferometric analysis of satellite-borne radar data that makes it possible to monitor subtle topographic changes over the years and therefore detect permafrost related changes both in the natural and constructed environments (Liu et al. 2010).

Further applied research should include developing a better understanding of the permafrost-processes/climate system and producing risk assessments based on climate predictions. Specific advances will be more and more necessary in the management of surface drainage and groundwater flow around thaw lakes and beneath man-made infrastructures as the role of convective heat transfer appears to play a major role in permafrost thawing. This still poorly quantified process recurs everywhere in the landscape. Indeed, final permafrost degradation around 0°C appears to be in great part under the influence of unfrozen water content and heat brought by groundwater flow. The principal adaptive measure lies in adapting foundation types to mapped permafrost conditions in

order to ensure a prolonged service life of buildings. In this respect, Salluit now appears as the first major case where difficult permafrost and topographic conditions have led to the creation of a model approach from which lessons are being learned and extended to other northern communities.

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Chapter 7. Arctic charr in a changing climate: predicting possible impacts of climate change on a valued northern species

Lead authors

Michael Power¹, Brian J. Dempson², Bill Doidge³, Wendy Michaud¹, Louise Chavarie¹, James D. Reist⁴, François Martin³, and Adam E. Lewis³

¹Department of Biology University of Waterloo, Waterloo, ON; ²Fisheries and Oceans Canada, Science Branch, ³Nunavik Research Centre, Makivik Corporation, Kuujuaq, Nunavik; ⁴Fisheries and Oceans Canada, Central and Arctic Region, Winnipeg, MB

Abstract

Arctic charr is considered a generalist species, exists in a wide variety of habitats throughout the eastern Subarctic and adopts a number of different life-history strategies, e.g., lake residency and anadromy. They are considered vulnerable to the predicted impacts of climate change because of their preference for coldwater conditions. Because of the ecological differences among populations it is important when considering the potential consequences of climate change on Arctic charr that distinctions are made between populations on the basis of anadromy and freshwater residency. The few environmental influence-based studies of Arctic charr that exist in Canada indicate clear environmental influences on Arctic charr populations, with temperature and precipitation being the most important as a result of their respective effects on fish metabolism and opportunities for acquiring surplus energy for growth. Studies have shown that lake resident Arctic charr vary in size and growth rate along latitudinal gradients largely as a result of environment-driven variations in lake water temperatures. Arctic charr that migrate to sea do not show the same pronounced variation in size or growth along the latitudinal gradient because of the moderating influences of sea surface temperatures. However, studies of marine migrants have shown that Arctic charr are nevertheless directly affected by inter-annual variations in local marine temperatures and that differences in growth patterns could be linked to ecosystem shifts such as changes in marine thermal regimes associated with predicted climate changes. Similar, although minor, effects have been shown for changes in fecundity in lake resident and anadromous Arctic charr along the same latitudinal gradient. In a warming environment lacustrine Arctic charr are the most likely to be impacted by predicted summer temperature increases, with effects being most acute at the southern edge of the distribution where the warming will be greatest and competition from other salmonid fish species better able to cope with warmer temperatures will be most intense. Warming temperatures will facilitate range extension of potential competitor fish species that are likely to force Arctic charr in many lakes to become restricted to the deeper parts of the lake. In contrast, anadromous Arctic charr may reduce their period of sea-residency, with the experience of limited anadromy in the south suggesting that marine migrations may be significantly reduced or eliminated as temperatures increase. Such changes will have profound impacts on Inuit that rely on Arctic charr as a significant source of dietary protein. To some extent such impacts may be mitigated by proactive environmental management as Inuit-led stream enhancement and population introductions have shown. Nevertheless, a key challenge facing resource managers is the continued collection and documentation of harvest-related impacts on Arctic charr. Given the few detailed harvest studies that do exist, it is currently difficult to design and implement the adaptive management strategies necessary to ensure the sustainability of Arctic charr fisheries in the face of climate change and other human driven development impacts. Key knowledge gaps concerning the biology (e.g., variations in age-at-maturity) and population dynamics (e.g., mortality rates) inhibit our abilities to accurately predict climate change impacts on Arctic charr and suggest there is considerable value in collecting long-term data sets specific to the species.

7.1 Introduction: General Considerations of Possible Climate Change Impacts

Based on southern studies, the concerns about climate change (e.g., Brown et al. 2011, chapter 2 of this report) and fish include: 1) significant reductions in the duration and extent of ice cover; 2) an earlier disappearance of the 4°C isotherm; 3) measurable declines in dissolved oxygen and slight hypolimnetic anoxia in shallower basins (Blumberg and Di Toro 1990, Schertzer and Sawchuk 1990); 4) and loss of suitable thermal habitat associated with lake warming that will differentially affect species within lacustrine fish communities (Magnuson et al. 1990).

Although many of the same concerns exist for northern fishes (e.g. Reist et al. 2006a), relatively less attention has been paid to understanding the possible effects of climate change on resident fish communities in the Canadian sub-Arctic. With respect to northern freshwater fish populations, the Intergovernmental Panel on Climate Change (IPCC) concluded that fish populations and habitats in streams and rivers at the margins of their geographic dis-

tributions (e.g., Arctic and Subarctic species) would be among the first to experience the effects of climate change. Subsequent reports, including the Arctic Climate Impact Assessment (ACIA 2005), the most recent IPCC reports (IPCC 2001, 2007) and projections provided in chapter 2 of this report (Brown et al. 2011) have validated and extended those predictions. Among the most locally important fish species in northern Québec and Labrador likely to be affected by climate change is Arctic charr (*Salvelinus alpinus*), which many communities in the region rely on as an important country food.

Modelled predictions of climate change in northern Canada suggest local warming will be more important relative to the rest of the continent. Temperature increases over land are expected to exceed those over the ocean (IPCC 2007), with the result that the physiological impacts on fish are expected to be biggest in fresh water (Jonsson and Jonsson 2009). While percentage reductions of ice thickness are likely, they are expected to be small and, depending on the changed spring runoff hydrograph, spring break-ups may become more or less benign (Beltaos and Prowse 2000). Nevertheless, alterations in the timing and magnitude of seasonal changes in aquatic ecosystems will invariably affect existing patterns of life-history phenolo-



gies, including the timing of migration, spawning, hatching and emergence events. Thus, approaches to studying the effects of climate warming on fish should take into account how the combination of physical factors that affect habitat suitability (e.g., temperature, flows) will also affect the myriad of fish behaviours. These behaviours have evolved to ensure occupancy of specific niches and have resulted in local adaptations that undoubtedly play a role in maximizing species reproductive fitness in harsh northern environments.

Temperature has an important environmental influence on fish. For example, temperature defines the lethal limits for fish, controls the rate of growth as well as other physiological processes, establishes the limits of metabolic rate within which fish can respire, and influences habitat selection. Fish possess little, or no control over body temperature. As a result fish body temperature is linked to the temperature of the surrounding environment. The options available to fish facing temperature changes are to move, or remain and cope. When temperature changes occur on a time scale significantly shorter than the life span of the organism, an individual may respond by altering habitat selection or by varying physiological rates (Clarke 1996). When temperature changes occur on a time scale significantly longer than the life span of a fish, fish may shift distributional range, adjust to the changing environment through some form of evolutionary adaptation, or go extinct (Clarke 1996).

Noting the deficiencies in our knowledge of the thermal biology of many northern fishes, we examine the possible effects of climate change on fish in northern Québec and Labrador generally, with particular emphasis on one of the most valued species, the Arctic charr (*Salvelinus alpinus*). The Arctic charr serves as the key focus of the discussion because of its importance as a harvestable renewable resource for Inuit. Food resources obtained from Arctic charr can be substantial and are extremely important for meeting the nutritional needs of Inuit and for contributing to both the social and economic fabric of northern communities. To that end, Arctic charr were identified by Inuit

as a species of concern. Much of the ArcticNet research on Arctic charr was conducted in collaboration with Inuit organizations with a view to improving the available information about the species and its likely responses to climate change. In this chapter we review the available scientific literature on Arctic charr as well as knowledge of the influence of temperature on life-history strategies as a means of inferring possible responses to climate change. We use detailed long-term monitoring data available from Nain, Labrador, to examine possible stock-specific responses to climate change and we conclude the chapter by commenting on existing approaches to Arctic charr management in the region and how current practices may have to be adapted in the face of climate change. The intention is to inform policy-makers about the concerns for Arctic charr in a changing environment, identify the key environmental drivers of change and suggest possible policy options.

7.2 Arctic charr and climate change impacts: predictions and knowledge gaps

7.2.1 The Generalist Arctic charr

Arctic charr are habitat generalists and may be found at appropriate times of the year in all suitable aquatic habitats (lakes, streams, rivers and the sea). Although there are fluvial and lacustrine stocks, as well as stocks in which individuals migrate between both habitats, lake occupancy dominates throughout much of the region, but particularly in northern Québec. Accordingly, lacustrine (or lake) populations have been the most studied and are the most well known. The research that has been completed on Arctic charr populations throughout their entire distributional range has tended to focus on the description of population characteristics, documentation of life-history differences and the study of genetic variability within, and among, populations (e.g. Johnson 1976, Hindar and Jonsen 1982, Johnson 1983, Griffiths 1994, Reist et al. 1995, Klemetsen et al. 1997, Adams et al. 1998). Little scientific

or traditional knowledge-derived synthesis work has focussed on defining latitudinal differences among populations or connecting observed population characteristics to large-scale environmental forcing events such as climate change. Reports in the scientific literature focussing on the physiology and physical factors influencing Arctic charr life-history strategies, however, suggest the impacts of climate change on Arctic charr populations may be significant.

Within the lakes they occupy, Arctic charr will use all habitat types (e.g., pelagic, littoral, profound), with usage dependent on the age and life-stage of the individuals and co-occurring species in the lake (Power et al. 2008). Because of the different ways in which Arctic charr use the habitats available to them, more than one life history form can be found to live in the same lake. The forms are often very distinctive, differing in body shape, size and colouration. In other instances, the forms differ subtly in appearance but are differentiated by their feeding habits (trophic ecology). Some examples exist in Canada (Reist et al. 1995, O'Connell and Dempson 2002), including a lake in Nunavik, Lake Aigneau, where Arctic charr occur in two distinctive size groups of sexually mature individuals that differ in shape and colour, live at different depths and feed differently (Power et al. 2009).

Where there are no obvious differences in form, variations in size among mature individuals often exists. Many lake populations of Arctic charr exhibit size polymorphisms in the form of bimodal length-frequency distributions dominated by peaks of smaller and larger individuals in the size-frequency distribution (Johnson 1995, Parker and Johnson 1991). In undisturbed unimodal populations, only a few individuals will typically grow to very large sizes, usually as a result of an early dietary switch to piscivory. Thus while large individuals exist in many lakes, they are generally the exception, not the rule and can be very easily removed by intensive fishing pressure. In many lakes throughout northern Québec and Labrador, differences in size critically depend on how Arctic charr use the marine environment. Those that migrate to sea will grow quickly,

whereas those that do not will grow more slowly, but may live to an older age (Johnson 1980). Populations of Arctic charr that use both lake and marine environments (anadromous populations) are numerous in northern Québec and Labrador where access to productive marine coastal margins is relatively easy. The fish returning from marine feeding are also highly valued as a food source and form the basis of important Inuit fisheries.

Arctic charr appear pre-adapted to low aggression (Power 2002) and in the face of competition from other species, will shift habitat or diet. A good example of this behaviour is in lakes where Arctic charr co-exist with brook charr and/or lake charr. In competition with these other species, Arctic charr reduce feeding competition and predation risk by ensuring non over-lapping habitat use (Fraser and Power 1989, O'Connell and Dempson 1996). The behaviour can often result in dramatic changes in the biology of Arctic charr. For example, when co-existing with lake trout, Arctic charr show faster growth rates, lower survival, and shorter life-spans in relation to co-habiting lake charr (Fraser and Power 1989). The same ability to adapt to competitive pressures is seen in the ability to adapt to the changing circumstances in which Arctic charr live. Arctic charr have been described as the most adaptable and opportunistic of the three charr species found in northern Québec and Labrador, and have relied on their flexibility and opportunism to spread more quickly and widely in the post-glacial period than either brook or lake charr (Power 2002). That same flexibility and adaptability to prevailing conditions is also seen in wide morphological variation in lacustrine Arctic charr populations (e.g., Klemetsen et al. 2003).

7.2.2 The Thermal Biology of Arctic charr

Effects of Temperature Increases on Arctic charr Growth

As early as 1964, Swift (1964) noted the detrimental effects on growth in Arctic charr of temperatures above 14°C. Jobling (1983) measured the physiological effects

Table 1. Temperature data (°C) for key salmonid fish species occurring in northern Québec and Labrador. Table data obtained from Power (1990), Elliott (1991), Baroudy and Elliott (1994), Larsson (2005), Larsson et al. (2005) and Jonsson and Jonsson (2009). The upper incipient lethal temperature defines the temperature above which fish cannot survive for significant periods of time, usually seven days. The optimal temperature for growth for each species of fish is the temperature at which fish grow fastest for a given amount of food. The range for growth defines the range of temperatures over which growth has been observed in each species of fish and the range of spawning temperatures define the temperatures at which spawning will occur.

SPECIES	UPPER INCIPIENT LETHAL TEMPERATURE	OPTIMAL TEMPERATURE FOR GROWTH	RANGE FOR GROWTH	RANGE OF SPAWNING TEMPERATURES
Atlantic salmon	27.8	15.0-20.0	5.6-22.5	2.0-10.0
Arctic charr	18.7-21.6	11.0-16.1	2.7-21.4	0.5-8.3
Brook charr	25.8	14.4-16.1	3.1-21.0	2.2-11.7
Lake charr	23.5	14.1	NA	< 6.0-14.0

of temperature on growth and found significant positive correlations up to 14°C, with sharp declines in growth thereafter. Jobling et al. (1993) also suggested that Arctic charr grow best at 14°C. Although Baker (1983) similarly reported an optimal growth temperature of about 13°C for both Labrador and Norwegian strains of Arctic charr, he also noted there could be differences among populations in the thermal optima for growth. More recently, Larsson and Berglund (1998) have extended studies of growth to include temperatures above 14°C to estimate an optimum growth temperature of 15°C for age 0+ Arctic charr and argued that within the 9-20°C range, there are no significant differences in measured growth rates among populations when fish can feed at will. Although the rate at which fish grew did not change appreciably with temperature, growth efficiency (defined as the change in weight in a defined interval of time divided by the weight of food consumed) decreased with increasing temperature, implying that increased ration was required to sustain growth rates at higher temperatures. Results suggest that Arctic charr experiencing temperatures in excess of 14-15°C for extended periods of time will encounter decreased seasonal growth patterns, with attendant effects on survival and fecundity, unless sufficient increases in ration are available to offset the increased metabolic costs of living at higher temperatures.

Comparison of critical thermal limits for Arctic charr with those of other salmonids have shown that Arctic charr is amongst the least resistant of salmonids to high temperatures, but probably the most resistant to low temperatures (Baroudy and Elliott 1994). For example, Table 1 compares critical measures of thermal performance for some of the more valued fish species in the northern Québec and Labrador region. In a comparative study of freezing resistance among five species of salmonids, Arctic charr showed the greatest resistance to freezing (Fletcher et al. 1988) and in one set of experiments with Swedish Arctic charr, Larsson et al. (2005) recorded growth at temperatures as low as 1.7°C. In several Swedish lakes, benthos has been found in the stomachs of Arctic charr actively feeding under the ice during the winter (Hammar 1998). Thus in the existing salmonid communities (Arctic charr, brook charr, lake charr and Atlantic salmon) common throughout the northern Québec and Labrador region, Arctic charr are the most likely to be negatively affected by predicted summer temperature increases (e.g., Brown et al. 2001) because of previous adaptation to colder environments. This is most acute at the southern edge of the distribution where the temperature warming is likely to be greatest, and competition from salmonids better able to cope with warmer temperatures is likely to become most intense.

Using Latitudinal Relationships to Understand Climate Change Impacts on Arctic Charr

Differences among populations by latitude provide a convenient means of predicting how fish may respond to climate warming. By comparing populations of the same species along a latitudinal gradient, scientists can form opinions about what may happen to fish species as the climate warms in the north. As a result, a fair amount of recent scientific effort has been put into identifying and studying relevant latitudinal gradients for many of the fish species. Findings have shown differences among populations in the critical thermal maxima for many species (e.g., Fields et al. 1987). Not all studies agree, as some have argued there is little support for the hypothesis that variation in fish growth rates reflects thermal adaptations to their home stream (Jonsson et al. 2001). For example, Larsson et al. (2005) compared growth performances of Arctic charr from 11 European populations and found no geographical or climatic trend in growth performance.

North American studies using data from the northern Québec and Labrador region contrast with European findings. Using biological data from 66 populations of Arctic charr from eastern North America, Chavarie et al. (2010) examined the effect of latitude on the size and growth rate of three forms of Arctic charr: anadromous, normal sized lacustrine and dwarf lacustrine (abnormally small charr that rarely exceed 25 cm when mature). The paucity of data sets for dwarf lacustrine populations, defined as those in which maximal observed fork-length did not exceed 22 cm, precluded definitive conclusions about the effect of latitude, as a proxy for temperature on dwarf populations typically found in homothermic environments at the bottom of lakes. Among anadromous and normal sized lacustrine population, length-at-age declined with latitude and age-specific growth rates varied with latitude.

Figure 1 plots some examples of latitudinal gradients in size-at-age and growth rate for normal lacustrine and anadromous populations at ages six and ten from the study populations sampled in eastern North America.

Among anadromous populations, the variation in size with latitude varied by age, the greatest variation seen in younger ages and growing progressively less important as fish aged. Among normal lacustrine fish, the effect of latitude on growth was evident and similar in all studied age-classes. Thus, growth rate appears to increase marginally across latitudes, with lacustrine fish in the north growing somewhat faster than those in more southerly locations (Chavarie et al. 2010). Results for anadromous fish were less conclusive. The effects of latitude on growth rate provide a reasonable explanation of the data for some of the older fish (age 10–12) but not for younger ones (<10).

Overall, results of this study provide some evidence for latitudinal compensation in the growth of normal lacustrine Arctic charr, but questionable evidence of the applicability of the counter-gradient hypothesis for anadromous populations. Contrasting results by population type may depend on the extremities of the thermal environments experienced by lacustrine and anadromous populations. For example, anadromous populations use a common thermal environment largely influenced by the Labrador Current and generally experience less of a difference in thermal habitat as a function of latitude than lacustrine populations (Chavarie et al. 2010). As with all retrospective analyses, conclusions from the study only help us gain insights into what has happened on the coast, while lake dwelling charr have shown a greater sensitivity to temperature fluctuations than anadromous charr. Future climate-driven impacts on anadromous Arctic charr in the region, therefore, will be critically linked to changes expected in Labrador sea surface temperatures.

Differences in European and North American studies and conclusions concerning the implications of latitudinal differences in size-at-age and growth rates, highlight the need for further focused regional studies of the thermal biology of key species, particularly of the increased difficulties associated with predicting the long-term effects of temperature increases where counter-gradient variation exists (Jobling 1997). For example, one effect associated with climate change and the increased opportunity

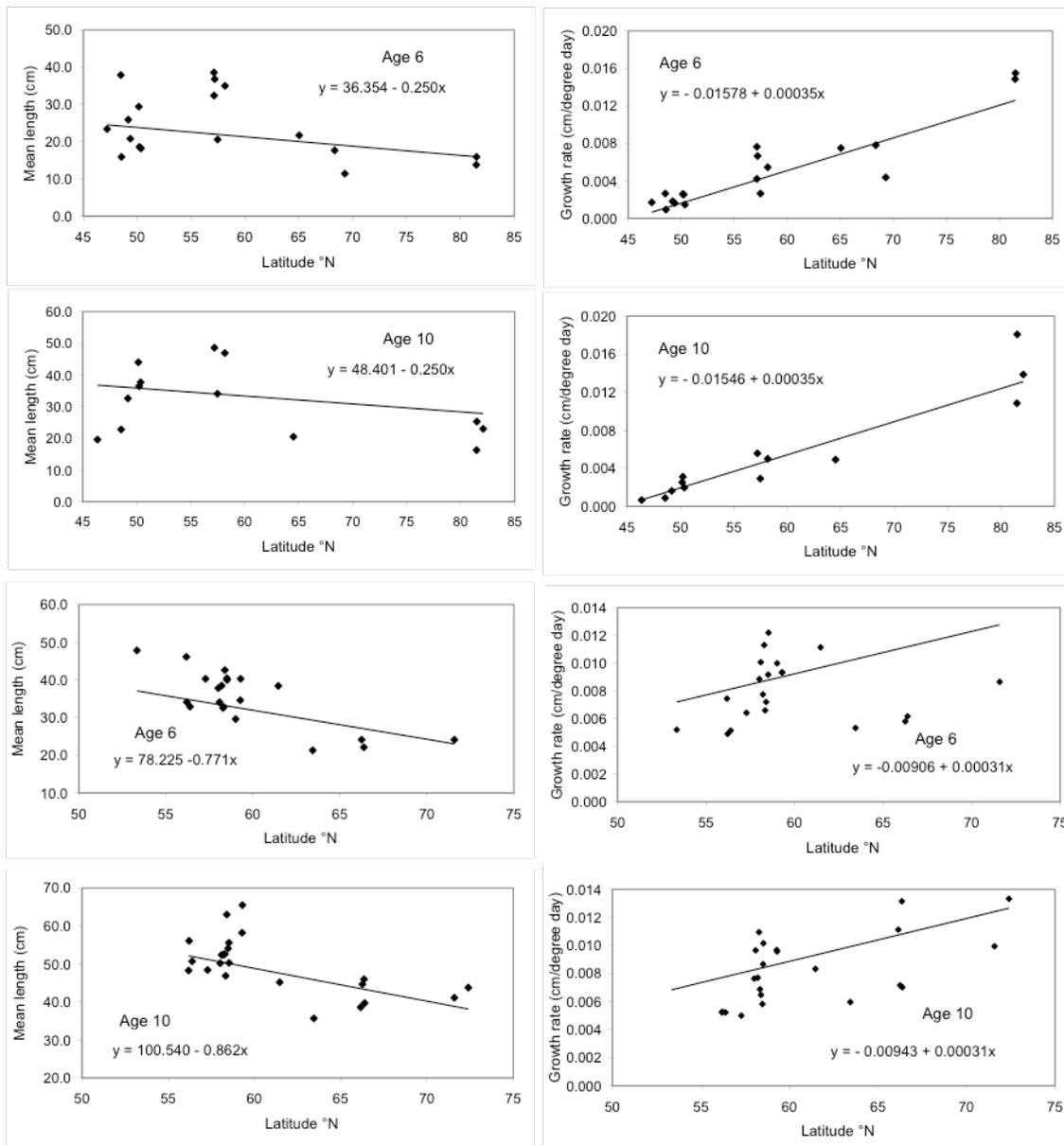


Figure 1. Scatter plots of mean fork length at age (left column) or mean growth rate at age (cm/cumulative degree-days; right column) versus latitude for age 6 and 10 lacustrine (top of two rows of plots) and anadromous (bottom two rows of plots) Arctic charr from eastern North America. Adapted from Chavarie et al. (2010).

for growth may be a reduction in the incentive for seaward migrations, provided sufficient food resources are available in the lake. Such a change in migration patterns would have obvious consequences for Inuit harvest ac-

tivities, which are based on coastal interception fisheries. Better understanding patterns of growth differences among Canadian populations and further in-situ studies of the thermal biology of lake resident populations from

Table 2. Summary of environmental influences on Nain Arctic charr biological characteristics of mean age, length and weight at catch. The direction of the environmental influence and its rank in terms of its importance for affecting the listed biological characteristic are given. Lagged variables are measurements of precipitation or temperature from previous years found to have a critical affect on Arctic charr; typically in the first year of life when Arctic charr mortalities are high.

ENVIRONMENTAL VARIABLE	MEAN AGE		MEAN LENGTH		MEAN WEIGHT	
	DIRECTION OF EFFECT	RANK	DIRECTION OF EFFECT	RANK	DIRECTION OF EFFECT	RANK
Spring temperatures			Negative	2		
Summer temperatures			Positive	1		
Lagged summer temperatures			Positive	4	Positive	3
Winter temperatures			Positive	3		
Lagged summer precipitation	Negative	1			Positive	2
Lagged winter precipitation	Negative	3				
Summer sea surface temperatures	Negative	2			Positive	1

a variety of locations are required before it can be conclusively established that possible intra-specific genetic differences in growth are likely to favour or perturb the continuation of existing patterns of anadromy.

Lessons Learned from Long-term Studies at Nain

Few attempts have been made to relate changes in biological characteristics of Arctic charr to environmental variables such as temperature and precipitation, which

are likely to be significantly affected by climate change. Using the biological data available from long-term monitoring of the native fishery for Arctic charr at Nain, Labrador (e.g., Dempson 1995), Power et al. (2000) examined the importance of environmental variables as explanations of observed variability in the long-term (1977-97) catch biometrics (length, weight and age) of anadromous Arctic charr (see Table 2). Landings from the Nain fishery are drawn from the Nain stock complex, which consists of all fish in an inshore zone centred on Nain, Labrador, and adjacent bays (Dempson and Kristofferson 1987, Dempson 1995). Results of detailed statistical analyses indicated mean age-at-catch of fish from the Nain fishery varied significantly with both summer and winter precipitation and average summer sea-surface temperature. The length (cm) characteristics of captured fish were also found to vary significantly with temperature, while the weight (kg) characteristics of captured fish varied with both temperature and precipitation. A summary of the temperature and precipitation periods found to be most critical for observed changes in the age, length or weight of Arctic charr are given in Table 2, as is an indication of the direction of the effect. Precipitation variables were linked with changes in nutrient dynamics that worsened or improved the productivity of the environment in which charr fed



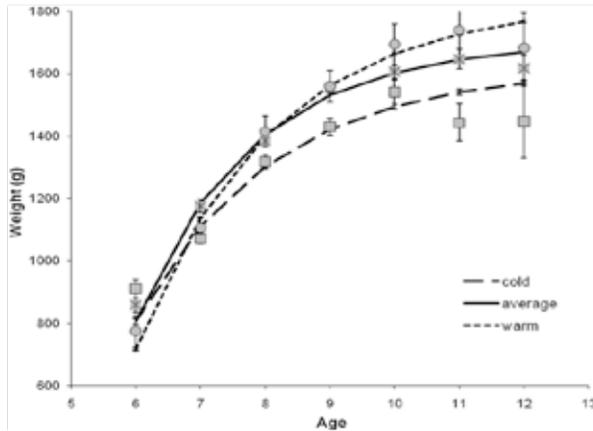


Figure 2. Estimate growth models for Nain Arctic charr under differing lifetime temperature scenarios. Fish were grouped by date of birth (cohorts) and the cohorts were grouped into those experiencing above and below average temperature regimes over the course of their lives. Temperature groups were divided as follows: “average” cohorts were within \pm one standard deviation of the mean number of cumulative degree-days experienced by all cohorts. Warm and cold cohorts exceeded the \pm one standard deviation rule. Points represent mean weight-at-age \pm 95% confidence interval for each group.

and grew. Temperature variables were linked with the implications of temperature for changes in fish physiology that determined overall increases in length or weight, often in critical growing periods such as the first year of life. Study results point to the importance of environmental variability at critical life-history stages. They suggest an important role for the environment in determining the dynamics of exploited Arctic charr populations through the effects that environment exerts on the measured stock age, weight and length characteristics that correlate with eventual spawning success (Power et al. 2000).

Michaud et al. (2010) used the same Nain data to extend the initial analysis of Power et al. (2000) to examine how cumulative life experiences might be influenced by environment. By sorting fish by their natal year (cohorts), Michaud et al. (2010) studied how different life experi-

ences that differ with respect to above or below average temperatures might affect fish growth. Results of the study (e.g., Figure 2) found that short-term temperature fluctuations can have significant impacts on the growth patterns of anadromous Arctic charr stock. Within a single growing season, mean summer temperature was not significantly related to inter-annual changes in length and was only weakly related to inter-annual changes in weight among cohorts. When adjusted to account for differences in age, cumulative temperature experiences explained over 80% of the variation in length- or weight-at-age among cohorts. In the context of regional predictions for climate change, temperature as represented by cumulative degree days is expected to increase by 30-60% in Nunavik and 30-65% in Nunatsiavut (Brown et al. 2011). Coupled with climate predictions, the results suggest the influence of past environmental conditions on growth history may and will have a more important impact on the biological characteristics of an Arctic charr population than temperatures experienced in a single growing season. Comparisons of growth among cohorts experiencing similar temperature regimes also suggested that differences in growth patterns could be linked to ecosystem shifts (i.e. changes in marine thermal regimes) associated with climatic changes.

Although significant relationships between temperature and growth were found, differences in growth patterns among cohorts may reflect coincident changes in prey availability, fish behaviour, and/or exploitation that occurred during the period of study. Combinations of these factors have been associated with changes in the distribution and productivity of other species in the Northwest Atlantic region (Mann and Drinkwater 1994, Atkinson et al. 1997, Rose et al. 2000, Carscadden et al. 2001, Sinclair et al. 2002). The agreement among study results suggest future climate-driven changes in the environment will have direct physiological impacts on the growth patterns of anadromous Arctic charr and important indirect impacts on growth associated with ecosystem responses to climate-driven changes in key environmental variables (e.g., temperature as detailed in chapter 2, Brown et al. 2011).

Results also highlight the fact that significant changes in growth can occur in relatively short periods of time. As the management implications of the various factors (e.g., temperature, changes in food supply) considered here are vastly different, it is clear that more research is needed to understand the complexity of possible interactions among the environmental factors that influence the growth patterns of Arctic charr in the wild.

How Other Fish Species May Affect Arctic charr in a Warming Climate

Among the salmonids of northern Québec and Labrador, the response to predicted temperature changes (e.g., chapter 2 Brown et al., 2011) is very likely to track physiological preferences for warmer waters. Several species present in southern areas, such as native Atlantic salmon and Brook charr and introduced brown trout and rainbow trout (*Oncorhynchus mykiss*), are very likely to extend their ranges northward (Power 1990). While the warmer-water percid and cyprinid species are restricted to the southwest and unlikely to extend their range to the north (unless moved by humans) because of dispersal barriers (Power 1990), the euryhaline salmonids are able to move from estuary to estuary as conditions allow. For example, Dumont et al. (1988) documented the successful movement of rainbow and brown trout and exotic salmon species in the estuary of the Gulf of St. Lawrence and there is some indication that brown trout dispersal in Newfoundland has been temperature limited. As a result of probable range extensions, Arctic charr could be reduced or replaced by anadromous Atlantic salmon and/or anadromous brook charr throughout much of the southern portion of the region and brook trout will become a more important component of native subsistence fisheries in rivers now lying within the tundra zone (Power 1990). Lake charr are likely to disappear from rivers and the shallow margins of many lakes and behave as currently observed in temperate regions further to the south (Martin and Olver 1980), occupying lake bottom habitats throughout much of the summer period. In lakes with both lake charr and Arctic charr, climate-induced changes in

habitat use are likely to increase competition between the two species to the detriment of Arctic charr (e.g., Fraser and Power 1989).

Marine Migrations in Arctic Charr

Anadromy is observed in most populations of Arctic charr where there is open access to the marine environment. Migrations occur in early spring coincident with ice break-up and summer marine feeding is usually confined to near-shore coastal waters (Dempson and Kristoffersen 1987). Use of the marine environment provides an important opportunity to increase size prior to reproduction. However, anadromous behaviour is thought to be facultative and will vary depending on local conditions. Factors determining anadromy appear to be primarily environmental (e.g., duration of ice cover versus open water in freshwater systems, productivity in natal freshwaters versus near-shore marine waters, costs versus benefits of migration, etc.). Watershed sizes and gradients appear to influence the prevalence of anadromy, with gradients of $>80\text{m/km}$, precluding successful upstream migration in the Ungava Bay region (Power and Barton 1987). Basin sizes of $>1000\text{ km}^2$ seem to guarantee sufficient river discharge to permit anadromy where gradient or other obstruction barriers (e.g., waterfalls) do not exist (Power and Barton 1987).

Arctic charr primarily exhibit anadromy in the middle latitudes of their geographic range, with sea surface temperatures considered as one of the most critical determinants. Jensen (1981) and Berg and Berg (1989) have offered evidence from Norway suggesting that average coastal water temperatures (measured as 10-day means) exceeding 14°C at the four to five metre depth provide an effective abiotic barrier to anadromous behaviour. The data suggests that as climate change occurs, increases in temperatures at the southern limit of anadromy may hold significant implications for the continued viability of anadromy in southern populations. Nordeng (1983), however, has discounted the theory that sea surface temperatures alone determine anadromy and suggests that non-anadromous

strategies may have evolved as a response to changes in freshwater habitats with increases in food availability accelerating the development of juvenile Arctic charr and increasing the propensity for freshwater residency. The hypothesis suggests that Arctic charr facultatively adjust to increased food availability in freshwater habitats and respond by not migrating. Increased freshwater productivity stimulated by climate-warming may induce increased freshwater residency in many populations, with obvious implications for the sustainability of existing subsistence fisheries. Recent evidence from glacial relict populations in southern Québec (Doucett et al. 1999) supports the view. Anadromy also appears to represent an infrequent life-history strategy among the studied populations, as the Nordeng hypothesis concerning the increased productivity of freshwater habitats forecasts.

Where anadromy does not occur, preference for lacustrine residency appears to result from unfavourable trade-offs between migratory costs and the benefits of marine feeding. Where anadromy does occur, the transition to summer marine feeding begins generally between the ages of three and eight years. Arctic charr will usually feed at sea for a period of six to eight weeks. Although the time spent feeding at sea is short, marine feeding migrations facilitate rapid growth and individuals can increase body size by as much as 42% during the period of marine residency (Johnson 1980). Overall Arctic charr populations are suspected of being facultative with respect to anadromy.

When in marine environments Arctic charr are also critically affected by temperature. Upon entering the sea, anadromous Arctic charr grow rapidly at temperatures up to 10°C (Berg and Berg 1989). Observed declines in growth at sea surface temperatures above 10°C have been interpreted as indicating Arctic charr are especially adapted to low temperatures. The timing of Arctic charr migrations and sea residency also coincide with lower marine temperatures. Because Arctic charr grow well in cold seawater, their residence at sea appears to be somewhat longer where the sea is colder. Migration timing thus appears related to the onset of the most favourable thermal condi-

tions for growth at sea and once past the favourable thermal period growth rates decline (Berg and Berg 1989).

Climate-induced reductions in the period of sea residency associated with the most favourable temperatures for growth hold obvious implications for reduced marine-related growth and eventual declines in the reproductive success of many anadromous populations. The reduced propensity to migrate in southern populations (Doucett et al. 1999), and similar anecdotal information about the low incidence of migratory behaviour in high Arctic populations (Babaluk, Power and Reist, unpubl. data) suggests that more complex ecological relationships govern the observed spatial and temporal variability in life-history strategies among Arctic charr populations. More information about the relative influences of temperature and other ecological variables in determining the occurrence and relative success of anadromous and lacustrine populations is required before detailed predictions about the possible effects of climate change across the distributional range of the species can be made. Nevertheless, possible climate-induced changes in migratory behaviour imply that continued harvest sustainability may require reduced harvesting of anadromous Arctic charr, possible shifts to the harvesting of other species (e.g., brook charr or Atlantic salmon) and/or changes in harvest activities that see more restricted near-shore marine and estuarine fisheries and greater use of lake populations. The consequences of such changes on local communities in northern Québec, and possibly Labrador, could be substantial as a result of both increased harvest costs and reduced harvest gains.

Reproduction

Other critical aspects of Arctic charr life-history are influenced by temperature. Jensen et al. (1989) reported the time to 50% feeding in post-hatch alevins was shortest for Arctic charr versus competing salmonid species in water temperatures <8°C. This demonstrates a low temperature developmental and survival advantage for Arctic charr relative to species such as Atlantic salmon (*Salmo salar*). At temperatures above 8°C, the Atlantic salmon

begin to feed more quickly than Arctic charr, reversing the developmental and survival advantages. Increases in temperature could, therefore, change the relative ecological advantage for sympatrically distributed salmonid species, leading to significant changes in community structure throughout much of the range overlap for the species concerned. Anecdotal evidence of such changes exists for some northern Québec lakes. Early studies of Lake Aigneau in the late 1950s (G. Power unpubl. data) found relatively few Atlantic salmon in comparison to Arctic charr, whereas a similar study in the 1990s (Power et al. 2009) found significantly greater numbers of Atlantic salmon and evidence of marginalization of a component of the Arctic charr population to deep water habitats within the lake.

Comparatively little work has been done on the temperature requirements for reproduction in Arctic charr except for a number of studies based on aquaculture experiments. Gillet (1991) found ovulation in Arctic charr was inhibited above 11°C, slowed at 8°C and if temperature remained above 5°C for several weeks, egg quality declined because of over-ripening. Increases in temperature were also associated with increased egg death, which suggests an inverse relationship between reproductive success and temperatures greater than 5°C (Gillet 1991). Hatching success and survival have similarly been shown to be greater at 3°C than 6°C (deMarch 1995). Recent hatching success and post-hatch survival experiments have shown similar results at temperatures above 6°C (Bebak et al. 2000). The estimated probability of 90-day post-hatch survival declines from the 0.78 to 0.97 range at 6–12°C to the 0.65 to 0.73 range at a constant temperature of 12°C. In view of the strong effects of temperature on egg viability and post-hatch success, the importance of cold temperatures for other Arctic charr life stages merits further investigation, particularly in the face of possible concerns over climate warming.

Using latitude as a proxy for temperature, a recent study (Power et al. 2005) noted environmental variation in fecundity among 32 populations of Arctic charr from east-

ern North America. Although fecundity predominantly varied with fish size (fork-length), when fecundity was adjusted to account for differences in fork-length, significant differences were found among populations, implying that fecundity was a continuously responsive trait influenced by local environmental factors (Figure 3). In contrast with some other studies of fecundity in salmonids (e.g., Fleming and Gross 1990), there was no evidence for a latitudinal cline in egg size. Patterns of change in fecundity and egg diameter as a function of length, latitude and morphotype found by Power et al. (2005) point to the reproductive plasticity of Arctic charr species and underline its ability to adapt to a wide variety of environmental conditions, either through the selection of life-history tactics or individual allocation of energy. Although latitude does not appear to be the major determinant of fecundity, latitude-based studies are relevant for understanding potential effects of climate change at several levels of ecosystem structure because latitudinal variation in key environmental parameters (e.g., temperature) may mimic predicted climate-driven shifts in biological characteristics over time.

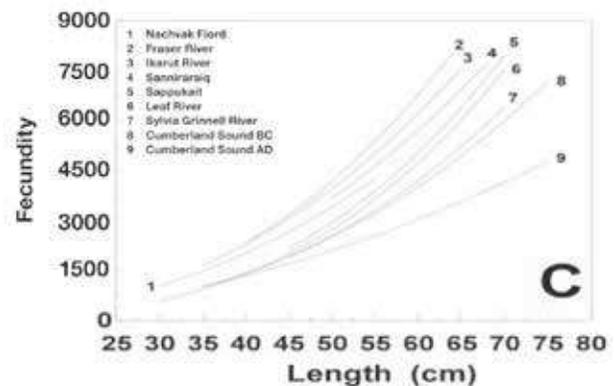


Figure 3. Differences in fecundity-length relationships for anadromous populations of Arctic charr sampled along a latitudinal gradient starting with southerly populations at the left. All but populations 7–9 originate in the northern Québec and Labrador region. For a given length, there is a general decline in fecundity. Figure adapted from Power et al. (2005).

Summarizing the Effects of Temperature

Temperature driven growth rates and migration strategies suggest that among Arctic charr populations the effects of global warming will depend critically on how and where temperature changes most impact life-history strategies. Anadromous stocks are most likely to be affected by changes in sea surface temperatures, possibly to the extent of reducing sea residency time and growth. Increased marine productivity may ameliorate the effect of reduced sea residency, but persistent warming may also act to reduce the distribution of anadromous populations in the south. Lacustrine populations, particularly those in shallow oligotrophic lakes, may be decimated (Lehtonen 1998). Increases in temperature will increase metabolic rates and individual food demand, possibly to the point where populations become food limited and size-at-age is reduced. For populations living in lakes that do not thermally stratify, warming will reduce the volume of viable summer habitat, thus increasing density-dependent mortality. If warming is as severe as predicted (e.g., chapter 2, Brown et al. 2011), lacustrine populations are likely to survive only in deep oligotrophic lakes that thermally stratify. Assuming that no factors other than temperature change in future climates, the reductions in summer habitat availability will probably lead to measurable reductions in many Arctic charr populations (Lehtonen 1998). Accordingly, it is important that careful distinction be made between Arctic charr populations on the basis of anadromy and freshwater residency when considering the potential consequences of climate changes on Arctic charr populations as a whole.

7.3 Management initiatives and ongoing research in Nunavik

The management of Arctic charr populations is challenging owing to incomplete harvest information and lack of sufficient resources allocated to explore alternative management initiatives. Dempson et al. (2008) notes characteristics of the species further complicate management,



including: 1) variable year class strength; 2) the noted lack of directional change in length or age structure in those populations that have been studied; 3) the absence of established biological reference points or conservation requirements; 4) and the complexity of Arctic charr migratory patterns that see fish move among rivers in local areas. Population-driven pressures for increased availability of Arctic charr in many communities throughout northern Québec and Labrador, as well as the likely impacts of climate change on Arctic charr (Reist et al. 2006 a, b, c), require the development of research programs aimed at better understanding the long-term dynamics of Arctic charr populations, both lacustrine and anadromous. In that regard, the data compiled for the Nain fishery (e.g., Dempson 1995, Dempson et al. 2008) has been invaluable for providing key insights into the impacts of fishing and varying environmental conditions on Arctic charr.

Although Arctic charr have traditionally been characterized as vulnerable to exploitation owing to relatively slow growth rates and late sexual maturity, evidence from the Nain area suggests otherwise. With peak catches representing between 50 000 and 90 000 Arctic charr per year during the late 1970s and early 1980s, the fishery for Arctic charr from the Voisey, Nain, and Okak stock complexes has not resulted in the short-term population collapses traditionally predicted for intensely fished stocks.

Indeed, over the past three decades catches of Arctic charr in the dominant age-classes (7-10 years) have shown little variation in mean length at capture (Dempson et al. 2008). Similarity in length and age composition to data reported for 1953 by Andrews and Lear (1956) indicate that over the span of a half century, the age and length composition of Arctic charr taken in the commercial fishery of north Labrador has remained relatively constant. Constancy has been interpreted as indicative of the capacity of the north Labrador region to produce as well as sustain anadromous Arctic charr fisheries over significant periods of time (Dempson et al. 2008).

Given the paucity of detailed management studies and the climate-related risks identified above, adaptive management approaches for the future would include the following: 1) conduct community consultations to review past results and trends in the fishery; 2) identify management goals; 3) and data deficiencies and incorporate traditional ecological knowledge. In that respect, management initiatives taken by the Nunavik Research Center represent a useful approach that allows local resource users to participate in the development of management policies designed to mitigate the possible impacts of climate change on populations of Arctic charr in northern Québec and Labrador, both lacustrine and anadromous.



7.3.1 Stream Enhancement in Nunavik

One management initiative of real interest involves the numerous efforts at stream enhancement that have been undertaken since the completion of the first Arctic charr population inventory in Nunavik, carried out as a joint project between the University of Waterloo and the Nunavik Research Center. Most enhancements aim for the simple removal of barriers to migration and/or the creation of passable channels for returning migratory Arctic charr. In most instances projects only require the removal of rock rubble from the main channel. While channels may be enhanced by hand, with little consequent environmental impact, there are instances when use of small machinery is required. Barriers to migration created by low summer flows can result in Arctic charr seeking other systems for spawning and over-wintering or in Arctic charr having to wait until river channels become passable. The energetic costs associated with delayed or more difficult upstream migrations are unknown, but may include reduced body condition and lower overall investment in reproduction. Both responses would clearly impact subsequent population dynamics, possibly reducing overall population abundances. The experience and success with simple, community-based stream enhancement projects is encouraging for predictions about the continued manageability of existing Arctic charr populations in the face of climate change. Most villages in Nunavik are now familiar with stream enhancement and well placed to continue the work needed to maintain access to clear migratory passages.

Not all management projects, are small or simple. In 1999, the Nayumivik Landholding Corporation of Kuujjuaq initiated a stream enhancement project for the Nepihjee River. Falls located near the mouth of the river were preventing Arctic charr from colonizing the watershed and, as a consequence, no anadromous charr could be fished near the community of Kuujjuaq. Bedrock was dynamited near the falls to create a fishway that would allow the fish to by-pass the obstacle. A hatchery was also set up to facilitate the colonization of Arctic charr within the watershed with in excess of half a million fry which

were successfully reared and planted in lakes upstream of the Nepihgee River. Monitoring of the fishway has been performed yearly since its creation by the Landholding Corporation and the Nunavik Research Centre and lately with the help of a scientific project funded by ArcticNet and led by the University of Waterloo. Anadromous Arctic charr now routinely migrate upstream, but with counts varying between 400 and 1000 individuals, the watershed is still not able to sustain the levels of local community demand. Nevertheless, the project has created great interest in Nunavik and most communities now have a nearby lake or a watershed where they would like to see Arctic charr introduced. Demand for introductions has increased because nearby stocks are subject to heavy fishing pressure and travel routes to more remote fishing sites are becoming more unpredictable as a result of recent environmental changes. Habitat enhancement projects are now considered a major management tool in Nunavik.

Although the project has yet to realize the large numbers initially anticipated, it has achieved a number of critical firsts. It has demonstrated the capacity of local initiatives to conceive, design and implement proactive management schemes aimed at establishing and managing sustainable populations of Arctic charr. In the face of the predicted impacts of climate change, the development of local management expertise is particularly encouraging for the continued sustainability of valued northern populations. The project has also led to the generation of several hypotheses regarding the viability of Arctic charr populations, that have particular pertinence for those interested in predicting climate change impacts. Lower than expected returns may relate to the existence of a well established and diversified fish community containing some ten other species, including important competitors such as lake charr. Lower than expected returns may also mean that hatchery fish generally have lower survival rates than wild fish. The complexity of the community structure may relegate Arctic charr to a small, marginal niche capable of supporting only a few individuals. Analogues of this configuration are numerous in the south (e.g., Power et al. 2002), and suggest that climate-driven changes in fish community

structure may lead to reduced numbers of Arctic charr in other northern systems where they previously dominated. Further research is clearly needed to explore the biotic and abiotic factors responsible for determining the successful establishment of new populations.

7.3.2 The Nunavik Charr Database

Key to any interventive management approach is a good information base. There are approximately 250 rivers and lakes and lake systems that support, or are capable of supporting, Arctic charr in Nunavik. The streams and lakes that currently support Arctic charr provide important subsistence and small commercial harvest opportunities for local communities. Isostatic rebound and changes in precipitation patterns associated with changing climates have obstructed Arctic charr migration routes on some streams. In the early 1980s, a team of fish biologists from the University of Waterloo, in conjunction with the Nunavik Research Centre, initiated a survey of coastal river and lake systems along the complete length of the Nunavik coastline with the objective of categorizing watersheds for their existing or potential suitability for sea-run Arctic charr. The project was undertaken to meet both the demand for scientific information about the distribution of Arctic charr in Nunavik and the community needs for an inventory of Arctic charr resources.

Rivers were initially classified as allowing free passage for Arctic charr or as preventing passage because of obstacles like waterfalls, rapids or very shallow areas. Obstacles were described and drawn and/or photographed for archival reference, and now form one of the only detailed archives of historic conditions available anywhere in the North. Lakes were classified according to size, depth and suitability as over-wintering habitat. Based on both riverine and lake assessments, drainage systems were then ranked as to their overall suitability for supporting Arctic charr populations, with the information essentially providing a guide to which populations would benefit most from simple enhancement initiatives. The information was released as a management reference book, and subsequently digitized under the aus-

Box 1.

The resulting GIS system is being constantly updated as new information is collected, especially the inclusion of Traditional Ecological Knowledge (TEK). Information on population location, presence/absence, abundance, spawning and over-wintering habitat, exploited lakes, related travel routes and hazards to fishing sites are now included in the database. The database is expected to serve as a relevant management tool in several ways. First, it will be used for a comprehensive mapping service where routes and fishing grounds can be queried. Second, the database will help improve understanding of which environmental factors have the greatest influence on Arctic charr distribution and success in Nunavik. With continued use and updating, it is expected the database will help improve understanding of temporal trends in the distribution and abundance of Arctic charr, thereby helping to offset the lack of consistent studies in the past which has hampered abilities to accurately predict the consequences of the large-scale environmental changes implied by climate change. Finally, the database has already proven its usefulness in the ranking and planning of stream enhancement activities. With continued updates, such as detailed community-driven data, it will help with the design and implementation of the necessary adaptive management initiatives required to ensure, in the face of climate change, the sustainability of all populations of Arctic charr in Nunavik.



GIS of stream potential for the introduction of Arctic Charr

pices of ArcticNet in a detailed geographic information system (GIS) which can be accessed and updated through a web-based portal by local community Hunting, Fishing and Trapping organizations (see Box 1).

7.4 Health of Arctic charr populations

7.4.1 Climate change potential threats

Sub-Arctic fishes are adapted to life in harsh, variable environments with few resources. The environments in which they live, however, are being continually perturbed by an increasing number of human interventions associated with northern development that have resulted in polluted environments (e.g., mining), increasing habitat eutrophication, barriers to migration, over-fishing and, most recently, climate warming (Maitland 1995). Of these stressors, climate-warming has the greatest potential to affect fish and fish habitats in the sub-Arctic. The ability of fish to adapt to changing climates will be population-specific and depend on the intensity and magnitude of other stressors that are affecting a local environment. Therefore, a general predictive scenario is difficult to construct. When considering the predicted 3-5°C increases in mean annual temperatures projected to occur by 2050 (Brown et al. 2011), there are three possible general outcomes for sub-Arctic populations of Arctic charr: 1) local extirpation resulting from thermal stress or increased competitive pressure; 2) reduced local abundance as a result of the northward shift in the geographic range of a pathogen or competitor species; and 3) increased local abundance resulting from the improved thermal conditions associated with climate warming (Lehtonen 1996, Reist et al. 2006 a, b).

Populations, in watershed systems draining to the north may be exposed to new species and pathogens that are able to shift their geographic distribution northward as a result of climate warming, eliminating temperature barriers that affect critical stages of life. The arrival of both

new species and pathogens is likely to result in reduced numbers of lake-dwelling Arctic charr and may, in some instances, eliminate populations altogether. In watershed systems draining to the east or west, climate-driven increases in temperature may be compensated by altitudinal shifts in Arctic charr populations where barriers to head-water movement do not exist. Impacts of climate change on Arctic charr populations will vary across northern Québec and Labrador, with populations at the southern edge of the area most likely to be negatively affected by warming temperatures and the introduction of new species and pathogens. Theoretical studies of climate change have suggested that global warming will increase available thermal habitats for fish, as a result of longer open-water seasons or the maintenance of water temperatures at optimal or near-optimal temperatures for fish growth (e.g., Magnuson et al. 1990). Thus, while Arctic charr in the southern Subarctic may have to cope with decreased availability of suitable thermal habitat and new competitors, populations in the northern Subarctic may enjoy increased availability of suitable thermal habitat and may, as a consequence, be positively affected by climate change (Reist et al. 2006 a, b).

The ability to predict the effects of climate-driven ecosystem change on sub-Arctic populations of Arctic charr is limited by the scarcity of long-term studies of existing populations and the lack of readily available spatial comparisons (e.g., Fraser and Power 1989, Power et al. 2009). In northern Québec and Labrador, salmonid communities in general are controlled by climate and environmental conditions, with temperature being the factor most likely to explain the distribution of a given species (Power 1990). Climate warming may change the suitability of habitats for all salmonids, not just Arctic charr, shifting many salmonid distributions northward in Québec and Labrador.

7.4.2 Possible contaminant issues

The amounts of persistent organic pollutants (POPs) and metals, such as mercury (Hg), widely distributed within

Subarctic aquatic ecosystems by long-range atmospheric transport have increased in recent decades (Macdonald et al. 2000). Within some catchments, deposition from the atmosphere may be augmented by local mining activities, although in general long-range transport is the exposure pathway of concern. Because climate change will invariably affect global circulation patterns, it will have direct implications for the existing global pathways that currently move contaminants to the north. Among the contaminants of concern, POPs and Hg appear to have the greatest potential for changing the freshwater ecosystems inhabited by Arctic charr (Macdonald et al. 2003). Little work has been completed on the possible impacts of POPs on Arctic charr, although generalized predictions have been made in the context of the widely disseminated Arctic Climate Impact Assessment and associated derivative publications (e.g. Wrona et al. 2006 a, b). Generally, increases in temperature and precipitation (e.g., chapter 2, Brown et al. 2011) are predicted to increase contaminant capture in the Subarctic, resulting in increased country food consumption risks for humans. Recent paleolimnological studies suggest that global warming is resulting in increased productivity that has enhanced the delivery of PCBs and mercury to lake sediments (Stern et al. 2005, Outridge et al. 2007), although other mercury flux studies have not corroborated the findings (e.g., Muir et al. 2009).

7.4.3 Susceptibility to diseases

As temperatures increase due to climate change, the higher temperatures will likely result in increasing outbreaks of pathogenic parasites that adversely affect resident fishes (Marcogliese 2001). Fish already stressed physiologically by the warmer water temperatures are likely to experience reductions in disease resistance (Jonsson and Jonsson 2009), with the net effect of increased fish mortality. Furthermore, diseased fish are more susceptible to predation and less able to perform essential functions such as feeding, migration and territorial defence and, as a result, may experience both reduced growth and fecundity. Reductions in either growth or fecundity will have consequences for population dynamics and the overall abun-

dance of a specific population of fish in a given locality. For human populations reliant on Arctic charr as a food resource, the associated declines in abundance will mean greater difficulties in accessing their needed or preferred food resources.

The specifics of disease effects, however, will be difficult to predict on a population by population basis. Pathogens depend on both the abiotic and biotic conditions prevailing in the environments in which they are found. The prediction of the implications of climate change for pathogen susceptibility is complex and context dependent (Marcogliese 2001). For example, to clearly understand the likely effects of pathogens on a fish population, one would require knowledge of alterations in intermediate host distribution, lake water levels, lake eutrophication and stratification potential, ice cover, acidification, ultra-violet-light penetration, and weather extremes (Marcogliese 2001). Generally, climate-driven increases in water temperatures are expected to affect parasite physiology, increasing developmental rates and reducing life-cycle times. Quicker parasite developmental rates suggest increased parasite burdens on fish hosts likely to result in decreased fish condition and increased parasite-related mortality (Marcogliese 2001). Climate-facilitated introductions of new parasites will further increase the challenges faced by endemic fish species in the northern Québec and Labrador region. In the long term, climatic change is likely to influence the susceptibility of the fish to pathogens simply because of inherited differences in disease resistance (Jonsson and Jonsson 2009). Whether such changes will be critical to the continued viability of fish populations, however, is less certain, in part because relatively little is known about their effects in Subarctic fish populations. Virtually all that is known about fish diseases is based on investigations of cultured fish. Thus, there is clearly a need for more knowledge about possible pathogenic effects on wild populations. In any case, the reduced condition or abundance of Arctic charr will render it either less palatable as a food resource or decrease its overall availability to Northerners.

7.5 Conclusion

Theoretical studies of climate change have suggested that global warming will increase thermal habitats for many northern fish species as a result of longer seasonal periods or larger volumes of water of optimal or near-optimal growth temperatures (Reist et al. 2006 a, b). Bio-energetic analyses have also indicated that growth will increase, with attained increases being sensitive to prey consumption and behavioural thermoregulation (Hill and Magnuson 1990). The geographic range of many of the lower latitude southern fishes is likely to expand into the northern Québec and Labrador region, forcing associated contraction in the distribution of stenothermic northern fishes such as Arctic charr in response to thermal habitat changes. Associated changes in the relative abundance of fish species are also likely to have top-down effects on the composition and abundance of species at lower trophic levels. Arctic charr are likely to be vulnerable to such changes and may be locally displaced in many localities (Reist et al. 2006 a, b).

Generalized predictions noted above suggest climate change will induce complex and varied change in Arctic charr populations through the northern Québec and Labrador region. Findings from the few environmental influence-based studies of Arctic charr in Canada that do exist (e.g., Power et al. 2000, Power et al. 2005, Chavarie et al. 2010, Michaud et al. 2010) indicate clear environmental influences on the biological characteristics of Arctic charr populations. Temperature and precipitation are the most important environmental influences, as a result of their respective effects on fish metabolism and opportunity for acquiring surplus energy for growth. Because climate change will affect both environmental variables, with increases in summer and winter temperatures, increases in total degree days and a decrease in the length of snow season (e.g., chapter 2, Brown et al. 2011), the climate-induced effects on the life-history and biology of resident Arctic charr populations can be expected to be pervasive and significant. The differential impacts of climate warming on the land, as compared to the sea, sug-

gest that lacustrine populations will be the most affected. Nevertheless, changing environments will have varying impacts on different populations of Arctic charr, and these will depend on the magnitude and specifics of the local impacts that occur and may be confounded by population adaptation to existing environmental conditions. Arctic charr, in particular, are known to be sensitive to minor changes in inhabited biotic and abiotic environments and are likely to show substantive variation in age-specific mean length and weight as a result of climate-induced environmental variation more quickly than other fish species that may be similarly impacted (e.g., longnose sucker). To understand and maintain sustainable fisheries for Arctic charr throughout the northern Québec and Labrador region, appropriate management regimes must be developed to account for the likely population-specific effects of climate variation and change. Well-designed management regimes will rely on the availability of suitable long-term data. Unfortunately, with the exception of studies at Nain, Labrador, long-term studies of Arctic charr have been lacking. As studies using the Nain data set have highlighted (e.g., Power et al. 2000, Power et al. 2005, Michaud et al. 2010), the availability of that long-term data has facilitated comment on the possible impacts of pervasive environmental change on valued Arctic charr populations. Thus, there is value in long-term fisheries data and the extension of programs in the North to acquire matching fishery and environmental data. This should be encouraged to facilitate better understanding of long term environmental change, including climate, on Arctic charr and other key northern fishery resources.

7.6 References

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Chapter 8. Trends in vegetation dynamics and impacts on berry productivity

Lead authors

Esther Lévesque¹, Luise Hermanutz², José Gérin-Lajoie¹

¹Département de chimie-biologie, Université du Québec à Trois-Rivières, Trois-Rivières, QC; ²Department of Biology, Memorial University, St. John's, NF

Contributing authors

T. Bell, S. Boudreau, A. Cuerrier, J. Jacobs, C. Laroque, C. Lavallée, L. Siegwart Collier and B. Tremblay

Abstract

The vegetation of Nunavik and Nunatsiavut changes from treeline to arctic/alpine tundra moving northward and upwards in elevation. Current and predicted environmental changes promote shrub growth as well as treeline expansion, but not in a uniform way. Research has documented an increasing trend in birch and willow cover, as well as an altitudinal expansion of larch. With the improved growing conditions (such as increased summer temperatures and Growing Degree Days (GDD)) favouring increased viable seed production and seedling recruitment, trees are expected to gradually expand beyond current boundaries; however, given the highly variable nature of abiotic and biotic factors across the region, the extent and rate of treeline change is currently unknown. Changes in the distribution of shrubs are expected to alter snow distribution and its persistence on the land, affecting permafrost, feedback to the atmosphere (e.g. altered albedo), vegetation, wildlife and human transportation routes.

Warmer and longer growing seasons may not benefit the growth and productivity of all berry producing plants. Berry shrubs that have a prostrate or dwarf growth form will face increasing competition from taller erect shrubs such as birch and willow. The potential lack of moisture if summers become drier will also compromise their ability to produce large berry crops. Changes in precipitation across the region are uncertain, and berry productivity is sensitive to amount and timing of precipitation, as well as wind and extreme events (e.g. late frost events in the spring). Berry species that have highest productivity in full sun (especially partridgeberry/redberry and bog bilberry/blueberry) will most likely decline under an increased shrub cover, yet the patchy nature of arctic vegetation should enable other species more tolerant to partial shade such as black crowberry/blackberry and cloudberry/bakeapple to take advantage of the changing conditions.

Further research is necessary to understand feedbacks of treeline and shrubline changes on ecosystems and to evaluate how the disturbance regimes will vary in response to climate change, including if and how insect outbreaks and fires will increase. Major uncertainties exist regarding how environmental changes will impact biotic interactions between vegetation and animals, herbivores (both insects and vertebrates) and pollinators.

Northerners have observed changes in their environment both in the past and present and have adjusted their berry-picking activities to the high spatial and inter-annual variability in berry productivity. Community-based monitoring is an important tool to enable the collection of long-term data, crucial to understanding current uncertainties about berry productivity. Such long-term, sustained monitoring will enable Northerners to track environmental changes in their communities and tailor appropriate adaptation strategies for their region. Longer time series from a wide range of sites will benefit researchers and communities and greatly enhance scientific predictive abilities. This will in turn help to select areas to be protected from development, to ensure easy access to high quality sites for this culturally important activity.

8.1 Introduction

The vegetation of Nunavik and Nunatsiavut ranges from the northern limit of the boreal forest to the arctic tundra. The transition zone between forest and tundra moves from more abundant closed canopy forest to sparse forest patches then to isolated tree islands, and finally to krummholz, which are stunted shrub-like trees (Payette 1983). This complex transition zone is called the forest-tundra ecotone, and can either be sharp with an abrupt transition from forest to tundra, or gradual with forests changing to shrub tundra over long distances (Payette et al. 2001, Harsh et al. 2009). Climate controls on the position and character of the treeline increase in complexity nearer the coast, as exemplified by the treeline in Nunatsiavut (Payette 2007, Hallinger et al. 2010, Kennedy et al. 2010) (Figure 1).

The forest-tundra ecotone is highly sensitive to changes in environmental conditions (Payette and Lavoie 1994), with examples of trees and shrubs moving northward and upwards into the tundra zone across Canada in response to climate changes (Payette et al. 2001, Danby and Hik 2007, Harper et al. 2011). In the Arctic zones, shrubs increase in growth and density and are moving into herb tundra areas. Changes in the distribution of shrubs are expected to alter the way snow is distributed on the land and how long it stays, affecting permafrost, vegetation, wildlife and human transportation routes as well as having feedbacks to the atmosphere, for instance through the exchange of greenhouse gases.

Shrubs could act as “nurse” plants for trees, accelerating their spread into the tundra (Cranston 2009). However, shrubs can form dense thickets that may not be suitable for tree seedling establishment and survival. Taller shrubs such as dwarf birch (*Betula glandulosa*), alder (*Alnus spp.*) and willow (*Salix spp.*), can also shade out shorter shrubs such as berry plants, causing localised loss of species such as bog bilberry/blueberry (*Vaccinium uliginosum*) and partridgeberry/redder (*Vaccinium vitis-idaea*), or affecting the berry productivity. Under thicker shrub

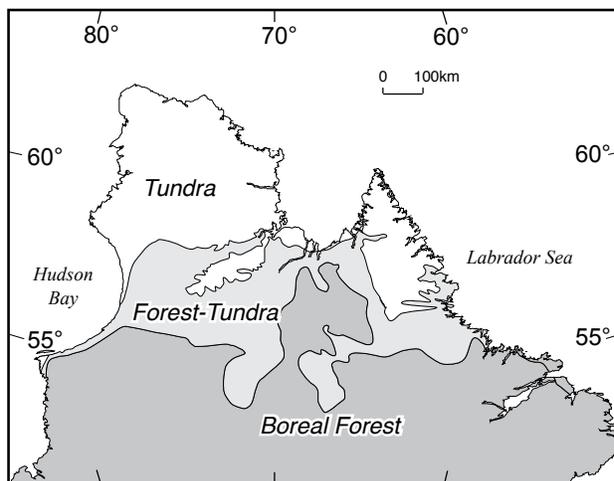


Figure 1. Vegetation zones for Québec and Labrador (modified from Payette 1983).

cover, other shade-intolerant ground cover species, such as lichens, will also be lost which may have negative effects on caribou food supply. Besides shrub encroachment and expansion, other competitive species may change the vegetation dynamics. In open areas, tall grasses may invade in areas and displace less competitive species such as *Rhodiola rosea* or cushion plants, like Lapland pin-cushion plant (*Diapensia lapponica*) and moss campion (*Silene acaulis*).

In Nunavik, Inuit have already noticed that tall shrubs are now invading some of their usual berry-picking spots, mostly where they used to find blueberries and black crowberry/blackberry (*Empetrum nigrum*) (Gérin-Lajoie et al. In Prep.). However, other species may become more abundant such as cloudberry/bakeapple (*Rubus chamaemorus*), reported in Kangiqsualujjuaq to have been mostly found among birches in the mountains in the past and now found growing everywhere. In addition, Elders from Umiujaq, Kangiqsujuaq and Kangiqsualujjuaq, are saying the permafrost is retaining less water (as discussed in chapter 6), resulting in lower water levels and plants invading dried up streams and lakes. This in turn has an impact on insect emergence and abundance as well as on fishing and travel on land.

In Nain, Nunatsiavut, community members have observed that trees and shrubs are more abundant now and are rapidly growing around their community and up the coast. Some individuals highlighted the difficulty in locating and using traveling routes because of their rapid infilling by shrubs. Community members have also indicated changes in berry crops, such as berries being less abundant, smaller and changing in taste. However, changes in berry crops were not linked explicitly with shrub expansion (L. Siegwart Collier, unpubl. data).

Influenced by climatic factors, vegetation changes like treeline patterns affect animal distribution and, consequently, Inuit and Innu people have had to modify their travel routes to follow migration of animals (Fitzhugh 1977, 1997, Fitzhugh and Lamb 1985). Today, Inuit depend less on hunting, fishing and gathering activities for their survival, but going on the land remains a very important part of their activities and a way to obtain a supply of fresh and healthy country food, including berries which are a significant part of country food for Inuit and Northerners (see Chapter 5). Berries are a valuable source of vitamins and antioxidants and a natural treat for people of all ages. Berry picking is a traditional activity very much enjoyed by community members, particularly women and children. It promotes intergenerational and family relationships as well as sharing, both values that are very significant in the Inuit culture.

This chapter on vegetation dynamics will cover tree and erect shrub expansion, examining the ancient and actual trends at treeline interface as well as above treeline, the associated processes, conditions, disturbance regimes and their effects on the landscape. Secondly, berry shrub productivity, abundance, growth and antioxidant activity found in the berries will be reviewed. Thirdly, community-based environmental monitoring and associated ongoing initiatives will be presented. Conclusions and recommendations will complete the chapter.

8.2 Trees and erect shrub expansion

8.2.1 Historical trends and current rate of change

Vegetation changes observed at treeline interface

Vegetation has always adapted to past climate variations over short and long time periods. The vegetation of Nunavik and Nunatsiavut was established following glacier retreat and soil development at the end of the last ice age (approx. 7000-8000 years ago) (Dyke and Prest 1987). Tree expansion reached its maximum during the warm interval known as the hypsithermal (Lamb 1985, Payette 2007, Bell et al. 2008). For instance, abundant subfossil tree remains (spruce, fir, larch) were found around the margins of shallow ponds above the treeline on the uplands of central Labrador (Photo 1); a random sampling of several of these trees provided C-14 dates of 3000-5000 years ago illustrating that trees grew higher during this period (Bell et al. 2008). The fragmented pattern of today's forest-tundra ecotone in Nunavik is a consequence of forest fires that opened the landscape and the failure of the postfire forest recovery processes (Sirois and Payette 1991, Payette et al. 2001, Asselin and Payette 2005).

The most recent cooling ended in the mid 19th century and is referred to as the Little Ice Age (LIA). During this cooler period, shorter growing seasons certainly constrained seed production and plant growth as shown by the tree-ring records from some long-lived woody species and by the reconstruction of tree pollen records preserved in lakes and bogs (as mentioned in chapter 2). These changes possibly have imposed migration on Inuit and Innu people (Fitzhugh 2009). Fitzhugh (1977, 1997) and Fitzhugh and Lamb (1985) demonstrated how Aboriginal people in Labrador and the Eastern Subarctic have adapted their migration patterns to climate factors and treeline patterns. These studies exemplify the strong interrelation among Inuit lifestyle, climate change and vegetation patterns.



Photo 1. One of over 600 subfossil tree remains recovered from shallow ponds above 600 m elevation in the Red Wine Mountains of central Labrador. The trees are as old as 5000 years and represent a time when climatic conditions were more favourable than today for tree growth on upland summits. Source: Trevor Bell.

Since the end of the LIA, a general increase in erect shrub and tree abundance was expected as temperatures have been warming (Hallinger et al. 2010, Sturm et al. 2005a, Chapter 2). However, this warming trend was not constant but characterised by successions of warm and cool periods favourable or not for erect shrub and tree expansion. Such increases have been reported in Nunavik for green alder (*Alnus viridis* subsp. *crispa*) (Gilbert and Payette 1982) and for trees (white spruce (*Picea glauca*) and black spruce (*Picea mariana*)) in many areas including Nunatsiavut; sometime resulting in local rises of the altitudinal or latitudinal treelines (Payette and Filion 1985, Lavoie and Payette 1994, Lescop-Sinclair and Payette 1995, Caccianiga and Payette 2006, Payette 2007).

In the last 50 years there are indications of altitudinal rise of the treelines. In western Nunavik, Gamache and Payette (2005) documented a transect straddling the forest-

tundra ecotone where black spruce increased through seedling establishment in the southern part of the transect and through vertical growth of stunted individuals in the northern part. Black spruce expansion near tree-line was constrained by very limited seed viability in the past (Sirois 2000) but current results indicate a sharp increase in viability over the last 18 years (Dufour Tremblay and Boudreau 2011). A recent study in the vicinity of Kangiqsualujjuaq (George River, northeastern Nunavik) recorded abundant and recently established seedlings and saplings of eastern larch (*Larix laricina*) on hillsides above pre-existing woodlands, suggesting an ongoing rise of local altitudinal treelines (Tremblay et al., In press, see Photo 2). In 2008, the cone production of eastern larch in this area was remarkable and laboratory germination trials revealed very high proportions of viable seeds (E. Lévesque, pers. comm.). People from Kangiqsualujjuaq (Nunavik) reported that trees have been starting to grow



Photo 2. Hillside northeast of Kangiqsualujjuaq, Nunavik, showing abundant eastern larch saplings recently established above the treeline, suggesting that local altitudinal treeline is rising. Source: Benoît Tremblay.

on the coast since the 1990s and an Elder mentioned that balsam poplar (*Populus balsamifera*), very scarce in the 1940s, was now becoming more abundant (Gérin-Lajoie et al. in prep.). Kangiqsualujjamiut have also mentioned the greater expansion of tamarack over black spruce, and some Elders have noticed that black spruce on hillsides facing the George River mouth were not seen some years before (Gérin-Lajoie et al. In prep.).

In coastal areas of southern Nunatsiavut, Payette (2007) found that treelines (mainly white spruce) advanced northward and that seedling establishment has increased in upland tundra ecosystems since the 20th century. Invading white spruces were observed several meters above current altitudinal and latitudinal treelines, suggesting that spruce is infilling suitable and unoccupied sites. An abundance of white spruce seedlings has also been observed in the Labrador interior at Mistastin Lake, about 25 km south of the northern tree limit (T. Trant and J. D. Jacobs, un-

publ. data, pers. comm.). In Nain, observations by local Elders suggest that trees (mostly spruce) and shrubs have been spreading and advancing upslope into upland tundra, expanding around their community and throughout their traditional harvesting/traveling areas (L. Siegwart Collier, unpubl. data, pers. comm., see Photo 3).

Vegetation changes observed above treeline

A recent study in tundra areas surrounding Kangiqsualujjuaq using past and recent aerial photos showed a substantial increase of erect woody vegetation from 1964 to 2003, attributed mainly to dwarf birch (Tremblay et al. In press). During the 40 years spanning the two photo series, more than half the area available to erect woody vegetation was affected by new colonization or infilling of dwarf birch. Expansion of dwarf birch was most prominent on mid to upper slopes with southerly and easterly exposures. The drivers of this change may be a combination of warmer



Photo 3. North-facing (foreground) and South-facing (nearground) hillside slopes surrounding the community of Nain, Nunatsiavut. Photo depicts the abundant and widespread distribution of predominantly spruce (*Picea* spp.), tamarack (*Larix laricina*) and dwarf birch (*Betula glandulosa*) surrounding the community. Source: Laura Siegwart Collier, 2009.



Photo 4. Repeated ground photography of a landscape near Kangiqsualujjuaq, Nunavik. View is from the east side of Akilasakallak Bay and shows substantial colonization of palsa summits by erect shrubs and trees in only 20 years. The 1988 photo was graciously provided by Marcel Blondeau and was taken at the end of July. The 2008 photo was taken August 7th. Source: Benoît Tremblay.

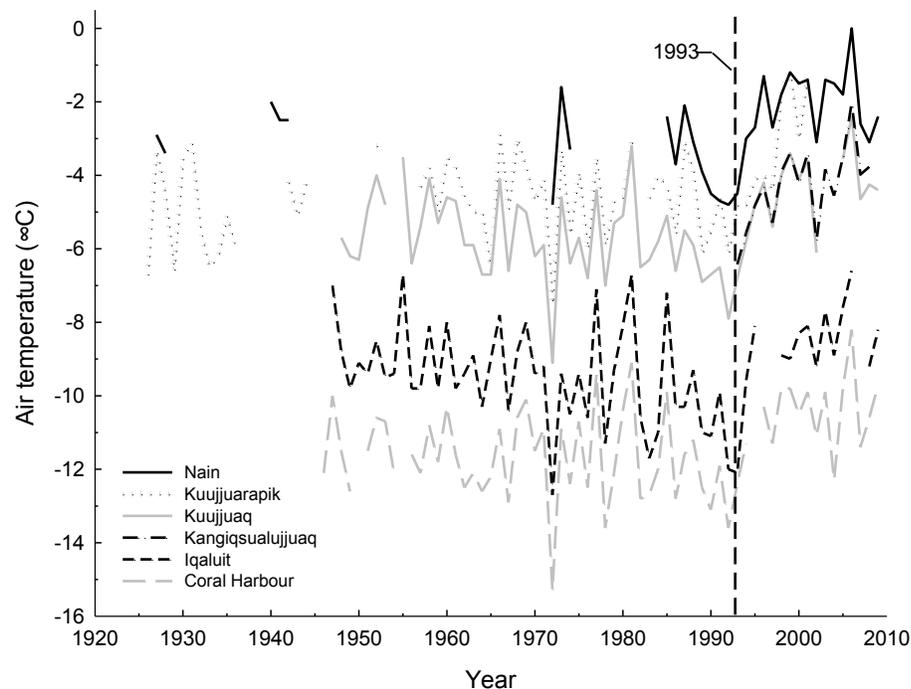


Figure 2. Mean annual temperatures of six eastern Canadian Arctic localities : Nain (Labrador, 56°33'N-61°41'W; 1927-2009 with incomplete data from 1927 to 1984), Kuujuarapik (Quebec, 55°17'N-77°45'W; 1926-2009 with incomplete data from 1937 to 1957, 2002 to 2004 and 2006 to 2008), Kuujuaq (Quebec, 58°06'N-68°25'W; 1948-2009), Kangiqsualujuaq (Quebec, 58°43'N-66°00'W; 1993-2008), Iqaluit (Nunavut, 63°45'N-68°33'W; 1947-2009 with missing data for a few years) and Coral Harbour (Nunavut, 64°11'N-83°22'W; 1946-2009 with missing data for a few years). Source of raw data is Centre d'études nordiques (Laval University) for Kangiqsualujuaq and Environment Canada for all other localities. Parallelism of all the curves is remarkable and they all show a similar trend of higher mean annual temperatures since 1993.

temperatures during the last two decades, coupled with a destruction of lichen cover associated with trampling and grazing by caribou during high density years. This increase of erect woody vegetation is consistent with a marked rise in mean annual temperatures in the Canadian Eastern Arctic since the beginning of the 1990s (Figure 2) and is further supported by repeated ground photography (Photo 4) and regional-scale NDVI analysis (W. Chen, unpubl. data, pers. comm.) as well as local ecological knowledge. Indeed, people have reported a “greening” of the area, mostly due to shrubs growing much more than before (Gérin-Lajoie et al. in prep.). The rings of some larch trees and saplings that were analysed showed an increase of annual growth since 1990 as was suggested by

the deceased Willie Emudluk from Kangiqsualujuaq (see Box 1). Further analyses are in progress to document tree-line dynamics at this site. In Western Nunavik, along the Boniface River, shrub cover (mainly *Betula glandulosa*) has increased significantly over the last 50 years. This increase could also be linked to warmer temperatures and caribou disturbances as in the case in Kangiqsualujuaq. However, the absence of tree regeneration following forest fires over the last thousand years has resulted in the progressive opening of the forested landscape (Sirois and Payette 1991, Payette et al. 2001). Such lack of tree regeneration could have contributed to creation of a suitable landscape for shrub expansion.

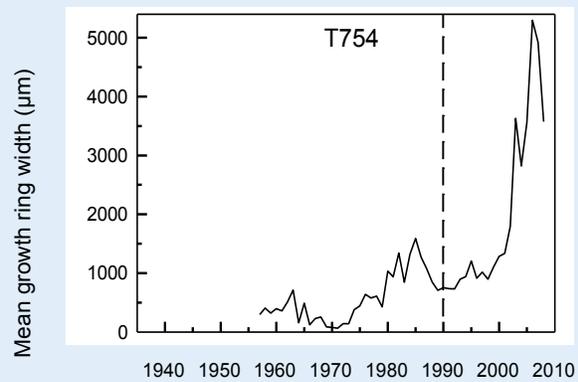
Box 1. Look at the trees!

During an interview on climate change, Willie Emudluk from Kangiqsualujjuaq told us that the trees were growing more, both in height and diameter. To support what he had said, he encouraged us to measure the growth rings of both larch and spruce.

He said: “If you cut a tree and examine the lines, you will find that trunks of trees have grown wider. Look at the trees!”.

Born on January 17, 1924 in Old Kuujjuaq, he passed away in Kangiqsualujjuaq on September 21, 2009. Willie Emudluk was an important figure in Nunavik, particularly in the Ungava region. Well respected, he worked towards the foundation of Inuit cooperatives in the hamlets of Nunavik, originally created for selling fish and wood. He possessed a good knowledge of animals, plants, Inuit territory and the history of his community. He was interviewed numerous times and was always willing to collaborate with researchers and share his expertise. It is important for us to honour his memory and to pay tribute to his open-mind, his humility, his passion for Nature as well as his generosity. Nakurmimarialuk Willie!

Willie Emudluk interviewed by Alain Cuerrier and José Gérin-Lajoie in 2007.



Near Umiujaq along the eastern shore of Hudson Bay, community members have reported increased shrub growth, especially of birches becoming more abundant and willows growing taller (Gérin-Lajoie et al. in prep.). Preliminary results from the comparison of 1990 aerial photographs and 2004 satellite images confirm such an increase in erect shrub distribution. Changes happened mainly in coastal lowlands, in openings in protected valley bottoms and on the tops of palsas. These changes were essentially due to dwarf birch and, to a lesser de-

gree, to Labrador tea (*Rhododendron groenlandicum*). No tree saplings were found at this site (E. Lévesque, pers. comm.). As for Nunatsiavut, M. Upshall and A. Simms (unpubl. data, pers. comm.) found, using Landsat images from 1985 and a SPOT image from 2008, that erect deciduous shrubs such as dwarf birch have spread from river valleys in the southern Torngat Mountains into the tundra, increasing in height and density. Further modelling exercises to predict future changes are underway.

The situation of erect shrub cover in areas underlain by continuous permafrost associated with the herb and shrub tundra vegetation subzones is poorly known. During interviews, people from Kangiqsujaq on Hudson Strait, have reported that since the 1980s, shrubs, especially willows, are growing everywhere, getting taller and bearing bigger leaves (Gérin-Lajoie et al. in prep.). The comparison of 1987-2001 Landsat images around this community revealed a slight increase of shrub-herb-like vegetation by approx. 3%, in valleys (W. Chen, unpubl. data, pers. comm.). No fine-scale study or ground truthing work has been done in this area to further support these results. However, a fine-scale study of erect shrub cover change using aerial photographs and high resolution satellite images is underway in the Deception Bay area, about 60 km east of Salluit.

A large part of the continuous permafrost zone of Nunavik is under the influence of the Rivière-aux-Feuilles caribou herd (presented hereafter in chapter 9), a population which has greatly increased in recent years (over 600 000 individuals according to the 2001 census, Gouvernement du Québec, 2008). Erect shrub increase in this area may be hindered by high grazing pressure, particularly in tundra ecosystems where erect shrub abundance was initially very low (herb tundra subzone). High caribou grazing counteracting the positive effects of warmer temperatures on shrubs is suggested by a recent study in northern Sweden (Pajunen 2009).

In the Torngat Mountains, the alpine /coastal arctic tundra is dominated by short/prostrate shrubs that occur at low densities, including dwarf birch, northern Labrador tea (*Rhododendron tomentosum* ssp. *decumbens*) and bog bilberry/blueberry. The predicted changes in vertical structure may lead to loss of shade-sensitive species such as ground lichens (Cornelissen et al. 2006, Walker et al. 2006), which may have negative consequences for caribou especially in winter. In study sites near Nakvak Brook (Nunatsiavut), dry sites support a high lichen cover, while wet sites support high moss and graminoid cover. Shrubs and graminoid species play an important role in structur-

ing both dry and wet plant communities (L. Hermanutz, unpubl. data, pers. comm.). Total shrub cover is similar among habitat types, but willows (*Salix* spp.) account for shrub cover in wet habitats, while dry plots are dominated by lichen cover in association with a range of shrub species that occur in prostrate form (e.g. *Vaccinium*, *Betula*, *Rhododendron*). It is hypothesised that these prostrate shrubs will increase in density and assume a more upright form with increased warming, resulting in a loss of lichen as described above.

Currently, treeline dynamics are highly variable across both Nunavik and Nunatsiavut. The response to current climate changes is likely to depend on site conditions (Payette et al. 2001), however, a general trend of altitudinal and possibly latitudinal, treeline rise is probable. Shrublines and treelines are being monitored to track changes in both regions.

8.2.2 Processes and conditions associated with increasing tree and shrub abundance

An important question currently being studied across Northern Québec and Labrador is: “How fast are trees invading tundra habitats and what factors limit or favour their establishment and growth?”

In the Mealy Mountains (central Labrador), experimentally sown tree seeds and planted seedlings were able to germinate and grow over 5 years (Munier et al. 2010). These results suggest that the bottleneck for tree expansion into the alpine tundra is due to lack of sufficient

“When I was young, plants were not growing much, even willows, because it was too cold and the ground was frozen. The snow was abundant and the unfrozen ground not very deep. The plants are growing more nowadays because their roots are less in the cold; and willows are growing faster because they have more water.” **Tivi Etok, Kangiqsuallujuaq.**

viable seed production (R. Jameson, unpubl. data, pers. comm.). In another study from this location, it was found that while there were negligible effects of nurse plants on growth in the first growing season, it was not until late in the second growing season that survival and growth rates began to show a positive association with their nurse plants. This suggests a weak net positive association between nurse shrubs and beneficiary seedlings during the first crucial life history stages (Cranston 2009). The documented impact was probably due to facilitation by seedbed species. Facilitation between the feathermoss (*Pleurozium schreberi*) and black spruce was observed as seedling growth and survival were highest on this seedbed and herbivory, seed predation and overwinter mortality were overall lower in feathermoss versus both reindeer lichens (*Cladonia* spp.) and bare ground seedbeds. The physical structure of the feathermoss likely reduces seedling exposure, and protects from temperature extremes and predators (Wheeler et al. 2011). In western Nunavik however, black spruce seedling establishment appears to be higher in sites disturbed by caribou (destruction of the lichen cover and exposition of mineral soil) (Dufour Tremblay and Boudreau 2011). Therefore, climate warming and caribou activity could act synergistically to increase black spruce regeneration. The expansion of trees into areas above current treelines of the forest-tundra ecotone, may be facilitated or “nursed” by shrub species. The shrubs could ameliorate harsh environments by providing shelter for tree seedlings (Sturm et al. 2005b).

In the Nunavik forest-tundra ecotone, sites with an increase in erect woody vegetation have been linked to variation in biogeographical, edaphic (soil related) and climatic factors. For instance, erect shrub increase is more or less restricted to lowland openings around Umiujaq on the east coast of Hudson Bay. At this location, further expansion on hillsides and hilltops, mostly made up of rock outcrops, may be impeded by rugged topography coupled with lack of loose substrate. In fact, tree abundance increase seems nonexistent or negligible around Umiujaq and changes may be in the form of loss of stunted growth of black spruce krummholz and through radial growth

increase of pre-established individuals. Larch is sparse around Lac Guillaume-Delisle where it is near its northern distributional limit at this longitude (Boniface River). This is not the case around Kangiqsualujjuaq where hillsides and hilltop plateaus are usually covered with till of varying thickness, facilitating an increase in tree cover through abundant larch recruits. Regional differences will influence vegetation processes, for instance, in western Nunavik, tree species associated with altitudinal and latitudinal treeline dynamics are mainly spruces (mostly black spruce) whereas in eastern Nunavik and Nunatsiavut, at least in coastal areas, larch probably plays a greater role in current changes.

8.2.3 Impact of increasing shrub cover on the landscape

Impact on snow distribution and ecosystem processes

Increasing shrub cover has profound consequences on many ecological factors, such as decreased albedo and heightened sensible heat flux to the atmosphere and ground (Sturm et al. 2005a) as well as greater snow accumulation, active layer depth and summer evapotranspiration (Sturm et al. 2001, Pomeroy et al. 2006, Strack et al. 2007) (Photo 5). A decreased albedo of the tundra surface will result in greater absorption of radiation and atmospheric warming (Chapin et al. 2005). Furthermore, soil nutrient cycling is altered through changes in production and accumulation of woody material (carbon sequestration), through higher amounts of organic debris retained during transit (Fahnestock et al. 2000) and through warmer winter soil temperatures. The latter enhances decomposition (Grogan and Chapin 2000, Schimel et al. 2004, Sturm et al. 2005b), which in turn may promote spring and summer growth. The microclimate of taller shrub communities will also influence recruitment and establishment of vegetation through reduced airflow, warmer soil temperatures, and changes in moisture availability (Jessen Graae et al. 2009). On the other hand, there are some indications that increased soil shading by higher and denser shrub canopy might decrease heat transfer to the ground during summer



Photo 5. *Snow trapped by vegetation.* Source: Alain Cuerrier.

and thus counteract warmer temperatures (Walker et al. 2003). Further studies are needed to better understand the impact of shrub cover changes on soil properties, particularly to identify winter conditions favouring a warming of permafrost and summer conditions leading to soil shading and cooling of permafrost.

Community members from Umiujaq, Kangiqsujuaq and Kangiqsualujjuaq are noticing shallower snow depths, partly due to later snowfalls (delayed from October to December) and more wind blowing snow accumulations almost immediately after snowfall. In addition, erosion phenomena are more frequently observed in Nunavik. For example, community members are reporting permafrost thawing and more landslides in Kangiqsualujjuaq, rock sliding in Kangiqsujuaq as well as beach and river bank erosion in Umiujaq (Gérin-Lajoie et al. in prep.).

In Nain, community members are reporting later arrival of snow (delayed from October to late December), lower abundance and reduced snow quality. In winter months, wet snow and rain are becoming more common, having

a detrimental effect on both inland and offshore ice conditions (L. Siegwart Collier, unpubl. data, pers. comm.). These trends are wide-spread across Nunavik and Nunatsiavut and are projected to continue for the next 40-50 years with earlier snowmelt (by 3-11 days), later onset of winter snow (by 5-16 days later), and warmer winter temperatures (3-5°C increase; Chapter 2). However, the snow-elevation dynamic is a complicating factor. The relatively warm winter 2009-2010 in Labrador was characterised by more snowfall in higher elevations (e.g. above 600 m), but by rain and winter thaw events at low elevation. More landscape-scale snow cover data are needed. These conditions compromised the ability of Nunatsiavut residents to travel, either by boat or snowmobile (L. Siegwart Collier, unpubl. data).

Disturbance regimes in a changing climate

In the context of a warming tundra and associated changing vegetation, it is expected that the impacts and nature of disturbances could change and then further modify the vegetation and landscape dynamics. In the boreal forest,

fire is the most pervasive large scale disturbance agent in closed canopy black spruce dominated stands. Biotic interactions (insect outbreaks, herbivory and fungal attacks) also play a major role in the overall dynamics of these forested ecosystems where they are interacting with fire (McCullogh et al. 1998, Malmström and Raffa 2000, Cairns and Moen 2004). Due to the low abundance of fuel provided by the patchy shrub/conifer cover in northern forest-tundra and shrub tundra, fire has lesser impact (0.4 fire/yr and 80 ha) than in the closed northern boreal forest (0.7 fire/yr and 8000ha; Payette et al. 1989). Similarly, fire was found to be very uncommon in central Labrador and usually associated with single trees, probably a result of very rare lightning strikes (Trindade et al. 2011). Although model projections show an increase in annual precipitation of 10 to 20% (see chapter 2), this projected trend may not be sufficient to maintain soil moisture given the expected rise in growing season temperatures (2°C by 2050; see chapter 2) and the corresponding increases in evapotranspiration. Consequently, with an increased vegetation cover, it is hypothesized that fire could be favoured and may become a more important driver of change in the North (Payette et al. 2001).

The impact of defoliating insects on erect shrubs and trees in Nunavik and Nunatsiavut, as well as frequency and extent of outbreaks, is poorly known. Near treeline in western Nunavik, the role of insect outbreak (particularly bark beetle) was important at the local scale and may explain the high mortality of the oldest cohorts of white spruce (Caccianiga et al. 2008). In central Labrador, larch sawfly is one of the defoliating insects that causes decreased tree growth and increased tree mortality (A. Trant, pers. comm.). However, impact of insect outbreaks in the forest-tundra ecotone might be minimal due to cold weather but also to patchy distribution and small extent of wooded areas. Current environmental changes could have major impacts on insect numbers and vegetation.

The interrelations between climate change, fire and biotic disturbances require more studies to better predict vegetation dynamics. For instance, fires can favour forest re-

generation if sufficient viable seeds are dispersed. Warmer conditions are expected to favour seed production in treeline trees. On the other hand, fires can destroy isolated forest patches and slow down tree expansion (Payette et al. 2001), especially if differential mortality of older, seed bearing trees linked with insect outbreak (Caccianiga et al. 2008) further reduces the seed rain.

8.3 Berry shrub productivity, abundance and growth

In general, experimental warming of tundra plots favours increasing cover and/or height of shrub species (Walker et al. 2006, Chapin et al. 1995). In addition, growth and reproductive phenology of tundra vegetation (i.e. green-up, bud burst and flowering) is shifting due to climate warming, and observations of these shifts have been verified by long-term passive warming experiments (Walker et al. 2006, Henry and Molau 1997). Shifts in flowering phenology may affect pollination success, influencing fruit production, seed ripening and dispersal (Fitter and Fitter 2002, Memmott et al. 2007, Galloway and Burgess 2009, Jentsch et al. 2009). Recent studies in Europe comparing simulated and natural extreme winter warming events have shown a significant reduction in flower and berry production, primarily due to damage to previous year buds (Bokhorst et al. 2008, Bokhorst et al. 2009). Similar impacts in Nunavik and Nunatsiavut may be expected as projections show similar increases in winter temperatures (3-5°C) in the region (Chapter 2). In addition, increased variability in late spring frost days may result in flower drop and loss of berry crops. Damage could be related to premature induction of flowering hormones, rendering buds or flowers vulnerable when seasonal weather conditions return.

While we know that warming-induced shading from upright shrubs reduces non-vascular plant cover and biodiversity (Cornelissen et al. 2006, Walker et al. 2006), there are few if any studies linking the effects of upright shrub expansion (shading) to variation in growth and re-

production of dwarf berry shrubs such as alpine bearberry (*Arctous alpina*), bog bilberry/blueberry, partridgeberry/reddberry, black crowberry/blackberry and cloudberry/bakeapple (Photos 6 to 10).

Naturally variable in time and space, the number of berries produced depends on weather and successful pollination. Yet, very little is known about pollinators in the Arctic and Subarctic, nor about predation of flowers and/or fruits, especially by insects. Berry production and insect activity are influenced by spring and summer rainfalls and by seasonal temperatures that contribute to the timing of thawing and growing degree days. Using an 11 year dataset from the Yukon boreal forest, Krebs et al. (2009) found that, in a given summer, rainfall and temperature two years prior can be significant predictors of tundra berry plant yield. Growth and productivity of previous years can also impact current year growth and berry production in ericaceous shrubs (e.g. *Vaccinium* spp.) (Krebs et al. 2009). Current climate warming scenarios predict changes in timing and total amount of thawing degree-days (increase by 30-60%; Chap 2) that will certainly influence berry productivity. In this context, it is even more urgent

to improve our understanding of factors influencing this inter-annual variability. Community-based monitoring of berry productivity and phenology events associated with climate monitoring is being developed to help address this issue.

In the Torngat Mountains, experimental warming using Open Top Chambers (OTCs) indicates an increase in shrub height and density in dry and wet tundra plots; changes in shrub height may occur in dry sites before wet sites. The results suggest that mesic shrubs (growing in average moisture conditions) such as dwarf birch and bog bilberry/blueberry will respond positively to warming across both wet and dry habitats (Hermanutz et al., unpubl. data). In Kangiqsualujjuaq, preliminary results of berry shrub growth assessed in a range of habitat types, from open tundra to continuous tree cover (C. Lavallée, unpubl. data, pers. comm.) confirm that bog bilberry/blueberry, partridgeberry/reddberry and black crowberry/blackberry plants were significantly shorter in open environments suggesting that plants modify their growing pattern under shrub or tree cover. In addition, the annual elongation of black crowberry/blackberry was measured



Photo 6. *Alpine bearberry (Arctous alpina)*. Source: José Gérin-Lajoie.



Photo 7. Bog bilberry/blueberry (*Vaccinium uliginosum*). Source: José Gérin-Lajoie.



Photo 8. Partridgeberry/redberry (*Vaccinium vitis-idaea*). Source: José Gérin-Lajoie.



Photo 9. Black crowberry/blackberry (*Empetrum nigrum*). Source: José Gérin-Lajoie.



Photo 10. Cloudberry/bakeapple (*Rubus chamaemorus*). Source: Benoît Tremblay.

Table 1. Berry productivity (g/m²) in Kangiqsualujjuaq, Nunavik, in relation to shrub height and various habitats from open to shrub cover to tree cover:

COMMON NAME	LATIN NAME	BERRY PRODUCTIVITY (G/M ²)		
		OPEN HABITAT	SHRUB COVER	TREE COVER
Black crowberry/Blackberry	<i>Empetrum nigrum</i>	++	-	+
Partridgeberry/Redberry	<i>Vaccinium vitis-idaea</i>	++	-	+
Bog bilberry/Blueberry	<i>Vaccinium uliginosum</i>	++	+	-

retrospectively using leaf scars up to 20 years; growth increased significantly over the last 10 years regardless of cover type (C. Lavallée, unpubl. data, pers. comm.) suggesting a response to the recent climate warming in this region. Similar results were seen in Sweden for *Empetrum hermaphroditum* and *Vaccinium uliginosum* when growing under a stand of *Betula nana* (Fletcher et al. 2010). Warming effects are more conspicuous in early Spring and might disappear during Summer. Efforts are being made in evaluating early growth in OTCs in relation to control plots near Nain, and then, re-measuring the same ramets (branches) in order to understand if differences will be blurred by later growth (L. Siegwart Collier, unpubl. data).

Analysis of vegetation cover and berry productivity data from recently established experimental warming sites (2008-2009) in Nunavut (Qamani'tuaq/Baker Lake), Nunavik (Kangiqsujuaq, Kangiqsualujjuaq) and Nunatsiavut (Saglek, Nain) suggests that site characteristics

play a very important role in berry production (Siegwart Collier et al., unpubl. data). Dwarf birch heights (ranging from 3-19 cm) had a strong negative effect on black crowberry/blackberry fruit set. More berries were found in open environments and under continuous tree cover and fewer under shrubs (Table 1). Birch height also had a weak negative effect on bog bilberry/blueberry and partridgeberry/redberry production. Regardless of shrub species, productivity of these three berry species was significantly higher in open environments (C. Lavallée, unpubl. data, pers. comm.). As for bog bilberry/blueberry, productivity under tree cover was even lower than under shrub cover.

With further warming as predicted in Chapter 2, it is expected that in areas where erect shrubs and trees are present, berry shrubs will need to invest more energy in growth to compete with taller shrubs for light. This may result in an overall decrease in berry productivity among sites. On the other hand, in open habitats, warmer conditions may increase berry productivity if moisture remains sufficient and pollinating insects abundant.

Northern communities are concerned about changes in berry shrub growth and productivity because of the importance of berries in tundra ecosystems to wildlife, human health and indigenous culture and identity. Interviews with community members in Nain suggest that berries are less abundant and smaller than in previous years. People also identified that the taste of berries has changed

“We go berry picking not only for fun, but for food. It is part of our culture. Even if I still have some in the freezer from last year, I will go to pick some more”.

Lizzie Irniq, Kangiqsujuaq.

“I hope we never lose our country food because without that, what will we do?” **Sarah Pasha Annanack, Kangiqsualujjuaq.**

and that the leaves and berries of berry plants sometimes appear “burnt” (L. Siegwart Collier, unpubl. data, pers. comm.). In Kangiqsualujjuaq, community members have noticed that the berries start to grow, bloom and ripen earlier in the season. In Kangiqsujuaq, people have already observed that greater snow accumulations mean lots of berries the following summer (Gérin-Lajoie et al. in prep.).

8.3.1 Antioxidant activity and phenolic compounds in berries

Berries around the world are rich in antioxidants and phenolic compounds. In the North, despite their important role in the diet, few studies have quantified antioxidant activity. Preliminary results obtained from Kangiqsualujjuaq and Kangiqsujuaq suggest that black crowberry/blackberry and partridgeberry/redberry are the two species with the highest antioxidant capacity and total phenolic compounds while bog bilberry/blueberry has lower antioxidant activity and total phenolic compounds (C. Lavallée, unpubl. data, pers. comm.) (Table 2). Harris et al. (in prep.) had comparable results from samples taken from boreal forest and the Eastern Subarctic, with black crowberry/blackberry having higher antioxidant activity after juniper berries with partridgeberry/redberry close in antioxidant activity. Samples of bog bilberry/blueberry harvested from different localities gave lesser activity, although they are still good candidates as antioxidants. Northerners are interested in studies on the importance of

latitudinal gradient in antioxidant as well as gene expression linked to substances known to possess antioxidant potential. Results demonstrate that coastal and more northerly samples are generally more active. (Fraser et al. 2007, Downing et al. in prep.).

Climate change will impact berry producing plants and in turn will modify the antioxidant activity of their berries. It is still unclear how berries will be affected. Factors are numerous and complex: temperature, shading, soil, rain pattern, photoperiod, even plant genetics as well as diseases and insects will contribute to the production of antioxidant substances in berries. Because northerly individuals tend to produce more phenolic compounds to cope with low temperature and long photoperiod, warming may bring the plant to produce less of those protective compounds that have medicinal value. In Finland, Kahkonen et al. (2001) and other researchers measured phenolic compounds and antioxidant activity of common berries and apples. All species showed some antioxidant activity, especially black crowberry/blackberry and partridgeberry/redberry. Similar studies in Alaska indicate that results are comparable (Leiner et al. 2006, Kellogg et al. 2010). Both black crowberry/blackberry and partridgeberry/redberry seem to be the best berries in terms of antioxidants. Beaulieu et al. (2010) also showed that partridgeberry/redberry is a potentially good antidiabetic plant and this correlates with its antioxidant activity. Harris et al. (in prep.) further analysed a number of berries and came to the same conclusion: berries are a healthy

Table 2. Antioxidant capacity ($\mu\text{mol Trolox equivalents/g FW}$) and total phenolic compounds ($\text{mg Tannic acid/g FW}$) analysed in berries from Kangiqsualujjuaq and Kangiqsujuaq, Nunavik, summer 2009.

COMMON NAMES	LATIN NAMES	KANGIRSUALUJJUAQ		KANGIRSUJUAQ	
		ANTIOXIDANT CAPACITY	TOTAL PHENOLIC COMPOUNDS	ANTIOXIDANT CAPACITY	TOTAL PHENOLIC COMPOUNDS
Black crowberry/ blackberry	<i>Empetrum nigrum</i>	+++	+++	+++	++
Partridgeberry/ redberry	<i>Vaccinium vitis-idaea</i>	+++	+++	+++	+++
Bog bilberry/ blueberry	<i>Vaccinium uliginosum</i>	+	+	+	+

food and contain medicinal agents. Members of different communities in Nunavik and Nunatsiavut have mentioned the importance of berries for health (Gérin-Lajoie et al. in prep., L. Siegwart Collier, unpubl. data, pers. comm., Cuerrier and Elders of Kangiqsujuaq, 2005).

There are potential positive and negative effects of warming on antioxidant concentration in berry plants. Further research is needed to document the relation between latitudinal gradient (or warming) and the berry's nutritive quality.

8.4 Community-based monitoring

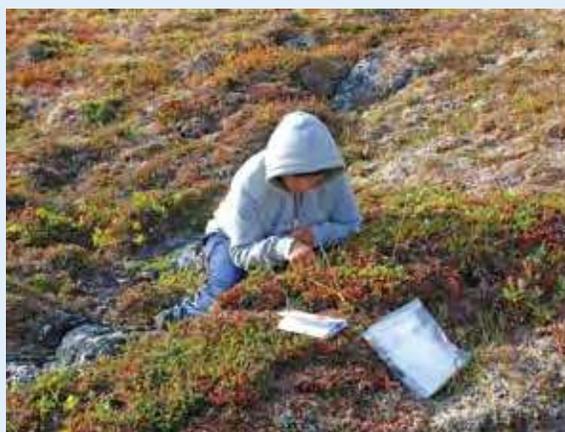
Throughout the world, berry productivity is known to be variable in time and space and the Arctic is no exception. However, this variability has rarely been documented in the Canadian Arctic and Subarctic despite the importance of berry-picking activities for Inuit culture and health. Through joint IPY and ArcticNet efforts, we presently collaborate with 3 Secondary schools in Nunavik (Umiujaq, Kangiqsujuaq and Kangiqsualujjuaq) to collect data about annual berry productivity, snow depth and various

Box 2. Community-based monitoring

Given the importance of berry picking activities to Inuit culture and health, researchers and high school teachers and students from three communities in Nunavik (Umiujaq, Kangiqsujuaq and Kangiqsualujjuaq) help collect information annually on the main berry species consumed by Inuit in areas easily accessible from the communities and representative of community gathering grounds.

Climate data from the local meteorological stations are also compiled and local students hired for snow measurements throughout the winter (Kangiqsujuaq and Kangiqsualujjuaq). In addition, an observation calendar was designed to collect dates and locations of various environmental and ecological phenomena, including phenological events for plants and insects.

This integrated approach is supported by Kativik School Board and a collaborative project is currently developing scientific learning activities using standard protocols to monitor berries. These educational activities are designed to be embedded in the Nunavik Science and Technology curriculum. Part of a larger initiative involving other communities in Nunavut (Kugluktuk, Baker Lake, Iqaluit, Pangnirtung, Pond Inlet), this contributes to capacity-building in science among Inuit Youth, and greatly enhances the understanding of berry productivity variability. Activities and protocols for monitoring other important ecological factors are also under preparation, such as snow depth variations, ice freeze-up and break-up and phenological observations.



phenological observations: blooming, green-down, berry ripening, insect emergence, sea and lake freeze-up/ break-up, etc. This initiative was part of a larger effort across a broad East-West gradient, involving other communities in Nunavut (Kugluktuk, Baker Lake, Iqaluit, Pangnirtung, Pond Inlet) and Nunatsiavut (Nain), as well as two field research sites (Daring Lake, Bylot Island) (Lévesque et al. 2009). Using a simple standard protocol, researchers, teachers and their students as well as various other interested individuals help collect berries (Box 2).

Long term data series are essential to understanding such naturally variable systems and even more so to detecting changing trends. The collaboration with community members greatly enhances our ability to understand northern environments since we can get information year round from people most concerned about this information. In addition, this initiative will contribute to capacity-building in science among Inuit youth, and favour exchanges between scientists and Northerners that may raise issues or phenomena not anticipated.

8.5 Conclusions and recommendations

Vegetation is already changing in Nunavik and Nunatsiavut. Conditions predicted by climate models, especially increased growing season length (11 to 27 days, Chapter 2) and growing degree-days (50% to 150%, Chapter 2) will promote erect shrub species establishment and growth. Their cover and height are predicted to continue to increase throughout the area except on bedrock outcrops. Currently the herb tundra zone has not been greatly colonised by shrubs, but birch and some willows are expected to expand even in these zones.

With the improved conditions favouring increased viable seed production, and seedling establishment, trees are expected to gradually expand beyond current treelines. At this stage, it is impossible to predict the level of change by 2050 according to the climate projections presented

in Chapter 2. Models are being developed to address this issue. Further research is necessary to understand feedbacks of these vegetation changes on the ecosystem and to evaluate how the disturbance regimes will vary in response to climate change, including if and how insect infestations and fire will increase.

Warmer and longer growing seasons may not benefit berry producing plants which will face increasing competition from taller shrubs, and potentially lack of moisture if summers are dryer. Changes in precipitation are expected to increase (Chapter 2) but remain uncertain due to the great spatial and temporal variability of precipitation. Berry productivity is sensitive to the abundance and timing of precipitation and extreme events (e.g. late frost in the spring). Berry species producing best in full sun (especially partridgeberry/redberry and bog bilberry/blueberry), will most likely decline under shrub cover, yet the patchy nature of arctic vegetation should enable other species more tolerant to partial shade such as black crowberry/blackberry and cloudberry/bakeapple to take advantage of the changing conditions.

Migration and/or expansion of boreal species (e.g. raspberries) are to be expected in the southern portion of the studied area. Some raspberries were reported near Umiujaq, but not in large abundance, and plumboy (*Rubus arcticus* subsp. *acaulis*) was newly observed in Kangiqsua-lujuaq (Kennedy et al. 2010). Raspberries are also thriving in the latter community, but they seem not to produce berries, which was also the case in Umiujaq in 2005 (A. Cuerrier, pers. comm.).

Major uncertainties relate to the impact of environmental changes on biotic interactions between vegetation and animals, herbivores (both insects and vertebrates) and pollinators. Warmer and longer growing seasons will affect food abundance and quality, as well as change the distribution, diversity and emergence patterns of insects. Changes in pollinator fauna and/or herbivorous insects may also affect berry production as insect distributions shift northwards and/or insect emergence occurs earlier

during warmer seasons. Further studies are needed to document these biotic interactions.

Community-based monitoring will contribute to Northerners' awareness of environmental changes and their capacity to document them. Longer time series from a wide range of sites will benefit communities and researchers and greatly enhance our predictive abilities.

In addition to their competitive impact on berry producing species and other plants, including lichens, taller shrub species (e.g. willow and birch) may affect traveling routes as well as traditional activities like berry picking. In winter, snow deposition patterns are being altered by taller shrubs and in summer, denser and taller vegetation can also restrict movements (see also Chapter 5).

Even if erect shrub growth (including berry producing shrubs) may be limited by grazing (in areas with high caribou density), by dryer conditions, or by other factors, warmer conditions may favour the expansion of species

at their northern distribution limit, such as cloudbberries and raspberries. All these changes will likely affect berry productivity but not in a uniform way, depending on species' ecology (e.g. shade-tolerant species, pollination), substrate characteristics and availability, pollinators as well as local climatic conditions, topography and perturbations.

Northerners have observed changes in their environment both in the past and present (Nickels et al. 2005), and have adjusted their berry-picking activities to the high spatial and inter-annual variability in berry productivity. Additional changes are expected and models are currently under development to integrate the climate and biotic factors to help predict areas most likely to change in berry productivity. This should be helpful in the future when-selecting areas to be protected from additional stress, such as community or industrial developments to ensure easy access to high quality sites for this culturally important activity.



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Chapter 9. Caribou herd dynamics: impacts of climate change on traditional and sport harvesting

Lead authors

Steeve D. Côté
Departement de biologie, Université Laval, Québec, QC

Contributing authors

M. Festa-Bianchet, C. Dussault, J.-P. Tremblay, V. Brodeur, M. Simard, J. Taillon, C. Hins, M. Le Corre and S. Sharma

Abstract

Caribou (*Rangifer tarandus*) are a key species in Arctic ecosystems including northern Québec and Labrador. They play a central role in the ecology of predators and the structure of Arctic plant communities. In addition, caribou provide socioeconomic and cultural benefits from subsistence and sport hunting activities. Changes in the distribution and abundance of caribou due to global climate change would have serious biological, societal, and economic implications. Direct and indirect consequences of climate change on migratory caribou herds may include alteration in habitat use, migration patterns, foraging behaviour and demography. For example, caribou may experience a further northerly shift in distribution due to several factors including longer ice-free periods, increases in snowfall and extreme weather events, alterations in the fire regime, and changes in the distribution of insects and predators. Future research by Caribou Ungava, a research group interested in the ecology of migratory caribou in the context of climate change, will address the factors outlining variations in the population dynamics of caribou, implications for survival and reproduction, as well as the response of caribou habitat to different climate change scenarios. Management efforts focusing on mitigating greenhouse gases to reduce the potential effects of climate change, preserving high quality habitat, limiting anthropogenic landscape disturbances, and managing hunting in a sustainable manner, could alleviate stressors on migratory caribou of the Québec-Labrador peninsula.



9.1 Introduction and importance of caribou for traditional and sport harvesting

Caribou (*Rangifer tarandus*) are a key species in Arctic ecosystems including northern Québec and Labrador. They play a central role in the ecology of predators and the structure of Arctic plant communities (Crête 1999, Bergerud et al. 2008). In addition, caribou provide socio-economic and cultural benefits from subsistence and sport hunting activities. Thus, changes in the distribution and abundance of caribou due to global climate change would have serious biological, societal, and economic implications (Festa-Bianchet et al. 2011).

9.1.1 Traditional harvesting

In the Arctic and Subarctic, caribou are the most important terrestrial subsistence resource for Aboriginal people. Traditional Aboriginal communities and individuals have a strong cultural connection to caribou and economic reliance on caribou for food (Miller 2003). For example, for 24 rural communities in interior Alaska, median caribou harvest was 3.5 kilograms per person per year, reaching as high as 22 kilograms per person per year (Nelson et al. 2008). In northern Québec and Labrador, subsistence hunters are thought to harvest about 15,000 caribou each year (MRNF 2009, unpubl. data), providing 347 tonnes of meat (AMAP 1998). The actual Aboriginal harvest, however, is unknown as there are no quota or registration requirements.

The health and cultural survival of indigenous peoples are directly affected by any potential impacts of climate change on caribou harvests. Most migratory caribou herds are declining or have recently declined (Vors and Boyce 2009). Current caribou numbers in northern Québec and Labrador are not known precisely because the last survey was conducted 10 years ago, but biological indicators of population size as well as observations by Aboriginal harvesters and outfitters suggest caribou are declining or

have declined substantially in the last decade. In addition, weather conditions are critical in the caribou's selection of seasonal migratory routes and winter grounds, affecting hunter success. Long-term climate changes may affect access to hunting grounds, for example by changing the timing of freeze-up and break-up of large bodies of water. If climate change alters the distribution of caribou away from northern villages, hunting may become increasingly difficult.

9.1.2 Outfitting industry and sport hunting

In northern Québec, there are 90 to 100 outfitting businesses and approximately 11,000 sport hunters who head north to hunt caribou. The sport hunt includes two seasons: 5,000 to 10,000 animals are harvested in the fall (August 1st to October 31st), mainly trophy males through outpost camps (MRNF 2009, unpubl. data); and the winter hunt (November 15 to February 15) which mainly involves Québec residents in the James Bay area with an average annual harvest of 12,000 caribou. Caribou sport hunting generates nearly \$20 million in annual revenues, for a total economic impact exceeding \$30 million, excluding tax returns to governments.

9.2 Caribou herd dynamics

9.2.1 Caribou herds in northern Québec and Labrador

Two migratory caribou populations are found on the Québec-Labrador peninsula: the Rivière-George herd (RG) and the Rivière-aux-Feuilles herd (RAF) (Boulet et al. 2007). These caribou travel up to 6,000 km per year (Bergerud et al. 2008). They occupy the peninsula north of 53°N although they have been seen as far south as 50° 30'N in recent winters. Although not genetically different (Boulet et al. 2007), these two herds differ in body size and condition, as well as in movement rates and demography (Couturier et al. 2010). The small (ca. 5000) Torn-gat herd which belongs to the mountain ecotype, migrates

up the Torngat Mountains in Labrador (Bélanger and Le Hénaff 1985). This herd is often confused with the RG herd, whose range it overlaps during part of the year (Schaefer and Lutich 1998).

9.2.2 Historical variation in population abundance

The RG and RAF herds exhibited dramatic population fluctuations in recent decades (Messier et al. 1988, Boudreau et al. 2003). After a population peak in the 1890s (Low 1896, Elton 1942), the RG herd remained extremely low until the 1950s when it included only about 5,000 animals (Banfield and Tener 1958). By 1993, the population had increased to more than 775,000 (Couturier et al.

1996). It then decreased to about 385,000 by 2001 (Couturier et al. 2004) and 74,000 by 2010. The RAF herd was first described in June 1975 when Le Hénaff (1976) saw a group of about 20,000 calving females near the Leaf River (58 °N, 73 °W). The RAF herd increased from 56,000 animals estimated in 1975 to 276,000 in 1991, and to at least 628,000 in 2001 (Couturier et al. 2004). The RAF herd has declined since 2001. An aerial survey is planned for July 2010.

9.2.3 Distribution, seasonal migrations and seasonal ranges

Migratory caribou of northern Québec and Labrador range over more than 1 million km² (Figure 1). The mi-

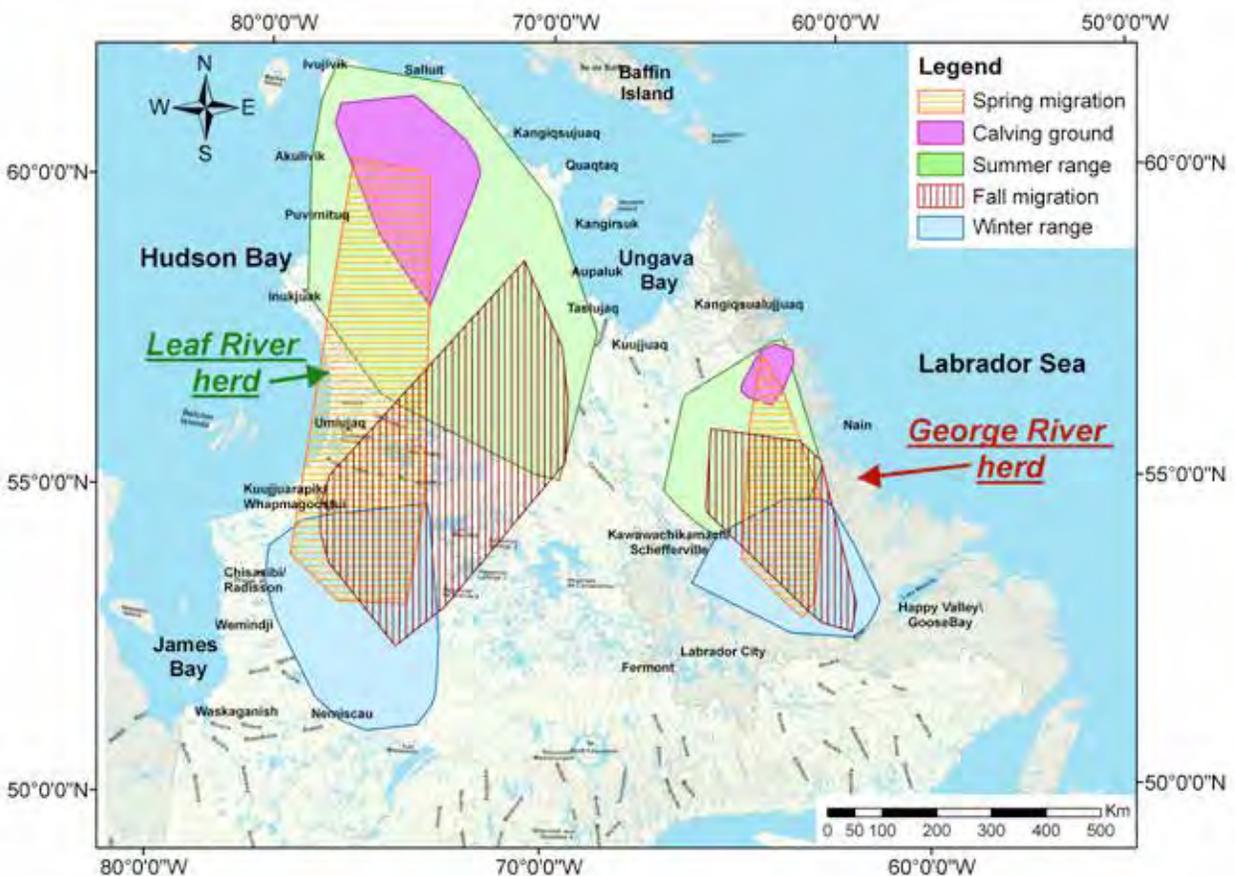


Figure 1. Seasonal ranges of the Rivière-George and Rivière-aux-Feuilles caribou herds, Québec-Labrador peninsula.

gration routes and seasonal ranges of caribou from the RG and RAF herds have been monitored during the last 25 years using radio and satellite telemetry. Between 1986 and 2010, more than 300 animals were fitted with satellite transmitters.

Migratory caribou undertake large seasonal migrations to use specific habitats, exploit seasonal resources and avoid predators. Seasonal migrations involve directional movements of 15 to 30 km per day. In early spring, caribou leave their winter ranges in the taiga and migrate over hundreds of kilometres (RG: 280 ± 20 km; RAF: 630 ± 15 km) to reach calving grounds in the tundra. Adult females usually initiate spring migration first, followed by adult males and non-reproductive sub adults. Initiation of spring migration by females of the RAF herd is earlier and more variable (mean: 3 April \pm 30 days) than for females of the RG herd (mean: 25 April \pm 10 days). Preliminary results suggest that a delay in the initiation of spring migration may lower calf birth mass and reduce fall recruitment rates.

Females of the RG herd calve on the high tundra plateaus on the eastern Québec/Labrador peninsula (57°N , 65°W), whereas females of the RAF herd calve on the Ungava Peninsula (61°N , 74°W , Figure 2). These calving grounds are more than 800 km apart (Boulet et al. 2007) and are used from early June (RG: 1 June \pm 6 days; RAF: 4 June \pm 6 days) to early July (RG: 1 July \pm 4 days; RAF: 2 July \pm 3 days). The size of the RAF calving ground has remained relatively stable since the 1990s (mean: $53,700 \pm 9,700$ km²), whereas the RG calving ground declined drastically from $46,500 \pm 8,800$ km² in the early 1990s to $5,300 \pm 1,100$ km² in the last three years. Although females generally show strong fidelity to their calving ground (Boulet et al. 2007), the locations of the calving grounds have changed over time for both herds. The RAF calving ground has shifted northward, whereas the RG calving ground has moved east to the Labrador coast (Figure 2).

Summer ranges are larger than calving grounds and are used from early July to mid-September. The size of the summer range of the RAF herd has remained rela-

tively stable since the 1990s (mean: $178,900 \pm 5,300$ km²), whereas that of the RG herd has declined from $234,600 \pm 12,800$ km² in the early 1990s to $88,800 \pm 2,700$ km² in the last three years. Caribou can travel hundreds to thousands of kilometres while on summer ranges (RG: 970 ± 35 km; RAF: 1000 ± 41 km). There is substantial annual variability in the period of use of summer ranges (for both herds: from 50 to 90 days). Preliminary analyses suggest that a longer period of use of the summer range is positively correlated with fall recruitment.

In mid-September, caribou leave their summer range and migrate south. Initiation of the fall migration is less variable than for the spring migration and is similar between herds (RAF: mean=10 September \pm 6 days; RG: mean=11 September \pm 9 days). During the fall migration, reproductive females and males form large aggregations. The peak of the rut is estimated to occur around October 23rd and the majority of adult females breed over a period of 2 weeks.

From November to April, caribou winter in the taiga and concentrate their activities in spruce stands with thick terrestrial lichen cover. During winter, the RAF herd is located mostly between Chibougamau and La Grande Rivière reservoirs, whereas the RG herd winters mostly in Labrador. During this period, caribou move about 5 km per day (RG: 3.2 ± 0.1 km/day; RAF: 5.7 ± 0.4 km/day). The use of winter range, however, is currently poorly understood.

9.2.4 Past and current variation in demography

The population dynamics of long-lived vertebrates, including caribou, are complex because they can be driven by many ecological factors that can affect multiple vital rates (such as natality, calf survival, adult survival and age of first reproduction) in different ways, often with substantial interactive effects. Both the importance of different limiting factors and the relative roles of different vital rates can vary over time (Coulson et al. 2005).

Over the past two decades, long-term studies of ungulates have elucidated the relative roles of different vital rates

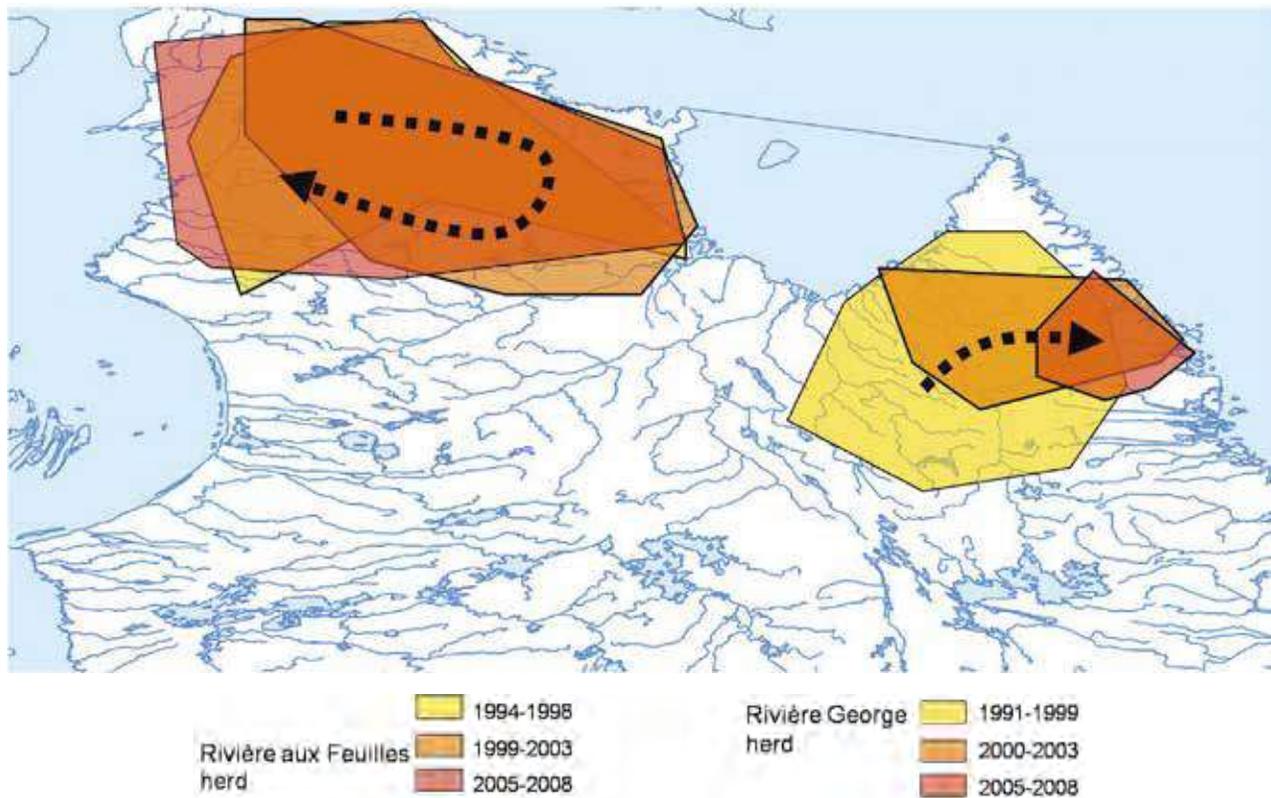


Figure 2. Calving grounds of the Rivière-George and Rivière-aux-Feuilles caribou herds, 1991-2008, Québec-Labrador peninsula.

in contributing to population growth, and the possible effects of various intrinsic and extrinsic factors in driving changes in population size. In general, variation in both adult survival and in survival over the first year of life can be important in determining changes in population growth rates, while variability in productivity is often less important, with the exception of possible changes in age of first reproduction (Gaillard et al. 2000). Ecological factors that affect ungulate populations include density-dependence, climate, disease, hunting and predation. These factors often interact. For example, predation rate can be affected by snow cover (Hebblewhite 2005), the effects of parasites and diseases can be exacerbated by density (Gulland 1992), and inclement weather typically is more pronounced at high population density (Jacobson et al. 2004).

Although it is likely that the population dynamics of migratory caribou, including those in northern Québec and Labrador, would be similar to those of other ungulates, they may show substantial differences for a number of reasons. First, long-distance migrations change the relationship between caribou and their predators. Migratory ungulates can reduce the impact of predators because they are a seasonal resource (Fryxell et al. 1988). Most caribou predators are unable to follow their migration because they must stop to raise their young, or because of intra-specific territoriality (Frame et al. 2008). Second, long-distance movements coupled with limited fidelity to some seasonal ranges mean that caribou population size does not necessarily correlate with density, because the areas used can change from year to year (Messier et al. 1988; Couturier et al. 2010).

Information on age-specific survival and reproduction of migratory caribou is limited, because few studies have monitored known-age animals. Consequently, although both scientific and Aboriginal Traditional knowledge suggest that caribou populations fluctuate widely over decades, the demographic changes underlying those changes are mostly unknown.

Survival and mortality

Studies of known-age ungulates generally report that survival of adult females is high and varies little from year to year, with notable exceptions due to predation, disease and, rarely, extreme weather (Gaillard et al. 2000). Survival of adults declines strongly with advanced age, so that while the survival of females age three to six years is usually 90-95%, the survival of females a decade older is typically less than 60%. Consequently, the age structure of a population strongly affects its expected survival (Festa-Bianchet et al. 2003).

Available estimates of adult female survival for RG caribou include an analysis of age distribution of 875 females that drowned in the Caniapiscau River in 1984. That analysis of cross-sectional data is based on several assumptions (equal sampling probability for all age classes, no difference in initial size of cohorts, stationary population size) that were unlikely supported. Nevertheless, it suggests age-specific survival rates that are typical of most studies of ungulates: average survival is approximately 94-95% for females age 2-7 years; this decreases for older females (Messier et al. 1988). Monitoring of radio-collared females age 2 years and older suggests a decline in survival from an average of 93% in 1984-1986 to 83% in 1990-1992 in the RG herd (Crête et al. 1996). Those estimates, however, do not account for age structure. Given that recruitment declined over this time period, it is likely the average age of radio-collared females also increased. For example, the average age of females harvested during a commercial hunt near Nain, Labrador increased from 4 to 5 years from the 1970s to the 1980s (Bergerud et al. 2008).

A preliminary analysis of survival of radio-collared caribou in the RG and RAF herds from 1996 to 2009 suggests that yearling female survival was only 69% (N=65), much lower than, for example, the 93% estimated by Fancy et al. (1994) for yearling females in the Porcupine herd in Yukon. Survival of adult females was 82%, increasing to 87% if known hunting mortality was excluded.

There are no age-specific estimates of adult male survival, although it is likely lower than for females of the same age, as is typical of ungulates (Toïgo and Gaillard 2003). Comparisons of sex ratio from fetuses to adults reveal a declining proportion of males (Bergerud et al. 2008). Data on radio-collared adult males in the two migratory herds in Québec-Labrador since 1996 suggest a low survival of 51%, based on 61 caribou-years of monitoring 39 adult males. If hunting mortality was excluded, adult male survival was 65%. In the Porcupine herd of migratory caribou (Fancy et al. 1994), adult survival was similar for females and males (84.2% and 82.6% respectively) but exact age was not accounted for.

Reproduction

In ungulates, reproductive rates are strongly affected by age (Gaillard et al. 2000). The age at first reproduction often increases with increasing population density, and pregnancy rates are lower for very young females than for prime-aged females. In most species, females age 3 to 4 to about 10 to 12 years have very high pregnancy rates, typically over 90% (Gaillard et al. 2000). Reproductive senescence begins later than survival senescence, and few females reach the age of 13 to 14 years when reproductive rates decline. Maternal age usually does not have an important effect on juvenile survival, with the exception of primiparous mothers, whose offspring tend to have lower survival rates than those of mothers who have given birth two or more times.

Productivity in northern Québec-Labrador appears to be generally high, although it was greater (average 91%) during years of population increase than during years of

population decline, when it was about 69% (Couturier et al. 2009a). Female age plays an important role in determining how population dynamics may affect pregnancy rates. Comparing the increase and decline phases of the RG herd, pregnancy rates of females age four and older declined from 96% to 82%, but for females age two or three the decline was from 77% to 24% (Bergerud et al. 2008).

Recruitment rate

In caribou, recruitment is best measured as the number of calves that survive to one year of age, because mortality of calves can be substantial and highly variable both pre- and post-weaned (Bergerud et al. 2008). Yearling survival is usually high and stable, although in most ungulates it remains lower and more variable than adult survival (Gaillard et al. 2000).

There is little information on calf survival from weaning (October) to the following June. Comparisons of calf to female ratios in fall and spring cumulate the errors and biases of two ratios. Nevertheless, looking at the time period between 1974 to 1992 suggests overwinter survival likely declined from years when the RG herd was increasing (1973 to 1983, average of 67.4% winter calf survival) to when it was declining (1985 to 1992, average 47% survival). The yearling to female ratio over these periods dropped from 33% to 16% (Bergerud et al. 2008). Calf survival is strongly affected by body condition, as revealed by the positive relationship between birth mass and recruitment rate measured as calf to female ratio in the fall (Couturier et al. 2009b). Although population statistics are often used to calculate the ‘minimum’ recruitment at either weaning or one year required to maintain a stable population, it is not a very good predictor of population growth because changes in age structure or in adult survival can have strong effects on population dynamics. Nevertheless, a series of years with poor recruitment will inevitably lead to population declines. Couturier et al. (2009b) estimated that when average calf birth mass is less than 6.0 kg, calf recruitment may be insufficient to maintain a stable population. A time series of classi-

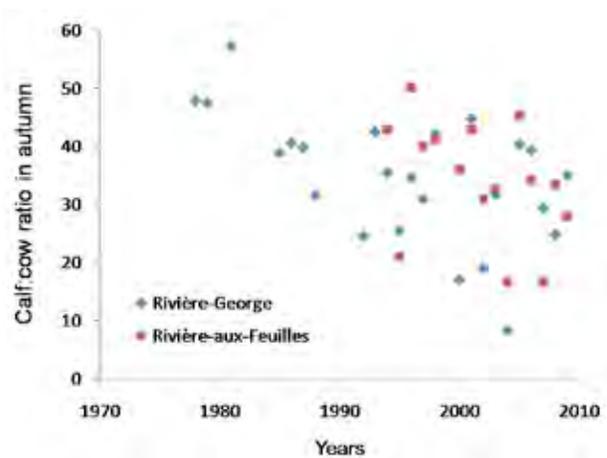


Figure 3. Cow:calf ratios in October for the Rivière-George and Rivière-aux-Feuilles caribou herds in northern Québec and Labrador.

fied counts conducted in the fall suggests that calf to female ratios have been lower in recent years in both herds, compared to ratios observed in the RG herd during the increase phase in the 1980s (Figure 3).

9.3 Expected impacts of climate change on herd dynamics

9.3.1 Impacts on migration routes

Migration is important habitat selection behaviour for large herbivores. These large-scale movements may allow animals to follow plant phenology (see section 9.3.2), adapt to seasonal changes in food availability, or limit predation risk during critical periods such as calving (Bolger et al. 2008). In spring, caribou migrate north to calving grounds where predation risk is low (Fancy and Whitten 1991) and high quality forage is available. Caribou arrival on calving grounds usually corresponds to a peak in vegetation productivity (Post et al. 2003). Migration, however, also involves high energy expenditures (Wikelski et al. 2003) and is a critical period of the year. Environmental variations related to climate change could have a dramatic impact on migratory species such as caribou.

***Timing of migration and freshwater ice formation:
Increasing risk of massive mortality associated with
crossing rivers and reservoirs***

The spring migration typically occurs just before ice cover breaks up on lakes and hydro-electric reservoirs, while the fall migration occurs at about the time lakes and reservoirs are freezing up. Migrating caribou use frozen lakes and rivers to facilitate movements. However, with climate change, the ice-free period is predicted to lengthen (see chapter 2, Magnuson et al. 2000) with earlier thaws and later freezing. Caribou will then be more likely to encounter partially frozen or ice-free lakes and rivers along their migration routes. Large bodies of water, once beneficial to caribou, could become obstacles, forcing caribou to go around them as observed in recent years. It is likely incidental mortality associated with crossing over thin ice will increase.

In the Northwest Territories, Miller and Gunn (1986) observed that migrating barren-ground caribou that encountered lake ice too thin to bear their weight hesitated to cross ice that had no snow cover and some, mostly bulls, broke through the thin ice. Although some caribou escaped, risk of death by drowning, hypothermia or exhaustion were high. Dead animals had severe injuries in their forelegs, obtained as they tried to extract themselves from broken ice (Miller and Gunn 1986; S. Côté, pers. obs.). Injured and exhausted caribou are vulnerable to predation. Caribou can swim across ice-free water, but the increase in precipitation expected under global warming (see chapter 2, Maxwell 1992) could increase water discharge in large rivers, thereby increasing the risk of massive drowning. For example, the death of 10,000 caribou that attempted to cross the Caniapiscou River (northern Québec) in 1984 was mainly attributed to the abnormally high water flow (Nault and Le Hénaff 1988). A delay in migration to avoid ice-free bodies of water could reduce reproductive success, as females might not be able to reach calving grounds in time and be forced to calve in suboptimal sites (Fancy and Whitten 1991). Unless caribou populations move to higher latitudes (Sharma et al.

2009), they may have to initiate spring migration earlier and fall migration later (Brotton and Wall 1997) in order to safely cross large bodies of water.

Snow depth and energy expenditures

Temperatures and snowfall are expected to increase with global climate change (Maxwell 1992), which will modify snow quality. According to the Canadian Regional Climate Model, snowfall in Nunavik may increase by 30 to 50% in the 2041-2070 period compared to the 1960 to 1990 average (CCCSN 2009). Snow depth and frequency of thaws could also increase, resulting in a denser and wetter snow layer. In addition to reducing forage accessibility (Miller and Gunn 2003; section 9.3.3.1), these changes will increase the energetic costs of movements during critical periods.

Higher temperatures in spring could induce an earlier onset of snowmelt. Snow cover may last longer because of greater accumulations. Caribou could then be forced to migrate over deep snow, increasing the energy cost of migration. Parker et al. (1984) showed that the energy costs of movements in cervids increase exponentially with sinking depth. Heavy and wet snow might further impede locomotion. Increased energy expenditures combined with lower resource availability could lower body condition and ultimately affect population dynamics because most life history traits are closely related to body condition. Couturier et al. (2009b) showed that winter snowfall experienced by caribou mothers has a negative impact on the mass of their offspring.

Changes in the snowfall regime in the fall, unlike spring, might be beneficial to caribou during migration. Delayed snowfall up to 16 days in Nunavik and Nunatsiavut (see chapter 2) in fall will facilitate access to resources and movements, thereby limiting energy expenditures (Brotton and Wall 1997). Energy savings, however, could be reduced by the costs of increased distance traveled if caribou must avoid ice-free water bodies.

9.3.2 Mismatch in the timing of calving and timing of forage availability influence recruitment rate

Caribou track variation in day length through complex hormonal processes to prepare for seasonal changes in foraging conditions (Bronson 2009). Normally, this adaptation guarantees synchrony between calving and the onset of the plant growing season. The nutritional content and digestibility of plants peak soon after their emergence and decline rapidly thereafter (Klein 1990; Albon and Langvatn 1992). Synchronizing calving with the peak in forage quality is crucial for reproduction since energy requirements for females increase 65-215% during the first month post-partum (Robbins 1993).

Climate change is likely to affect the relationship between the timing of calving and forage availability by changing the timing of green-up and the length of the growing season (Bradshaw and Holzapfel 2006). The timing of plant development and growth is mainly driven by changes in temperature, with warmer springs leading to earlier onset of plant growth (Parmesan and Yohe 2003). The annual timing of calving is much less variable than that of plant growth since it is partly driven by photoperiod (Post and Forchhammer 2008), generating a mismatch between the timing of spring green-up and of caribou calving. A two-week advance in the onset of plant growth in West Greenland has been related to a fourfold decline in calf production (Post and Forchhammer 2008; Post et al. 2008).

9.3.3 Impact of climate change on forage availability

Winter forage

Lichens growing on the ground (terricolous) and in trees (arboreal) form the staple of caribou diet in winter (Crête et al. 1990a). They contain a high amount of digestible energy (Côté 1998), providing the fuel needed by caribou to travel, forage in deep snow and maintain body temperature. Winter forage ensures caribou do not use the fat and protein re-

serves accumulated during the snow-free period which are required by pregnant females to grow their fetuses. Lichen cover is globally decreasing in the Arctic in response to climate change. In Alaska, higher occurrence of wildfires and competition from grasses and shrubs induced by climate change has led to a widespread decline in lichens over the last decades (Joly et al. 2009).

Extreme weather events associated with climate change can drive the dynamics of caribou herds through their effect on winter forage. Freezing rains on snow have led to massive die-offs of Peary caribou in the Canadian High Arctic (Miller and Gunn 2003) and on Svalbard (Solberg et al. 2001, but see Tyler 2010). Frozen layers of snow affect the ability of ungulates to travel and forage. Some climate scenarios suggest an increase in the prevalence of rain or snow in the winter ranges of the RG and RAF herds (Rennert et al. 2009). Alternatively, the occurrence of wet and heavy snow in the winter habitat of migratory caribou may increase the litter fall of arboreal lichens and provide an additional source of food (Tremblay et al. 2005).

Spring and summer forage

Caribou depend on high-quality forage during spring and summer for reproduction, growth and replenishment of body reserves. Because their winter diet is based largely on low-protein lichens, caribou have a negative protein balance for 7 months of the year (Gerhart et al. 1996). Protein requirement increases steeply in late winter when up to 80% of the fetal mass is deposited (Robbins 1993), using up protein stored during the previous summer. After calving, females use protein obtained from growing plants to produce milk. A summer diet rich in protein is also essential for males that must regain body mass lost in winter and reach prime condition for the autumn rut.

Deciduous shrubs such as dwarf birch (*Betula nana*) and willows (*Salix* spp.) account for 70% of the rumen content in caribou from the RAF herd in July (Crête et al. 1990b). Shrubs respond dramatically to warming in

arctic ecosystems. In Alaska, Tape et al. (2006) reported a 33 to 160% increase in the relative abundance of deciduous shrubs from 1945 to 2002. A similar study near Kangiqsualujjuaq revealed a relative increase of 29% in the cover of erect shrubs from 1964 to 2003 (Tremblay and Lévesque, unpubl. data). Increasing cover of shrubs (further discussed in chapter 8) could increase summer forage for caribou, but earlier onset of the growing season (as projected in chapter 2) may reduce digestibility of leaves through the accumulation of lignin, tannins and phenols (Herfindal et al. 2006). The response of plants to warming varies among species (see chapter 8), soil nutrients and the level of temperature increase. In nutrient-poor soils such as those found in Nunavik, a decrease in protein is expected (Turunen et al. 2009).

9.3.4 Changes in abundance and distribution of competitors, predators, parasites, and diseases

In Nunavik, musk ox (*Ovibos moschatus*) are caribou's only potential competitors (Wilkinson et al. 1976). The introduced population of musk ox occupies a small portion of the caribou range at moderate densities. They are mostly located along the coast northwest of Kuujjuaq and number only a few thousand individuals (Jean et al. 2004). Climate change is unlikely to impact their abundance to a point that would be detrimental to caribou. The main predators of caribou in northern Québec and Labrador are wolves (*Canis lupus*) and black bears (*Ursus americanus*). Almost no information exists on these predators on the northern Québec-Labrador peninsula, and the potential impact of climate change on their population dynamics is unknown.

Caribou diseases in RG and RAF herds are not regularly monitored, but the possible impacts of climate change on caribou disease are well documented elsewhere in Canada (Bradley et al. 2005; Hoberg et al. 2008). Direct changes such as an increase of insect harassment may cause secondary infections and a loss of body condition (Weladji et al. 2002). A study on the RG showed that pregnant

females reduced feeding time and moved towards snow patches during the period of insect harassment (Toupin et al. 1996). An increase of biting flies that are carriers of parasites may increase infection rates. For example, *Besnoitia tarandi* can cause severe skin and reproductive organ infections in caribou and is suspected to be transmitted by biting insects (Wobeser 1976; Glover et al. 1990). The number of *B. tarandi* cysts is higher in the RAF than in the RG herd and other sampled western herds (e.g. Bathurst, Bluenose West, Porcupine, Southampton) (J. Ducrocq, pers. comm.). Higher temperatures shorten the development time of larval nematodes (from the Strongyle group) in slugs and snails, hence increasing parasite abundance in caribou that accidentally ingest them while feeding (Kutz et al. 2001; Kutz et al. 2005; Jenkins et al. 2006; Ball et al. 2001). Snails are also hosts to the giant liver fluke (*Fascioloides magna*), present in caribou of both the RG and RAF herds, especially the RG (Choquette et al. 1971; Lankester and Luttich 1988).

The transmission of the parasitic protozoa *Toxoplasma gondii* is dependent on environmental factors such as warmer weather which is optimal for oocyst (egg) development. Abundant rainfalls increase run-offs and parasite transportation and thus increase infection risk while drinking or feeding (Meerburg and Kijlstra 2009). In eastern Canada, Canada lynx (*Lynx canadensis*) are the only felids that caribou may encounter. Lynx are the only animal in which *Toxoplasma gondii* can reproduce and produce oocysts that can be deposited into the environment. Lynx are present as far north as Kuujjuaraapik and Kuujjuaq (Anderson and Lovallo 2003). With a change in habitat, lynx may expand their range northward and infect new Arctic wildlife species or increase the parasite's abundance in the environment. The last survey reported that 0.8% of Nunavik caribou have been exposed to *Toxoplasma gondii* (Leclair and Doidge 2001). Abundance of *Giardia* sp. and the protozoan parasite *Cryptosporidium* sp. may also be influenced by extreme rainfall events, and changes in stream runoff patterns. Bacteria, such as *Leptospira* sp. and Q-fever (*Coxiella burnetii*), may persist in the environment when water surfaces are warmer,

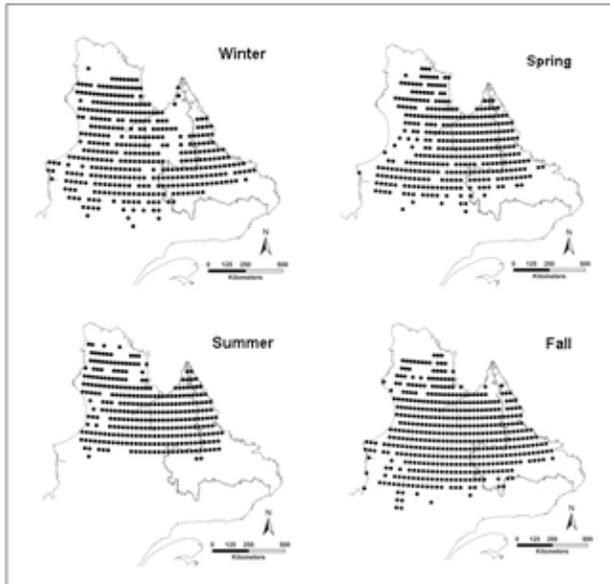


Figure 4. Rivière-George migratory caribou occurrence for 1988-2003, Québec-Labrador peninsula (from Sharma et al. 2009). Points represent at least one occurrence of satellite-tagged caribou between 1988-2003.

or during desiccation and drought (Hoberg et al. 2008). Evidence of infection by these bacteria has been found in Nunavik musk ox (M. Simard, pers. comm.). As well, these last five pathogens are a concern for Inuit health in Eastern Canada (Messier et al. 2008).

9.4 Modeling of population dynamics and spatial distribution

9.4.1 Predicted occurrence of the Rivière-George and Rivière-aux-Feuilles herds

Global change is predicted to impact many ecosystems by altering species distributions (Walther et al. 2002, Parmesan and Yohe 2003). Arctic ecosystems are especially vulnerable to changes in temperature and precipitation regimes. We compared the current and potential future oc-

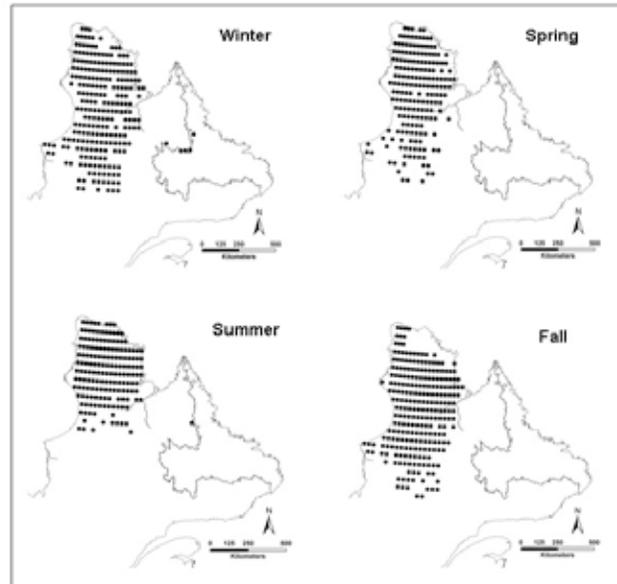


Figure 5. Rivière-aux-Feuilles migratory caribou occurrence for 1994-2003, Québec-Labrador peninsula (from Sharma et al. 2009). Points represent at least one occurrence of satellite-tagged caribou between 1988-2003.

currence of the RG and RAF caribou herds under a Canadian General Circulation Model climate change scenario on the Québec-Labrador peninsula, using climatic and habitat predictor variables (Sharma et al. 2009). Our models were based on Argos satellite-tracking collars on >200 caribou between 1988 and 2003. We assembled a database of climate (temperature, precipitation, snowfall, timing and length of growing season) and habitat data obtained from the SPOT VEGETATION satellite sensor.

Migratory caribou demonstrate spatial and temporal variation in habitat use (Figures 4 and 5). In particular, high quality habitat is a reliable predictor of caribou distribution (O'Brien et al. 2006). Migratory caribou appear to prefer regions with higher snowfall and lichen availability in the fall and winter (Sharma et al. 2009). In the summer, caribou prefer cooler areas likely corresponding to a lower prevalence of insects, and avoid disturbed and recently burnt areas. Using projections from a Canadian General Circulation Model climate change scenario for

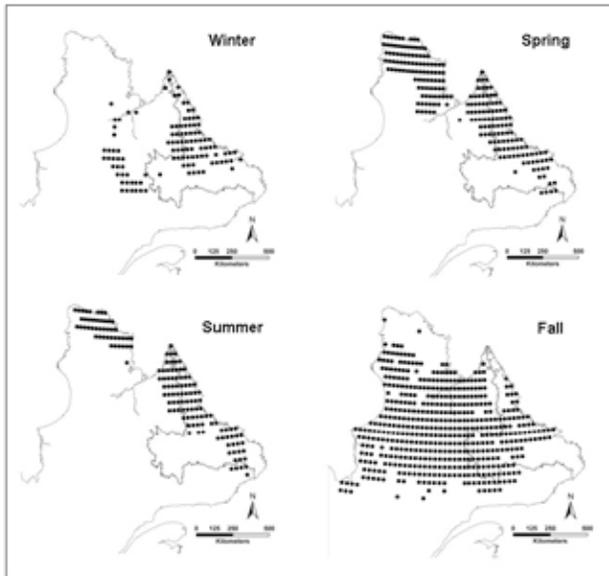


Figure 6. Predicted Rivière-George caribou distribution for 2040-2069 under a climate-change scenario for the Québec-Labrador peninsula (from Sharma et al. 2009).

2040-2069, we predicted that winter, spring and summer RG caribou occurrences will be restricted to the north-eastern portion of Northern Québec and Labrador (Figure 6). In the fall, climatic conditions are likely to be suitable for caribou from the RG herd throughout most of its range. Spring and summer RAF caribou occurrences should remain the same (Figure 7). In the winter and fall, however, climatic conditions should be suitable for caribou from the RAF herd throughout most of the study region. The RAF migratory caribou herd is predicted to expand its range across all seasons, by as much as 47.4% in the winter. Furthermore, the spatial overlap between the two migratory caribou herds is predicted to increase in spring and fall, and decrease in winter and summer. Greater overlap may increase competition on the calving grounds but may also affect their location. In the last two to three decades, the calving grounds of the RG and RAF herds have been separated by about 800 km and the vast majority of females have shown fidelity to very specific calving grounds (Boulet et al. 2007).

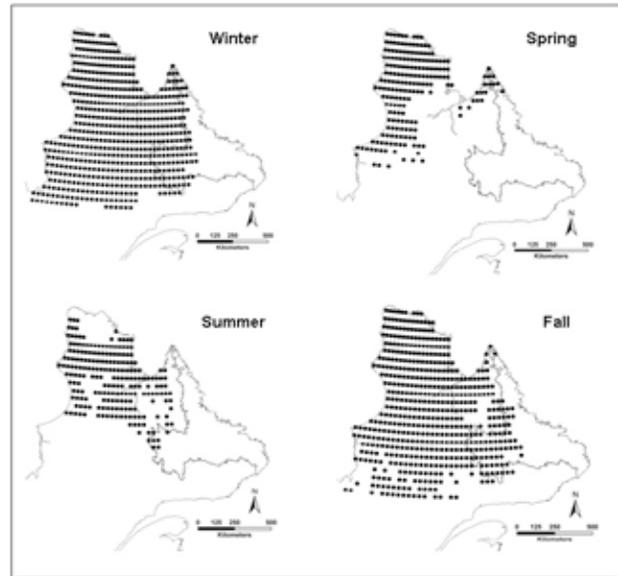


Figure 7. Predicted Rivière-aux-Feuilles caribou distribution for 2040-2069 under a climate-change scenario for the Québec-Labrador peninsula (from Sharma et al. 2009).

9.4.2 Consequences of changes in occurrence

Direct and indirect consequences of climate change on migratory caribou herds may include alteration in habitat use, migration patterns, foraging behaviour and demography, as well as social and economic stress for Aboriginal populations. In addition to the direct effects of climate change on caribou occurrence modelled in this study (Sharma et al. 2009), caribou may experience a further northerly shift in distribution due to several factors including longer ice-free periods, increases in snowfall and extreme weather events, alterations in the fire regime, and changes in the distribution of insects and predators. Reductions in the predicted distributions of these two migratory caribou herds could result in changes in population sizes, further affecting caribou distribution (Bergerud et al. 2008; Couturier et al. 2010). It should be noted, however, that these projections were based on current climate and habitat use during a period when both herds were abundant. If migratory caribou population numbers decrease, there may be range constrictions independent



of climate change (Messier et al. 1988; Bergerud et al. 2008), underlining the difficulty of modelling range use and population dynamics of large migratory herds in a context of changes.

9.5 Adaptability to change in caribou populations

9.5.1 Population monitoring and assessment

Conservation and harvest of caribou require knowledge of population size and structure. The rapid changes in population trends and annual variability in recruitment and survival of caribou require constant monitoring. Satellite telemetry guides field operations and provides valuable information on behavioural and demographic parameters. Known-age individuals are needed to monitor the survival rates of different age classes (Festa-Bianchet et al. 2003). The main purpose of telemetry is to monitor the spatial components of caribou ecology, such as habitat selection, migration patterns and distribution. Maintaining a sample

of radio-collared animals representative of the population requires sustained investment and effort, especially to satisfy the requirements for aerial censuses (Rettie 2008).

Conducting an aerial photographic census is widely used to estimate caribou population abundance in North America (Fisher et al. 2009), based on the seasonal aggregation of animals in open areas. Populations can be estimated from the number of females that aggregate on the calving grounds, or on the post-calving ranges, where the entire population aggregates during the fly harassment period (Couturier et al. 2004). Over the past twenty years, two population censuses have been conducted during the post-calving aggregations in Québec and Labrador (Couturier et al. 2004). The most recent census in 2010 documented the rapid decline of the RG herd. Population censuses are often limited by budget and frequency varies from five to ten years.

Monitoring caribou population structure is essential to assessing population trends between censuses. The annual classification conducted in fall provides information on

BOX 1. The Caribou Ungava website.**An efficient tool for knowledge transfer**

(www.caribou-ungava.ulaval.ca)



Caribou Ungava is a large research program focussing on the ecology and population dynamics of migratory caribou of the Québec-Labrador peninsula in the context of climate change and industrial development. The program is supervised by scientists at Laval University (QC), University of Sherbrooke (QC) and the Ministère des Ressources naturelles et de la Faune du Québec. It was initiated in 2009 to increase knowledge on the ecology of caribou and to respond to various concerns of industry, outfitters and Aborigines. To quickly communicate new knowledge, the team uses a highly efficient and accessible tool, its website. The site is the most important means of communication between the research team, partners, managers and users of the resource. Anyone can track the progress of the research program by visiting the News section where all field activities, conferences, photos, publications and upcoming events are frequently updated. Information vignettes presenting various components of the research program and publicizing new results are also available. These vignettes summarize results in plain language. The website is dynamic, accessible and continuously updated according to the needs of each stakeholder. Anyone interested in migratory caribou can obtain information and find the answers to many questions for personal, scientific and management needs.

the proportion of males, females, yearlings, and calves in the population. The fall female to calf ratio is an indicator of annual recruitment (Couturier et al. 2009b). Close observation of caribou during the classification (in fall) allows biologists to distinguish males of different age categories based on antler size. These results are combined with harvest registration reports and population estimates to calculate harvest rates.

Changes in population abundance influence the body condition of caribou (Couturier et al. 2010). Body condition indices provide information on recent and past environmental conditions. Indicators such as seasonal fat reserves, protein ratios, body size and parasite load are useful to better understand population dynamics (Morellet et al. 2007). Caribou body condition varies with habitat quality and environmental conditions (Couturier et al. 2009a).

9.5.2 Management and conservation of migratory caribou under climate change

In Québec, migratory caribou are subject to a specific management plan developed following consultation with all stakeholders to allow for sustainable subsistence, and sport and commercial harvests (Jean and Lamontagne 2004). The Québec government developed the Management plan in close cooperation with the Hunting, Fishing and Trapping Coordinating Committee (HFTCC), who's mandate is to integrate the rights of the signatory Aboriginal peoples into the management of wildlife species in the Territory covered by the James Bay and Northern Québec Agreement and the Northeastern Québec Agreement.

The RG herd ranges over Québec and Newfoundland/Labrador. They are managed by different jurisdictions and hunting modalities depending on location and time

of year. The spatial organization of hunting management is based on known seasonal ranges. Climate change could modify the seasonal distribution of caribou and changes in their conservation and management could be required (Sharma et al. 2009).

The current management plan for migratory caribou in Québec was not developed in collaboration with Newfoundland and Labrador. It was planned to be revised in late 2011 based on the population estimates obtained through the aerial survey of July 2010 for the Rivière-George herd and the one planned for the Rivière-aux-Feuilles herd. Collaboration between the two provinces, the HFTCC, the Labrador and Québec Innu, and the Inuit of Nunatsiavut is essential for the sustainable management of caribou. Communication is fundamental to adapting management guidelines to the changing environment and caribou populations.

9.5.3 Conservation and protection of caribou habitat

The protection of caribou habitat can contribute to the conservation of the species by limiting habitat loss and exposure to human-induced stresses. Calving grounds are critical areas where caribou are most vulnerable. The RAF and RG calving grounds are currently the only areas protected by Québec law as habitat for migratory caribou (Loi sur la conservation et la mise en valeur de la faune, L.R.Q., c. C-61.1, r.18). These calving grounds are protected only from 15 May to 1 July, when most activities are prohibited or have to be authorized by the Ministry.

It is difficult to legally define the habitat of migratory caribou because the area concerned is extremely large and changes over time. Variations in migration patterns and in the distribution of the two herds require a flexible approach. For example, the location of the calving grounds of the RG herd has changed substantially over time (Figure 9.2), and its protection must be adaptable over time as well. This difficult task will require large buffers around current calving grounds to allow for future movements.



Our increasing knowledge of caribou ecology and the potential effects of climate change on vegetation will contribute to better protect caribou habitat from industrial activities.

9.5.4 Hunting caribou in the future

Preliminary analyses of hunting mortality of radio-collared caribou over the last few years suggest that harvest levels may be substantial. In particular, hunting-related yearly mortality of males may exceed 20%, and harvest of radio-collared females in the RG herd is over 10%. We offer several recommendations to improve the consumptive management of migratory caribou. Our recommendations are driven by two fundamental considerations: harvests should be sustainable (both ecologically and evolutionarily); and based on science. As well, the collection of information from harvested caribou should be improved.

Sustainable harvests require information on population size and composition, or as a minimum, on harvest rates. Continued monitoring of harvest rates of marked caribou will provide managers with essential information on herd, gender and to some extent age-specific harvest rates. In this regard, efforts to discourage harvest of radio-collared caribou may be counterproductive, as they will negatively bias the estimation of harvest rate.

There is currently much emphasis on the size of antlers of harvested males, and in recent years the proportion of large males appeared to have declined precipitously. As managers realize the evolutionary and ecological importance of large mature males, it is to be hoped that the future harvest will no longer be based principally on the size of antlers. Sociocultural changes in the attitude of caribou hunters may be as effective as changes in regulations to improve the sustainability of caribou harvesting.

The continued sustainable harvest of migratory caribou, whether as subsistence or sport hunting, requires information on what is available and what is being harvested. The large yearly harvest of caribou of all gender and age classes during the winter hunt may not be sustainable, and the autumn trophy hunt may remove a very large proportion of mature males before the rut. Information on the numbers and gender and age composition of caribou harvested

in the autumn, winter, and Aboriginal hunt would allow managers to assess the impact of these different harvests, particularly if collected over several years.

9.6 Conclusion

The RG and RAF herds are two of the largest migratory caribou populations in the world (Vors and Boyce 2009), and declines in their numbers could have negative social and economical implications, particularly for northern arctic and subarctic First Nation and Inuit cultures that rely on caribou for subsistence (Miller 2003). Changes in the distribution of caribou, for example a shift to Labrador for the RG herd (Sharma et al. 2009), as well as decreases in abundance, are expected in the near future. We anticipate the negative effects of changes in the distribution of animals and reduced abundance of caribou will be stronger than the positive effects of an earlier and longer



period of vegetation growth. Available evidence suggests that caribou abundance and distribution will change in the near future. Managers, stakeholders and communities should be prepared for a lower abundance of animals and perhaps a less predictable distribution, further away from communities. Future research by Caribou Ungava (Box 1), a research group interested in the ecology of migratory caribou in the context of climate change, will address the factors outlining variations in the population dynamics of caribou, implications for survival and reproduction, as well as the response of caribou habitat to different climate change scenarios. Management efforts focusing on mitigating greenhouse gases to reduce the potential effects of climate change, preserving high quality habitat, limiting anthropogenic landscape disturbances, and managing hunting in a sustainable manner, could alleviate stressors on migratory caribou of the Québec-Labrador peninsula.

9.7 Acknowledgements

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Chapter 10. A first look at Nunatsiavut *Kangidualuk* ('fjord') ecosystems

Lead author

Tanya Brown^{1,2,3}, Ken Reimer³, Tom Sheldon⁴, Trevor Bell⁵

¹Department of Biochemistry and Microbiology, University of Victoria, Victoria, BC; ²Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, BC; ³Environmental Sciences Group, Royal Military College of Canada, Kingston, ON; ⁴Nunatsiavut Government, Nain, NF; ⁵Memorial University of Newfoundland, St. John's, NF

Contributing authors

S. Bentley, R. Pienitz, M. Gosselin, M. Blais, M. Carpenter, E. Estrada, T. Richerol, E. Kahlmeyer, S. Luque, B. Sjare, A. Fisk, S. Iverson

Abstract

Long marine inlets that are classified as either fjords or fjards indent the Labrador coast. Along the mountainous north coast a classic fjord landscape dominates, with deep (up to ~300 m) muddy basins separated by rocky sills and flanked by high (up to 1,000 m), steep sidewalls. In contrast, the fjards of the central and southern coast are generally shallow (150 m), irregularly shaped inlets with gently sloping sidewalls and large intertidal zones. These fjords and fjards are important feeding grounds for marine mammals and seabirds and are commonly used by Inuit for hunting and travel. Despite their ecological and socio-cultural importance, these marine ecosystems are largely understudied. The *Nunatsiavut Nuluak* project has, as a primary goal, to undertake baseline inventories and comparative assessments of representative marine ecosystems in Labrador, including benthic and pelagic community composition, distribution and abundance, fjord processes, and oceanographic conditions. A case study demonstrating ecosystem resilience to anthropogenic disturbance is examined. This information provides a foundation for further research and monitoring as climate change and anthropogenic pressures alter recent baselines.



10.1 Introduction

Spectacular fjords indent the Northern Labrador coastline. These fjords are influenced by both Atlantic and Arctic water masses and receive freshwater, nutrients and sediments from glaciers and rivers. Fjords are typically long, narrow inlets carved by glacier ice. Classic fjords have deep muddy basins separated by rock sills and flanked by tall, steep sidewalls. In contrast, shallow, irregularly shaped inlets with gently sloping sidewalls and large intertidal zones dominate the central Labrador coast. These less spectacular inlets, though also glacially carved, are termed fjards.

Labrador fjords and fjards host both Arctic and boreal flora and fauna and are an important feeding ground for marine mammals and seabirds. Humans have inhabited these inlets for millennia, drawn to the rich and diverse natural resources and favourable climate. Labrador Inuit depend on these environments for harvesting, travel and economic development; they also recognize the increased pressures placed on these sensitive systems from natural (e.g. climate) and anthropogenic (e.g. industry) changes.

Although these coastal zones are extremely important for Inuit health and wellbeing, they remain understudied and relatively unknown from a scientific perspective. For instance, only scant details are available on their ecology, physical oceanography and land-ocean linkages. In order to assess the potential impacts of elevated or new stressors, it is necessary to establish a baseline against which observed or predicted changes can be measured. Consequently, since 2006 our multi-disciplinary team of university, industry and government researchers has undertaken baseline inventories and comparative assessments of four representative marine ecosystems in Labrador.

The broad objective of our program is to address Inuit concerns regarding the ecological integrity of these marine environments in the face of climate change, natural resource extraction and contamination. The four marine ecosystems are: Nachvak Fjord, a pristine fjord in north-

ern Labrador surrounded by Torngat Mountains National Park (TMNP); Saglek Fjord, a fjord with a point source of contamination also in northern Labrador; Okak Bay, a fjard in central Labrador frequently used for harvesting and travel by Inuit from Nain, the nearest community approximately 100 km to the south; and Anaktalak Bay, another fjard in central Labrador that is the shipping route to a mine and concentrator at the head of the bay (Figure 1). Nachvak and Saglek fjords are located above 58°N latitude, north of treeline and within the Arctic ecoregion, whereas Okak and Anaktalak bays are located between 56° and 58°N latitude within the Subarctic ecoregion, south of treeline.

Prior to the modern era, the only permanent settlements established along the northern Labrador coast were Hudson's Bay Company (HBC) trading posts and Moravian Mission settlements (Fitzhugh 1980). During the 19th and 20th centuries, Okak Bay supported the largest Inuit population on the Labrador Coast. Nutak, located in Okak, was a Moravian Mission and later a HBC post from 1920 to 1956 (Kleivan 1966). The remains of mission sites and HBC trading posts also exist in Saglek and Nachvak fjords. Hebron, the last permanent settlement in northern Labrador, was closed in 1959 when Inuit were forced to re-settle in communities farther south. For the most part, large scale settlement and industrial development are absent in Nachvak Fjord and Okak Bay. TMNP was established in 2005 and research carried out in Nachvak Fjord forms an important component of the park's research and monitoring program.

Outer Saglek Fjord (Saglek Bay) and inner Anaktalak Bay are sites of industrial and modern day human activity. Saglek Bay was used extensively in the 1960s during the construction and maintenance of the Saglek military radar station. Historical operations resulted in extensive polychlorinated biphenyl (PCB) contamination of local soil (Brown et al. 2009, Kuzyk et al. 2005) and prior to soil remediation in 1997-1999, the original contamination spread to the marine environment. Elevated PCBs were measured in marine sediments and the coastal food web

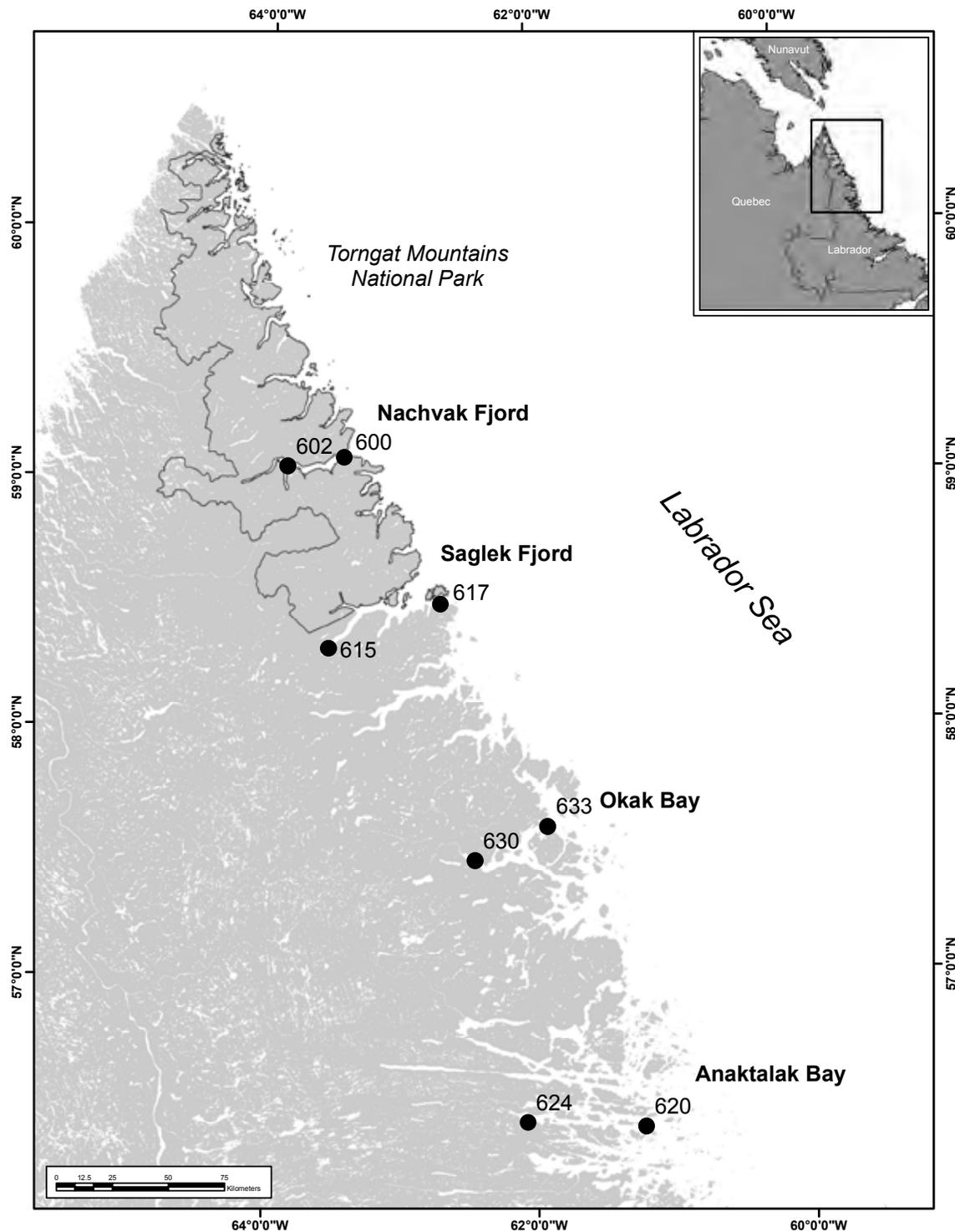


Figure 1. Location of marine study areas in Nunatsiavut (Nachvak, Saglek, Okak and Anaktalak). Oceanographic stations at the head and mouth of the fjords and fjards are indicated.

more than 7.5 km from the original contamination (Kuzyk et al. 2005). Also in Saglek Bay, the kANGIDLUASUK base camp, located on Inuit land at the southern boundary of the TMNP, is the venue for a summer youth camp.

The head of Anaktalak Bay is the site of a nickel-copper-cobalt mine and concentrator that Vale NL (formerly Voisey's Bay Nickel Company) has operated since 2005. Labrador Inuit are concerned with the potential environmental impacts of the mine and concentrator, especially with respect to winter shipping from the dock facility at Edward's Cove along Anaktalak Bay to the Labrador Sea, and the treated effluent from the mine that is discharged into the bay.

This chapter presents what we have learned about these four ecosystems over the past 5 years and identifies information gaps that are critical to fill in the coming years. The baseline work that is being conducted in these marine ecosystems includes: patterns of the community structure; distribution and abundance of both benthic and pelagic fauna and flora; marine sedimentological, palaeoceanographic and palaeolimnological analyses over timescales of Inuit and European settlement and modernization; and the study of Arctic ecosystem resilience to anthropogenic disturbances.

10.2 Physical Features

Nachvak Fjord is a 45-km-long glacial trough that cuts through the heart of the Torngat Mountains, producing 1000-m-high sidewalls and 200-m-deep basins. The fjord is 2-4 km wide, increasing gradually eastward to Nachvak Bay, which opens to the Labrador Sea (Bell and Josenhans 1997). Fjord basins become increasingly deeper from head to mouth, ranging in water depth from 90 to 210 m (Copeland et al. 2008). The basins are separated by sills between 10 and 180 m below sea level, composed of either bedrock or glacial deposits. Seismic profiling of basins revealed unconsolidated sediments more than 180 m thick and spanning two glacial episodes (Rogerson et al. 1986; Bell and Josenhans 1997). Nachvak Fjord re-

ceives most of its modern sediment from Ivitak Brook, a glacier-fed river that drains the south-central part of the fjord catchment. The average, annual sediment load to the basins ranges between 35,000 and 100,000 tonnes (Kahlmeyer 2009).

Saglek is a 65-km-long, large branching bay/fjord system (Fitzhugh 1980). Saglek Fjord strictly describes the classic glacier trough morphology represented by West Arm and its tributaries North and Southwest Arm. Farther east, the fjord opens out into Saglek Bay, which is over 14 km wide and dotted with large and small islands. The fjord sidewalls are generally steep, extending up more than 800 m vertically from sea level. Fjord basins become increasingly deeper from head to mouth, ranging in water depths from 80 to 256 m. Sills between 45 and 96 m below sea level separate the basins. Saglek Fjord receives most of its sediment from Nachvak Brook, a nival-fed river that drains the north-central part of the fjord catchment. The average, annual sediment load for the basins ranges between 16,000 and 380,000 tonnes (Kahlmeyer 2009).

Okak Bay (fjord) is an irregularly shaped, 50-km-long inlet with north and south entrances either side of Okak Island. The surrounding catchment is undulating and low lying (on average 100-200 m) with only local summits above 400 m height. Underwater, the average depth is between 40 and 80 m, with flat-bottomed basins separated by low-relief sills. The head of the bay is relatively shallow (45-50 m water depth) with two major freshwater inputs, Saputit River and North River. The deepest basins by far are on the northeast side of Okak Island along the northern entrance, where average water depths reach 200 m. The southern entrance is narrow and shallow, bordered by Ubilik Peninsula to the south and Okak Island to the north. Siorak Brook enters the central bay west of Okak Island from the north.

Anaktalak Bay is a long, narrow, straight fjord, over 65 km long and for the most part 2 km wide. The fjord sidewalls are low and discontinuous, composed of numerous islands of varying size. Much of the bay forms a large

basin between 100 and 120 m deep that shallows to a sill at 85 m depth in the outer bay. The average sediment load entering Anaktalak basin ranges between 1300 and 14,000 tonnes per year (Kahlmeyer 2009).

10.3 Oceanography

Physical oceanographic observations of the fjords and fjards are limited to a few CTD stations in each inlet with measurements taken every 1-2 years; unfortunately, this is insufficient to yield information about water circulation and exchange patterns, but some comments can be made about water column characteristics. The surface stratification of the fjords and fjards is supported by both

freshwater runoff and ice melt. During summer, a strong pycnocline (where the water density gradient is greatest) with fresh surface water overlies more saline intermediate water. During the fall, the water column is more homogeneous (less-stratified). Anaktalak Bay surface layer in the summer is brackish (salinity ~28‰) and extends to 15 m depth (Figure 2). Similarly, Nachvak and Saglek fjords also recorded their lowest salinity values in summer (29.0 and 30.4‰, respectively; Figure 2). Vertical circulation or turnover of the stratified water column likely occurs in each inlet because both surface (average=8.07 ml/l; range=7.24-8.86 ml/l) and bottom (average=6.77 ml/l; range=5.88-8.00 ml/l) waters have similar oxygen levels.

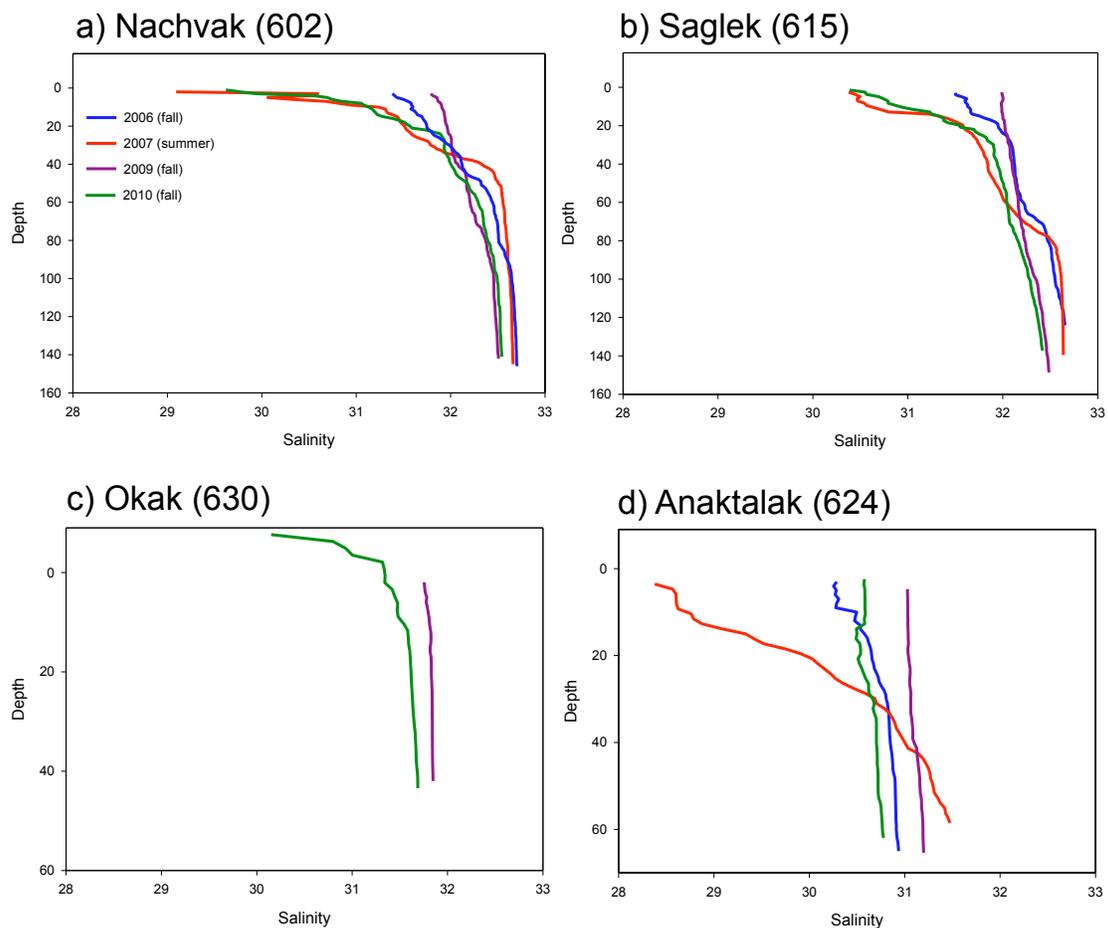


Figure 2. Vertical profiles of salinity (‰) as measured at inner stations in the fjords and fjards.

10.4 PCBs in Saglek Bay: Mitigation works but concerns still linger at the top of the food chain

Outer Saglek Bay has been the site of a military radar station since the late 1950s (Brown et al. 2009, Kuzyk et al. 2005). During an environmental investigation of the LAB-2 radar site at Saglek in 1996, extensive PCB contamination was found in soil and later in sediments near the local beach and biota in the adjacent bay, Saglek Anchorage. Total PCB concentrations in the benthic-based food web in the bay were significantly higher than background levels for at least 7.5 km from the contaminated beach. Relatively high PCB concentrations were also discovered in some wider-ranging species, such as great black-backed gulls (*Larus marinus*) and ringed seals (*Pusa hispida*) (Kuzyk et al. 2005). The presence of such compounds in the marine environment was of particular concern due to their tendency to bioaccumulate and biomagnify in the food chain (Addison 1982, Addison et al. 2005, Muir et al. 1988, 1992).

From 1997 to 1999, in conjunction with the excavation and removal of the PCB-contaminated soil from the terrestrial environment (Brown et al. 2009, Kuzyk et al. 2005) (Figure 3), an extended study was undertaken to assess the contamination in both the marine sediments and biota in Saglek Bay. An effects-based ecological risk assessment (ERA) was completed to identify potential risks to the local biota (ESG 2002, Kuzyk et al. 2003, 2005, Brown et al. 2012). Average PCB concentrations in the nearshore marine sediments exceeded the Canadian sediment quality guideline (21.5 parts per billion dry weight (ppb dw)) by 41-fold and PCB concentrations in several wildlife species were well above Arctic background levels (Kuzyk et al. 2005). Results of the ERA indicated that the survival and reproduction of shorthorn sculpin (*Myoxcephalus scorpius*) and black guillemot (*Cepphus grylle*) nestlings were at risk (ESG 2002, Kuzyk et al. 2003, 2005, Brown et al. 2012) (Figure 4). By relating levels at which there were effects on reproduction and survival



Figure 3. Beach area in Saglek Anchorage before (top, 1996) and after (bottom, 1999) contaminated sediment excavation and removal. The volume of sediment removed was 16,240 m³ (arrows indicate where sediment was removed), enough to cover a Canadian football field to a depth of around 4 m). Runoff and sediment erosion carried PCBs offshore into the bay.

to concentrations of PCBs in the sediments, it was estimated that risks were posed by sediment PCB concentrations greater than 77 ppb (dw) for black guillemots and 355 ppb (dw) for sculpin (ESG 2002, Brown et al. 2012). Consequently, the most conservative estimate (77 ppb) was used as a site-specific risk level. Since black guillemots occupy a relatively high trophic level, have a relatively small home range, and forage locally, the derived site-specific level (77 ppb) is likely to be protective of all bird and fish species in the area. Like shorthorn sculpin, black guillemots tend to be associated with shallow water where benthic prey species are relatively abundant. They forage most commonly in waters less than 18 m deep and rarely in water more than 40 m deep (Cairns 1982, 1987). Ecologically, these conditions occur throughout the shallow subtidal portions of Saglek Anchorage, around the



Figure 4. Black guillemot nestling (*Cepphus grille*) (left), Shorthorn sculpin (*Myoxocephalus scorpius*) (right).

former contaminated beach and to the west and east for a distance of 1-1.5 km. The specific area represented by these two parameters – PCB concentrations greater than 77 ng/g (dw) and water depths less than 40 m – is illustrated in Figure 5. Since black guillemots were the most sensitive receptor examined in the ERA, this area also represents the best estimate of an Ecological Risk Zone (ERZ) in Saglek Bay, wherein sediment contamination represented a significant ecological risk, during the study period (1997-1999).

In 2002, researchers from Laval University Research Hospital (CHUQ-Public Health Research Unit) conducted a human health risk assessment (HHRA) to provide information on the potential health risks associated with harvesting and consumption of wild foods in Saglek Bay (Ayotte et al. 2002). The HHRA found that harvesting within 5 km of the contaminated beach would result in higher long-term PCB exposures than harvesting elsewhere in Labrador, Nunavik or Nunavut. As a result, Labrador Inuit were advised by their local health commission to avoid harvesting the most affected wildlife within a 5 km exclusion zone (Ayotte et al. 2002).

In 2006-07, PCB concentrations were again measured in the sediments and biota of Saglek Anchorage to determine

whether the local ecosystem had recovered since the removal of the PCB source on the beach and to gain a better understanding of the extent of PCB contamination in the adjacent bay (Brown et al. 2009). PCB concentrations in the sediment and two at-risk species (shorthorn sculpin and black guillemot nestlings and eggs) showed a significant decrease between 1999 and 2006-07 (Brown et al. 2009; Figure 5). More recently, environmental monitoring between 2008 and 2011 demonstrated that sediment PCB concentrations in the exclusion zone had decreased rapidly and average concentrations were below the site-specific threshold established for probable effects in black guillemot nestlings. Moreover, PCB concentrations in black guillemot nestlings were below concentrations previously associated with risks of impaired reproduction and survival (Brown et al. 2009, ESG 2002, Kuzyk et al. 2005). Sculpin liver PCB concentrations showed a similar recovery trend; however, they are still above the lower range of thresholds thought to impair fish reproduction (50 ppb wet weight (ww); Kime 1995). An updated HHRA is in progress using current data for marine and terrestrial species from Saglek Anchorage and exposure scenarios that are relevant to the current and intended uses of the site. The goal of the site-specific HHRA is to ensure adequate protection of current and probable future users of the site.

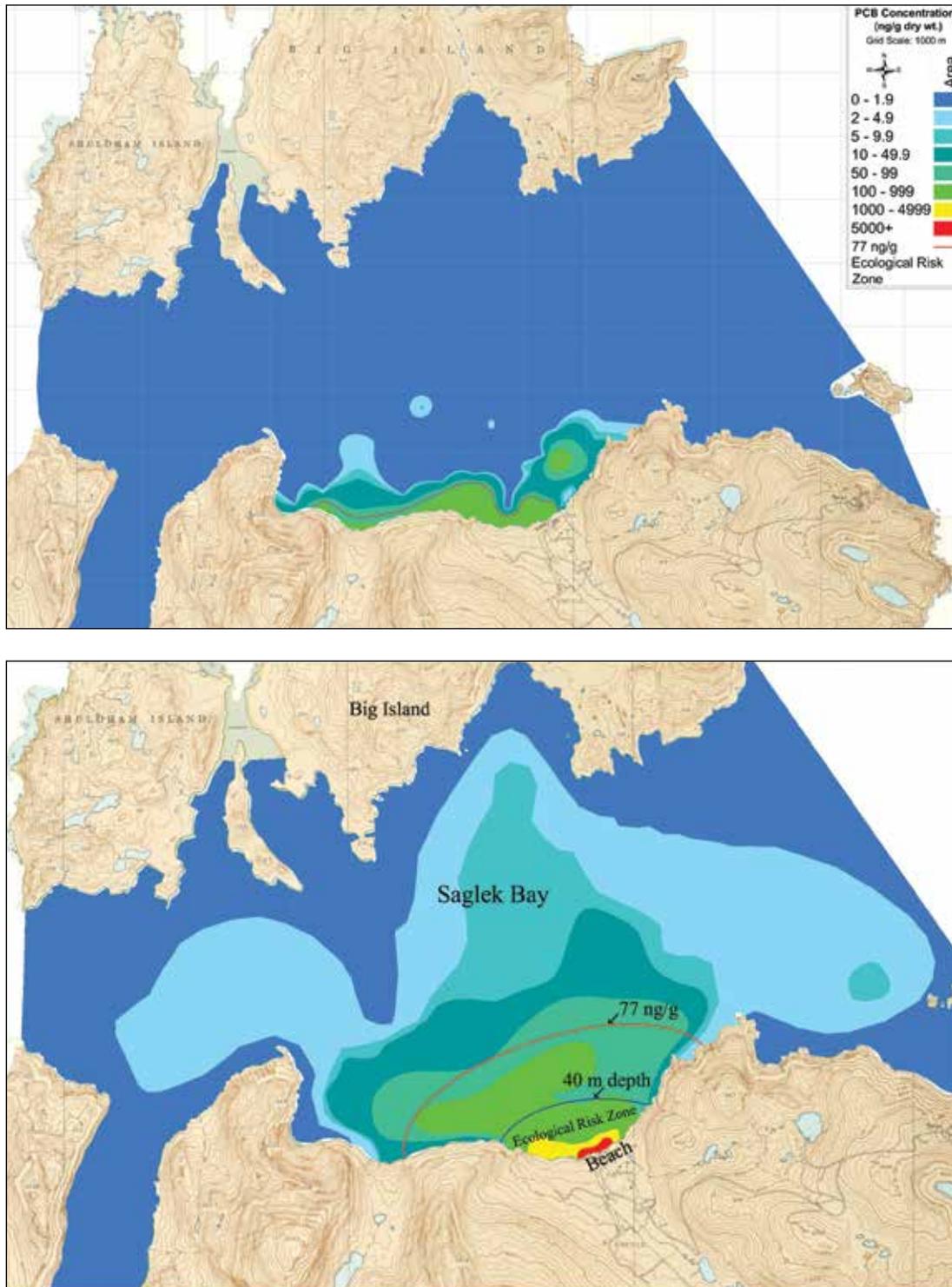


Figure 5. PCB plume maps for surface sediments in Saglek Anchorage (concentration (ppb dry weight): top, 2006; bottom, 1998 (from Brown et al. 2009).

Although PCB concentrations in the surface sediments, shorthorn sculpin and black guillemots have decreased dramatically in Saglek Bay during the last decade (Brown et al. 2009), relatively high PCB concentrations have persisted in ringed seals (Figure 6). This PCB persistence in ringed seals posed two important questions for researchers: 1) Is the PCB contamination in Saglek Anchorage contributing to elevated levels found in some ringed seals, sometimes referred to as ‘hot’ seals; and 2) Why do seal concentrations remain relatively high while levels decline in other biota? Age and sex do not appear to be contributing factors for the elevated concentrations, as seals of the same sex and approximately the same age have concentrations significantly lower than those of ‘hot’ seals. Ringed seals have been known to range over hundreds of kilometres, and for this reason they are not expected to be strongly influenced by local sources of contamination (Smith, 1987). It is possible, however, that the seals with elevated PCB concentrations are ranging over a more local area within Saglek Bay for longer periods of time. Another possible explanation for these ‘hot’ seals is a difference in diet. It is conceivable that the seals with elevated concentrations are feeding preferentially in the most contaminated area and/or on fish, such as sculpin, rather than less contaminated areas and/or prey (Kuzyk et al., 2005). A study of ringed seal feeding ecology, movement and foraging behaviour together with PCB contaminant patterns and concentrations is currently underway to better understand the reasons for the elevated levels in ringed seal.

Feeding Ecology: Stable isotopes of carbon and nitrogen have been used to assess food web transfer of PCBs in aquatic food webs (Fisk et al., 2001). The ratio of the heavier to lighter stable isotopes of nitrogen (e.g. $^{15}\text{N}/^{14}\text{N}$), expressed relative to a standard, generally increases with trophic position in aquatic food webs, providing a continuous variable with which to assess both trophic level and food web transfer (Fisk et al., 2001). The use of stable nitrogen isotopes has advantages over traditional methods, such as analysis of gut contents, as it averages dietary assimilation over a longer period of time (Hoekstra et al., 2003). However, stable nitro-

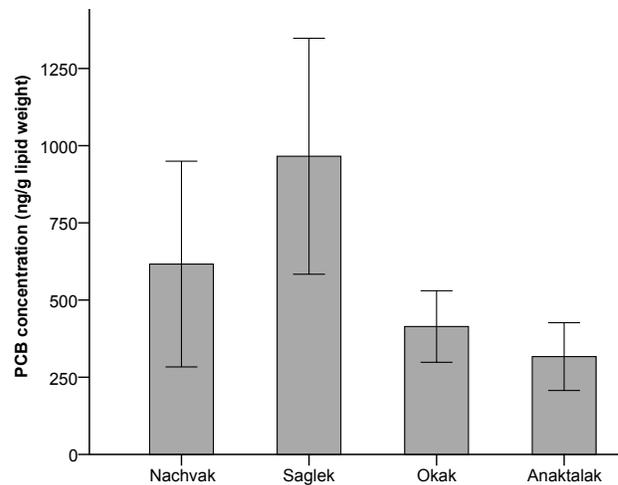


Figure 6. Arithmetic mean PCB concentrations (vertical line = 95% confidence limit) for male and female ringed seals from four northern Labrador inlets.

gen isotopes do not allow for specific identification of prey and relative proportion of ingestion (Hoekstra et al., 2003). In contrast, the ratios of stable carbon isotopes ($^{13}\text{C}/^{12}\text{C}$) in biota can help to elucidate trophic interactions by establishing the relative contribution of marine (or pelagic) versus coastal (or benthic) carbon sources (France and Peters, 1997).

In addition to stable isotopes, fatty acids have emerged as a powerful tool for quantitative assessment of predator diets (Budge et al., 2006; Iverson et al., 2004). Studies that have compared the fatty acids found in predator fat stores with those found in their prey have allowed both qualitative and quantitative comparisons of the spatial and temporal scales of foraging (Iverson et al., 2004; Falk-Petersen et al., 2004). This is possible because the fatty acids consumed by predators with single-chambered stomachs are deposited into adipose tissue with little modification or in a predictable pattern, thus providing an integrated record of dietary intake over time (Budge et al. 2006). Fatty acid distributions or “signatures” can be used to answer qualitative questions about spatial or temporal variations in diets both among and within individual seals or seal populations (Iverson et al., 1997).

In summary, the quantification of stable C and N isotope ratios and fatty acid signatures are being used to provide valuable information on the feeding ecology of ringed seals in northern Labrador in general and Saglek specifically. Results of the coastal food web study suggest there may be differences in feeding patterns of ringed seals in the four marine inlets that may have potential implications for the levels of contaminants in this species.

Movement and foraging behaviour: Satellite tagging of ringed seals has been used in southern Hudson Bay to study their movement and foraging behaviour. Since 2008, a similar study of ringed seals captured from the Saglek area has been undertaken to better understand the reasons for the presence of ‘hot’ seals. In particular, the ringed seal tagging study is providing insight into the following questions: 1) Where do ringed seals concentrate their foraging effort? and 2) How do ringed seal forage in those areas? In total, 13 ringed seals (2 adults, 11 subadults) were captured during August and September (2008-2011) and fitted with satellite-linked transmitters. Movement tracks show that there are distinct differences in the movement and behaviour patterns among

the tagged ringed seals. Ringed seals displayed both resident (remained in Saglek Fjord) and non-resident behaviour during their tagged period (Figure 7).

Contaminant concentrations and patterns: To further understand the reasons for ‘hot’ seals, we are investigating not only PCBs in ringed seals and their prey but also PBDEs (polybrominated diphenyl ethers), which exhibit behaviour similar to that of PCB concentrations and patterns. No known local sources of PBDEs exist at Saglek Bay; seals that therefore forage more within Saglek Anchorage would likely show elevated levels of PCBs relative to PBDEs. There was a significant correlation between PCBs and PBDEs in ringed seals from reference inlets (Nachvak, Okak, and Anaktalak), but not for seals from Saglek Fjord (Figure 8).

PCB congener analysis can also be used to determine ‘local’ versus ‘global’ signatures. There are 209 distinct PCB compounds (known as congeners) which are identified by the number and position of chlorine atoms on a biphenyl molecule. The source of PCBs at Saglek is the commercial Aroclor 1260 mixture, the congener composition of which is dominated by higher-chlorinated



Figure 7. Satellite tracks and inferred foraging locations (red dots) for two (left: SAGB-2008-0002; right: SAGB-2009-0005) of the thirteen ringed seals tagged in Saglek Fjord. SAGB-2008-0002 stayed resident to Saglek Fjord.

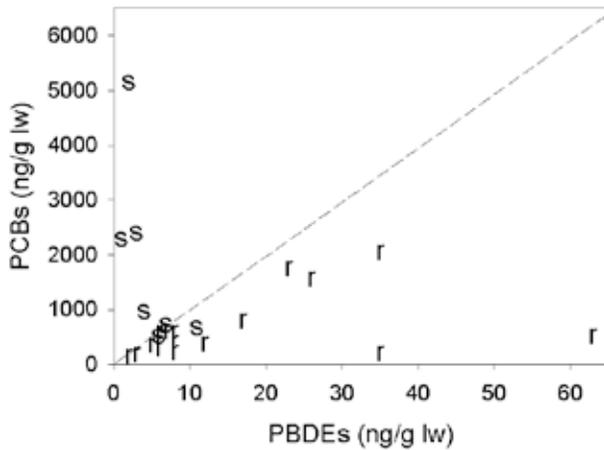


Figure 8. Total PCB and PBDE concentrations in male and female ringed seals from Saglek Fjord (s) and reference fjords (r). Reference fjord concentrations ($R^2=0.90$; $p<0.001$); Saglek Fjord concentrations ($R^2=0.43$; $p=0.16$).

congeners. This ‘local’ congener signature can be distinguished from the background ‘global’ congener signature that results from long-range atmospheric transport. Congeners 138, 183 and 187, which contribute a large proportion to Aroclor 1260 and are highly chlorinated, were relatively enriched in seals with elevated concentrations of PCBs, compared to seals with low levels. These results further suggest that Saglek Fjord ringed seals have been exposed to local PCB sources, in addition

to PCBs and PBDEs associated with long-range transport (i.e. background). Studies are also underway to evaluate the PCB-associated health risks to Labrador ringed seals.

10.5 Fjord Processes

Rivers deliver nutrients to fjord marine waters, and are used by a range of animal species through the ice-free months. Sediments carried by rivers to the sea carry some history of the land within the sediment deposits. Rivers provide drinking water. How are these rivers changing over time? Is more fresh water being delivered, or less? Is the quality of the water better, or has it diminished over time? These questions have been the focus of a seabed study in Nachvak and Saglek fjords, to evaluate patterns of sediment delivery from land to sea, and how those patterns may inform us about past, present, and future interactions between rivers and fjords.

Modern fjords are products of the advance and retreat of glacial ice and relative sea level fluctuations (Syvitski and Shaw 1995). They commonly contain one or more submarine sills created from bedrock or glacial moraines (Figure 9), leading to poorly coupled ocean circulation below the sill height. The restricted deep-water circulation and resulting slow currents, reduced oxygen, and

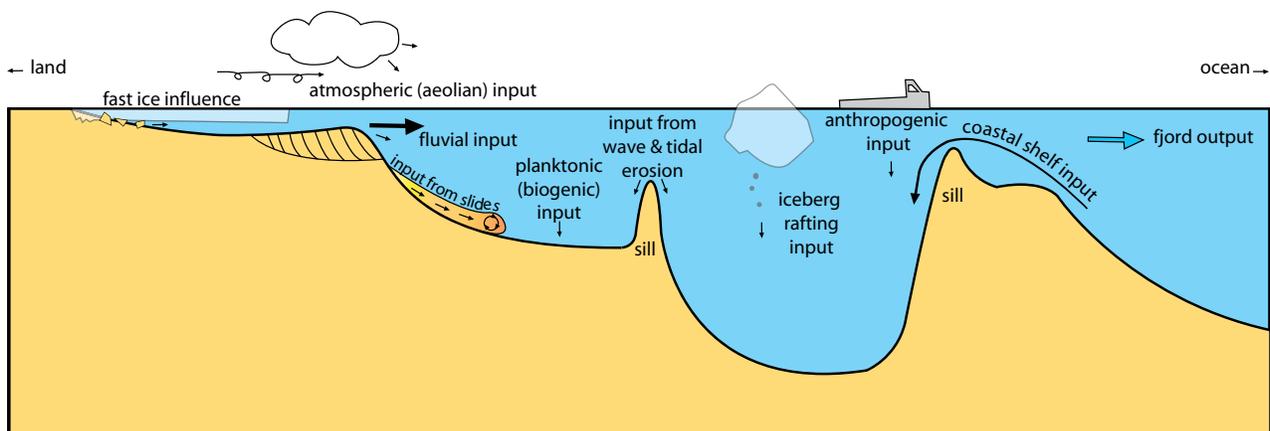


Figure 9. Sediment delivery to fjords, modified from Syvitski and Shaw 1995

reduced bioturbation make silled basins in fjords excellent natural sediment traps.

The fluvial input to river-influenced fjords mainly consists of erosional products from weathering, reworked glacial and raised marine deposits, as well as freshly produced glacial flour (Syvitski and Shaw 1995). The coarsest sediments carried into fjords by rivers deposit quickly, but the finest sediments are carried seaward within the river plume, the concentration of which increases exponentially with increasing stream discharge. Thus, a change in river runoff will be reflected in the sediments deposited. As a result, fjord sediment deposits retain high quality records of terrestrial processes, while also recording the influence of marine processes (Howe et al. 2010). The deep, quiet waters of fjord basins retain this sediment, preserving a very detailed record of environmental processes in the buried sediment texture, composition and age.

10.5.1 Labrador Fjords and Their Rivers

The overall objectives of this project are to (1) determine the present rate of sediment supply to Saglek and Nachvak fjords, (2) relate present sediment supply to present water supply, and (3) study the sedimentary history of the past several centuries to learn if water supply from rivers, represented by sediment flux, has changed over time in association with climatic fluctuations. To date, we have achieved the first two objectives, and are in the process of completing the third, i.e., learning about the recent history of the region. This has required making measurements of water flowing from rivers (Figure 10), mapping the size of river and stream drainage basins, mapping the thickness, extent and age of sediment deposits in the fjords, and then combining these results to gain temporal and spatial perspectives. None of these measurements have ever been conducted previously in fjords along the Labrador or Ungava coasts.

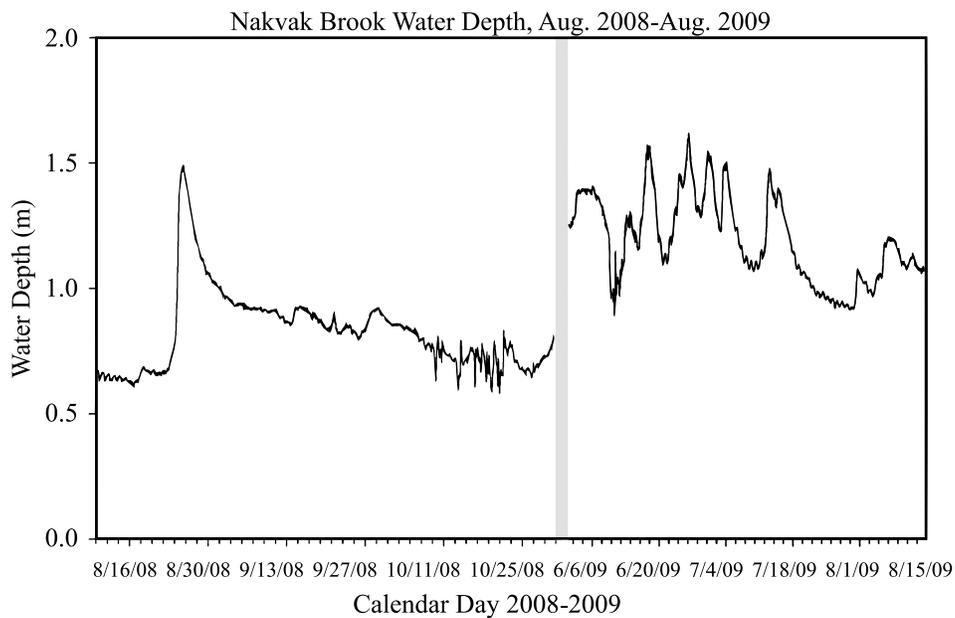


Figure 10. Water level data from Nakvak Brook main stem during period of August 2008 to August 2009. Data for the time span where water temperatures fell below zero has been excluded (shaded areas).

10.5.2 What We Have Learned

The rivers flowing into Saglek and Nachvak fjords deliver much of their water, and probably most of their sediment, to the fjords during short periods of intense flooding, both during the melt season, and during rainstorms in the summer (Figure 10). Sediment transport capacity increases exponentially with water discharge velocity, which suggests that these storms and melt events are responsible for delivering much of the seabed sediment we have mapped to the fjords. So, it is likely that sediment deposition probably records the impact of high discharge events (melt and summer floods) rather than average conditions.

We have identified and begun to age-date thick and extensive sediment deposits in bathtub-shaped basins within Saglek and Nachvak fjords. The uppermost sediment layers visible in Figure 11 (identified as postglacial sediments) have been deposited over the last ca. 8000 years or less. Our ongoing more detailed analysis of finer layers within this sediment mass has allowed us to measure the rate of sediment supply from rivers over the past ca. 150 years, and compare conditions in Saglek and Nachvak fjords.

The rate of sediment supply from the landscape surrounding Nachvak Fjord is approximately five times the sediment supply per area of land draining into Saglek Fjord (approximately 262 tons of sediment delivered to the ocean per square kilometer per year of river basin for Nachvak Fjord, compared to ~47 tons of sediment per square kilometer per year for Saglek Fjord). Rivers entering Saglek Fjord, characterized by Nachvak Brook, tend to have larger drainage basins that are fewer in number than in Nachvak Fjord, which has smaller and steeper river basins. The upper reaches of Nachvak Fjord river basins are also more commonly occupied by glaciers than in Saglek Fjord. The difference in sediment supply between the two fjords may relate to steeper basins and glacial influences in Nachvak Fjord, combined with harder rocks in the Saglek landscape, that are more resistant to erosion.

10.5.3 Future Objectives

Our next goal is to look for patterns of change in sediment deposition over time, for comparison with the present. In particular, we hope to learn if climatic patterns recorded in sediments can inform us about conditions during periods of human settlement and migration along the coast, and how rivers have responded in the past to periods of relatively high temperatures, similar to what the region is beginning to experience now under the changing climate regime. This work is ongoing, and should yield results within the next two years.

10.6 Paleooceanographic Conditions in Subarctic Fjords and Fjards

In order to document long-term climate cycles for the Arctic, geological records archived in ocean sediments can help establish the link between historical (instrumental) and pre-historical sea-surface parameters. Dinoflagellate cysts (dinocysts) are used as proxy indicators of sea-surface parameters (temperature, salinity, sea-ice cover, primary productivity) and jointly with transfer functions and a modern dinocyst reference database can reconstruct the evolution of sea-surface conditions at decadal and millennial timescales (Rochon et al. 1999, de Vernal et al. 2001, 2005, Mudie and Rochon 2001, Voronina et al. 2001, Kunz-Pirrung 2001, Grøsfjeld and Harland 2001, Boessenkool et al. 2001, Radi et al. 2001, Radi and de Vernal 2008, Richerol et al. 2008a, b).

The dinoflagellates are a group of microscopic unicellular biflagellate protists, some species of which can be toxic, forming what is known as red tides (Taylor et al. 2008). The life cycle of some species comprises a dormancy phase during which the vegetative stages form cysts. The cyst membrane is composed of a highly resistant polymer, dinosporin, allowing the cyst to be preserved in the sediment (Richerol et al. 2008a).

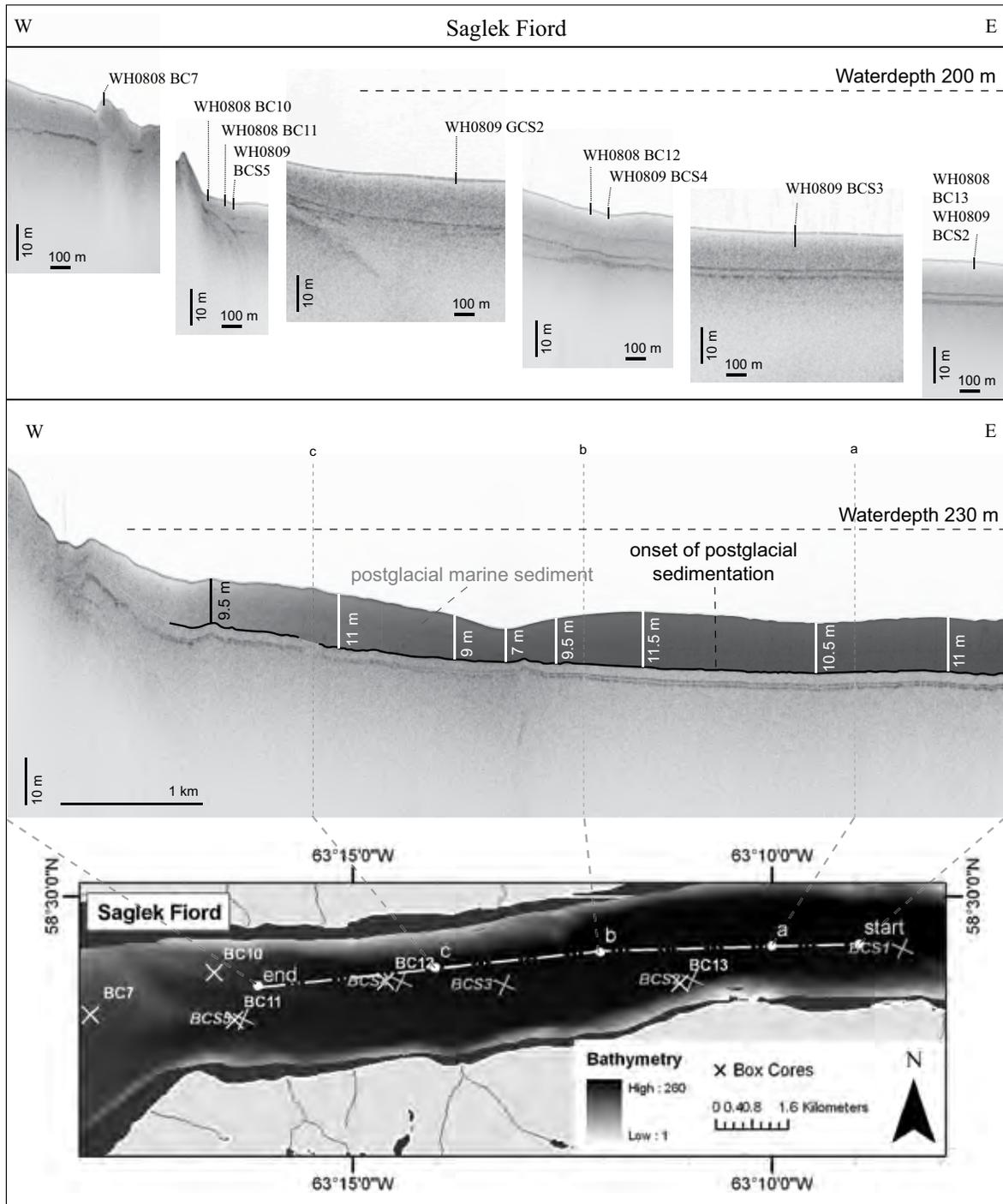


Figure 11. Color-shaded map of water depth (bottom) showing core locations and location of sonar cross section (top two panels) of sediment thickness in Saglek Fjord, south and east of Nakvak Brook. Postglacial time represents the last ca. 8000 years. During this time, climate has been more similar to the present subarctic conditions (with seasonal ice cover) than to the Ice Age, when permanent ice sheets covered Labrador.

10.6.1 What We Have Learned

The distribution of modern dinocyst distribution

Surface sediment (first 5 mm of the sediment) samples were collected from the CCGS *Amundsen* in 2009 and 2010 and analyzed to document the regional distribution of dinocyst assemblages and their relationships with current environmental conditions (summer sea-surface temperature and salinity, sea-ice cover duration). The results illustrate an increase in concentration from the inner to the outer parts of each fjord and an increase from the northern fjords (Nachvak and Saglek) to the southern fjords (Okak and Anaktalak; Figure 12). In 2010, the same regional trend as the previous year was observed with an overall increase in productivity, in some locations by an order of magnitude. This dramatic increase in productivity was confirmed through corresponding analyses of the phytoplankton community in the water column of the fjords and fjards (see Section 10.9). The biodiversity of dinocysts also increases from north to south, with the occurrence and dominance of dinocysts from autotrophic species in the two southernmost fjords (Figure 12).

Three distinct dinocyst assemblages occur in the surface sediments of the Labrador fjords and fjards. From north to south, they are:

- Assemblage 1 (Nachvak and Saglek fjords) is dominated by dinoflagellates that are strongly dependent on the availability of nutrients and the presence of prey (heterotrophic). It seems to be characteristic of sea-ice driven fjords and Arctic water conditions.
- Assemblage 2 (Okak Fjord) is characteristic of a fjord less influenced by sea-ice conditions but more by sea-surface salinity and temperature and nutrient depletion (autotrophic).
- Assemblage 3 (Anaktalak Fjord) is controlled by sea-surface salinity and temperature and water column irradiance (autotrophic). This fjord, being the less Arctic of the investigated fjords and fjards,

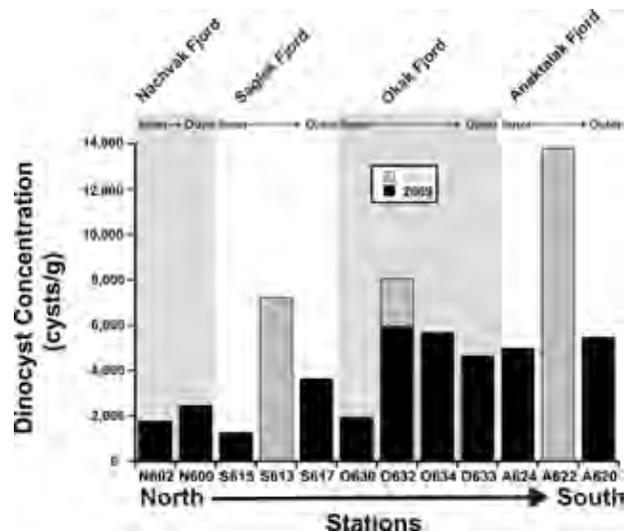


Figure 12. Distribution of the total dinocyst concentration in the surface sediment samples retrieved in the fjords in 2009 and 2010. Stations labeled N are from Nachvak Fjord, S from Saglek Fjord, O from Okak Bay and A from Anaktalak Bay.

has the lowest abundance of the Arctic species *I. minutum* s.l. (Figure 13). The cyst of the calcareous dinoflagellate taxon *Scrippsiella* cf. *S. crystallina* is found in the surface sediments from Anaktalak Bay, in close proximity to Edward's Cove (dock facility for Vale Inco. and location where treated effluent from the mine is discharged into the bay) and may be a useful indicator of pollution by the mine's effluents and/or the transport by ballast waters released from the ships. Additional data are required to confirm these hypotheses.

The paleoceanographic reconstruction

A short box-core was taken in each of Nachvak Fjord, Saglek Fjord and Anaktalak Bay in November 2006 on-board the CCGS *Amundsen*. The reconstruction of past sea-surface parameters was performed for all three inlets. The three sedimentary records reveal a steady general decrease in marine productivity over the last 30-50 years, with a return to increased productivity over the last 10 years. In gen-

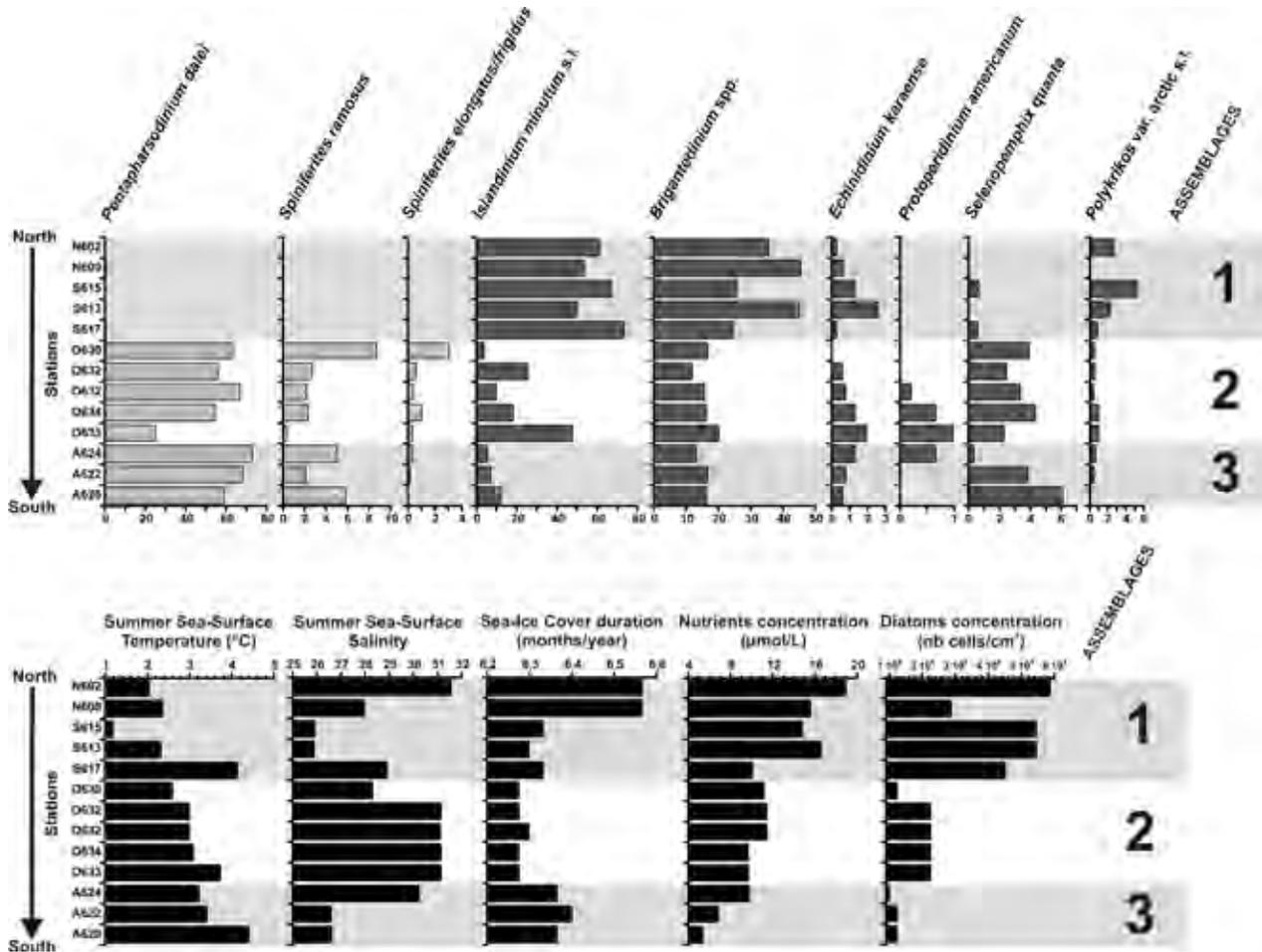


Figure 13. Relative abundance of major dinocyst taxa, hydrographic parameters (temperature, salinity, sea-ice cover, nutrients and diatoms) and modern assemblages of dinocysts. Note the difference in dinocyst assemblages between northern fjords (Nachvak and Saglek) and southern fjords (Okak and Anaktalak).

eral, paleoceanographic reconstructions suggest a relatively stable climate. A slight decrease in the temperature with a slight increase in the salinity is inferred between ~1980 and 2000 AD in Nachvak Fjord (Zone II), which could be linked to an intrusion of cold and salty waters from the Labrador Sea into the fjord (Figure 14). A slight and continuous decrease in the annual duration of the sea-ice cover (~1 month/yr total) is reconstructed since ~1940 AD in Saglek Bay. Anaktalak Fjord shows the greatest climatic stability, except for a peak in the reconstructed temperature in ~1987-1990 AD concomitant with a significant reduction in the inferred sea-ice cover (in Zone II, Figure 14).

10.6.2 Future Objectives

Holocene paleoceanographic reconstruction in Nachvak Fjord

In November 2009 an 812 cm-long piston-core was recovered from a deep basin in Nachvak Fjord. We will be using this core and fossil dinocyst assemblages to reconstruct the long-term history of paleoceanographic conditions in northern Nunatsiavut to help determine past climate variability in the region going back about 6000 years.

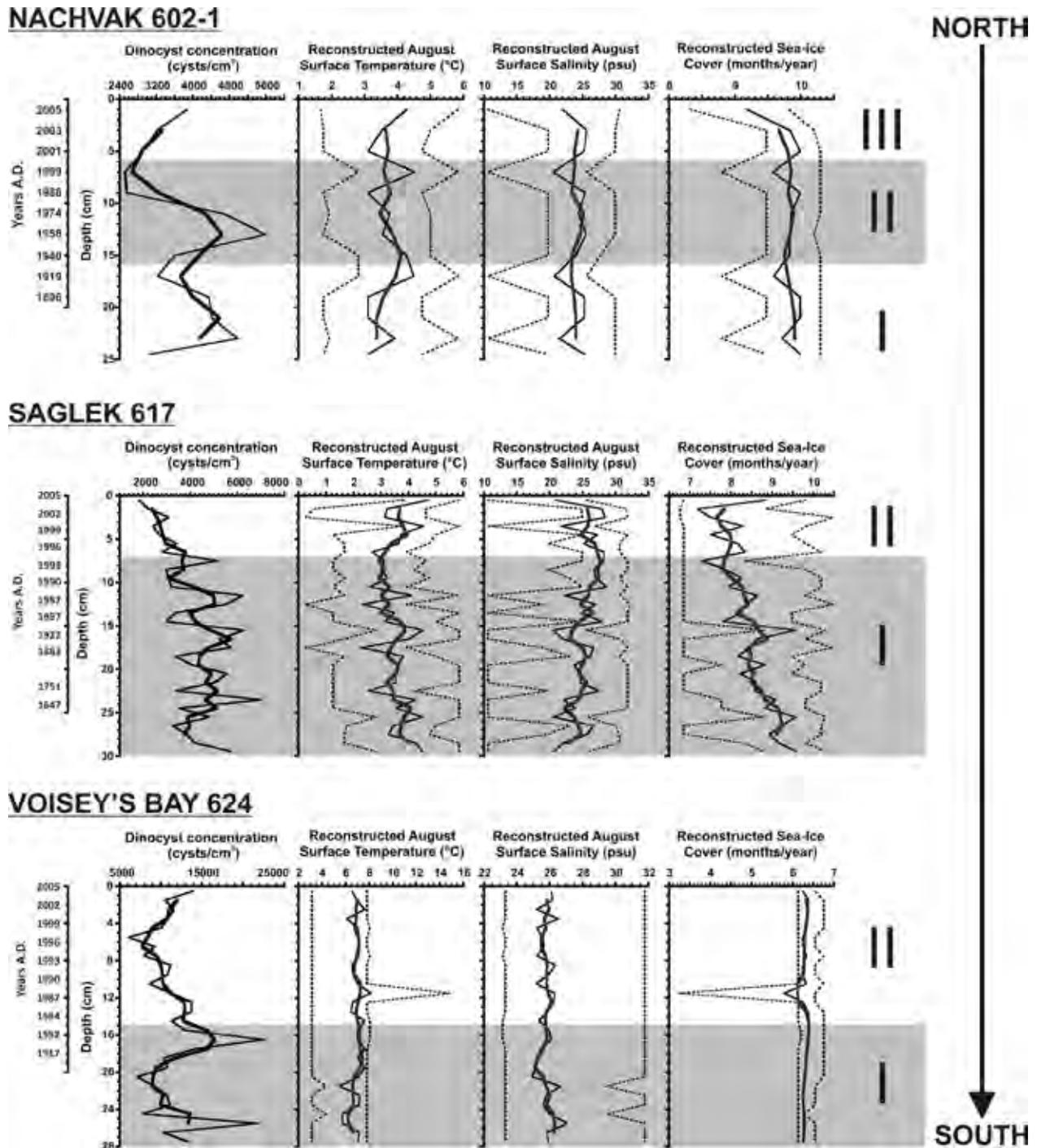


Figure 14. Evolution of the dinocyst concentration (cyst/cm³) and the three reconstructed oceanographic parameters for the sediment cores Nachvak 602-1, Saglek 617 and Voisey's Bay 624: August sea-surface temperature (°C), August sea-surface salinity (psu) and sea-ice cover duration (months/year). The thick lines represent an average of the evolution of the parameter and the dashed lines the confidence interval for the reconstruction.

10.7 Benthic Habitat Mapping

Knowledge on benthic marine habitats in the Subarctic and Arctic is relatively limited and very little information has been gathered on the marine habitats of coastal Labrador. Seafloor mapping is an accurate and efficient way of gathering baseline information about the nature and distribution of benthic habitats within coastal environments. It employs a supervised classification approach, using multibeam sonar data ground-truthed with substrate and biotic samples. Multibeam sonar collects two types of data, depth and backscatter. Backscatter is a measure of the strength that the acoustic signal returns to the sensor and is a reflection of the type of substrate. By sampling substrate and habitat, we can use the backscatter data to interpolate a habitat map for the entire seafloor, providing information about the nature and distribution of benthic habitats.

In the past, benthic habitat mapping products have contributed to fisheries management, long-term monitoring practices and the creation of policies relating to marine protected areas. It is an important initial step in coastal resource management, in particular ecosystem-based management, as it provides baseline information about the coastal environment at the seafloor level.

10.7.1 Benthic Habitats in Labrador Fjords and Fjards

The main objectives of this project are to (1) collect baseline information and develop a better understanding of benthic habitats within the fjords and fjards of northern Labrador, and (2) to determine patterns in biodiversity within the coastal region and identify habitats which may be sensitive to natural and anthropogenic impacts. To date, Nachvak Fjord, Saglek Fjord and Okak Bay have been sampled extensively at depths ranging from 7 to 210 m and partially mapped. Figures 15 and 16 illustrate the sampling coverage in these three inlets. Sampling methods consist of video and box-core sampling for substrate

and biota. The sample data along with existing habitat mapping methodologies will be used to generate substrate and habitat maps for the four study inlets. Figures 17 and 18 illustrate interpolated substrate and habitat maps for Okak Bay, respectively.

10.7.2 What We Have Learned

Benthic macrofauna is found at all depths, but the diversity and abundance of individual species varies with depth and substrate. Initial results show that the two northern fjords (Nachvak and Saglek) are characterized by broadly homogenous habitats that are repetitive in nature from the head to the mouth of the fjords. The habitats are heavily influenced by the typical fjord basin sill bathymetry, with flat sandy regions at the heads of arms (where there are major sources of freshwater), mud-dominated deep basins, and coarse substrates on the sills. Distinctive biotic patterns include large numbers of juvenile bivalve species, such as *Astarte borealis*, *Macoma calcarea*, *Nucula delphinodonta* and *Portlandia arctica*, on the sandy seafloor at the heads of all the arms. *Macoma calcarea* was also found in shallow muddy substrates along with several polychaete species, *Pectinaria granulata* and *Mal-dane sarsi*. Biotic assemblages are consistent across each region with a trend towards increasing biodiversity at the mouth, reflecting increased salinity.

Okak Bay differs from the two northern fjords in both physiography and biology. Okak Bay is an irregularly-shaped, generally shallow, low elevation estuary typical of a fjard. High slope areas are not as common as in fjords and bedrock sidewalls are rare. Although there is some similarity in the type and distribution of substrate types, such as flat sandy areas of high sedimentation near freshwater inputs, there are also important differences, such as the occurrence of coarse substrates both on sills and in shallow basins. Similar species are also found in the northern and southern inlets; however, species more typical of a “boreal” marine ecosystem are found in southern fjards.

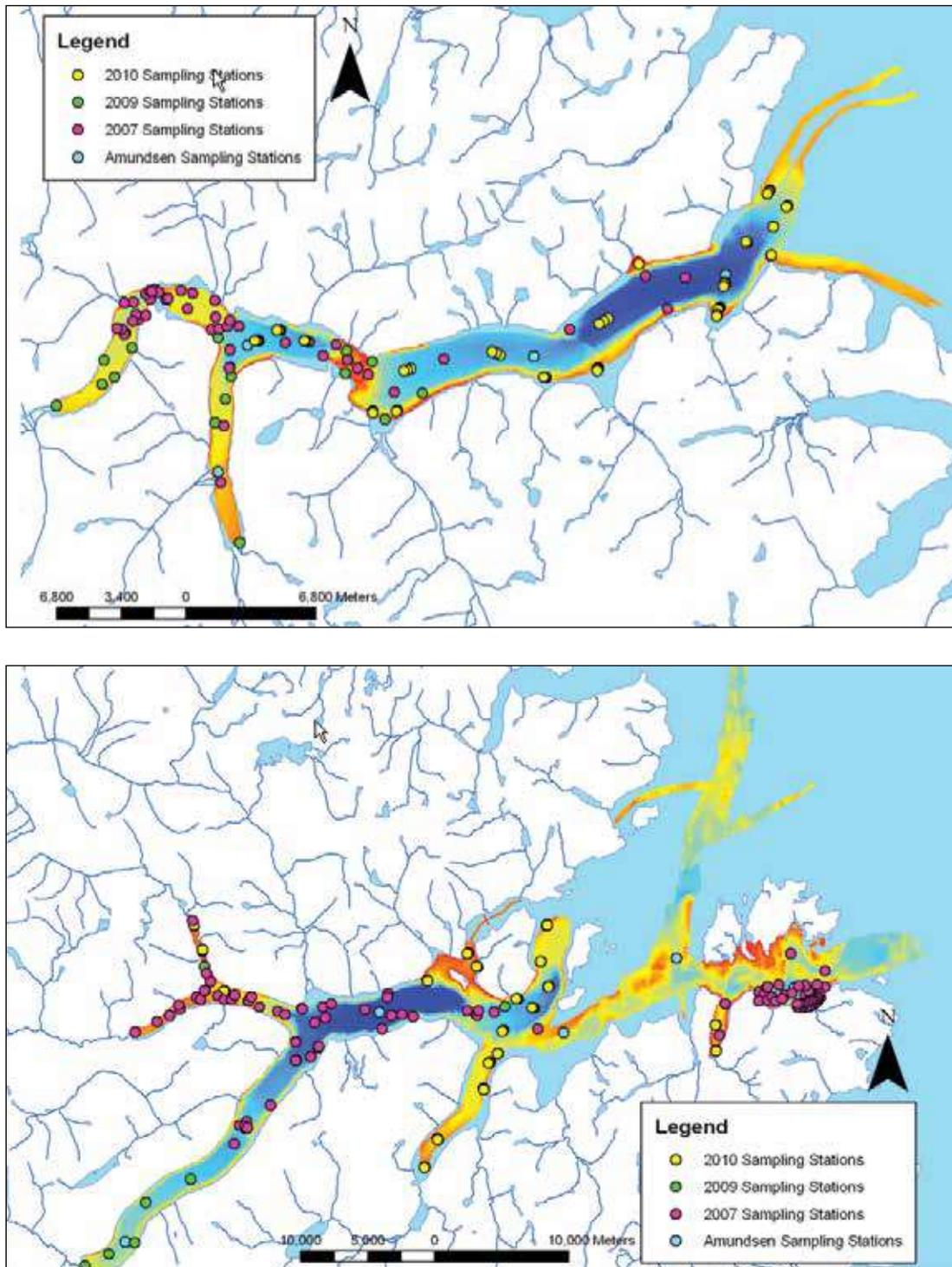


Figure 15. Multibeam bathymetric map of Nachvak Fjord (top, depths range from 5-180 m) and Saglek Fjord (bottom, depths range from 5-256 m), showing benthic sampling stations.

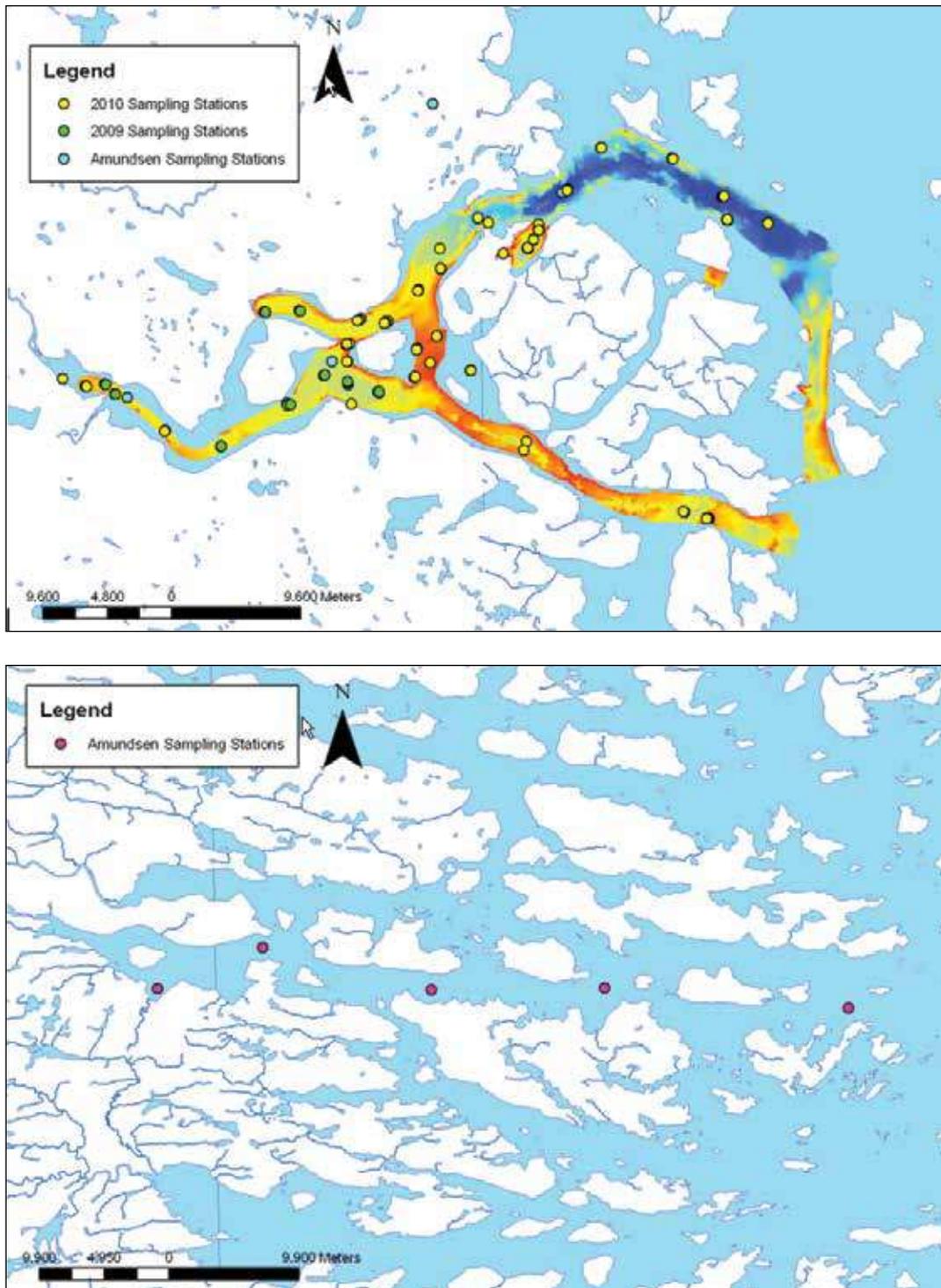


Figure 16. Multibeam bathymetric map of Okak Bay (top, depth range from 5-200 m) and map of Anaktalak Bay (bottom), showing benthic sampling stations.

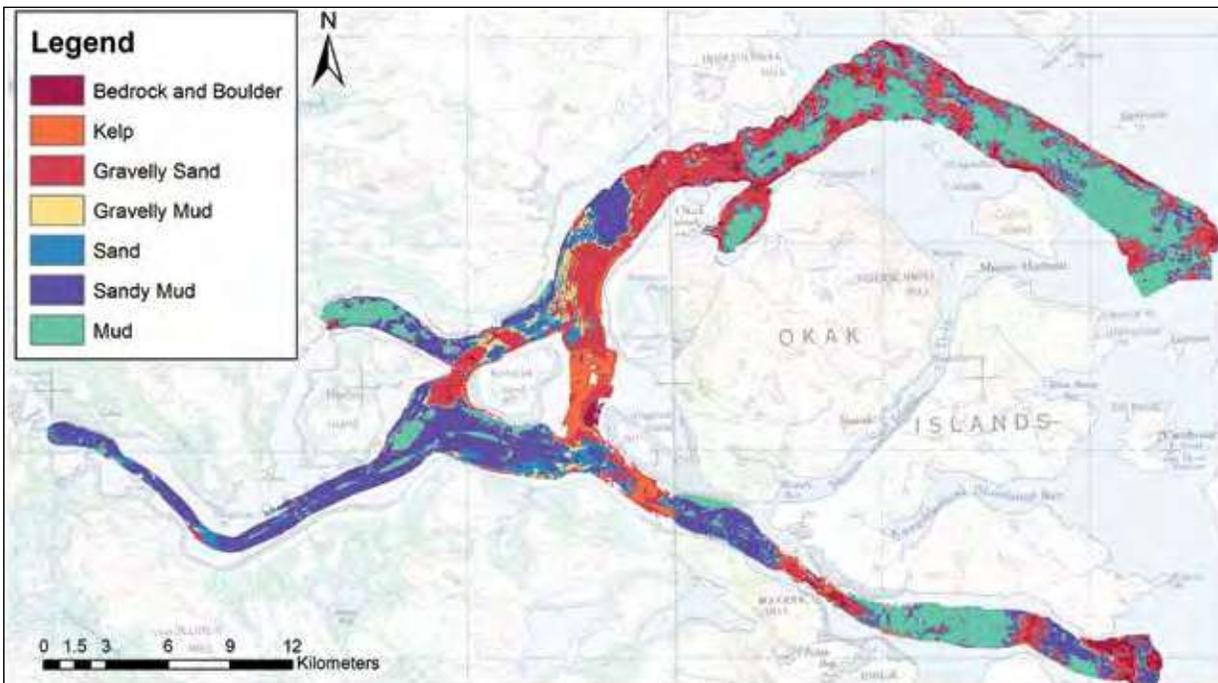


Figure 17. Substrate map of Okak Bay distinguished on the basis of substrate type, depth and backscatter.

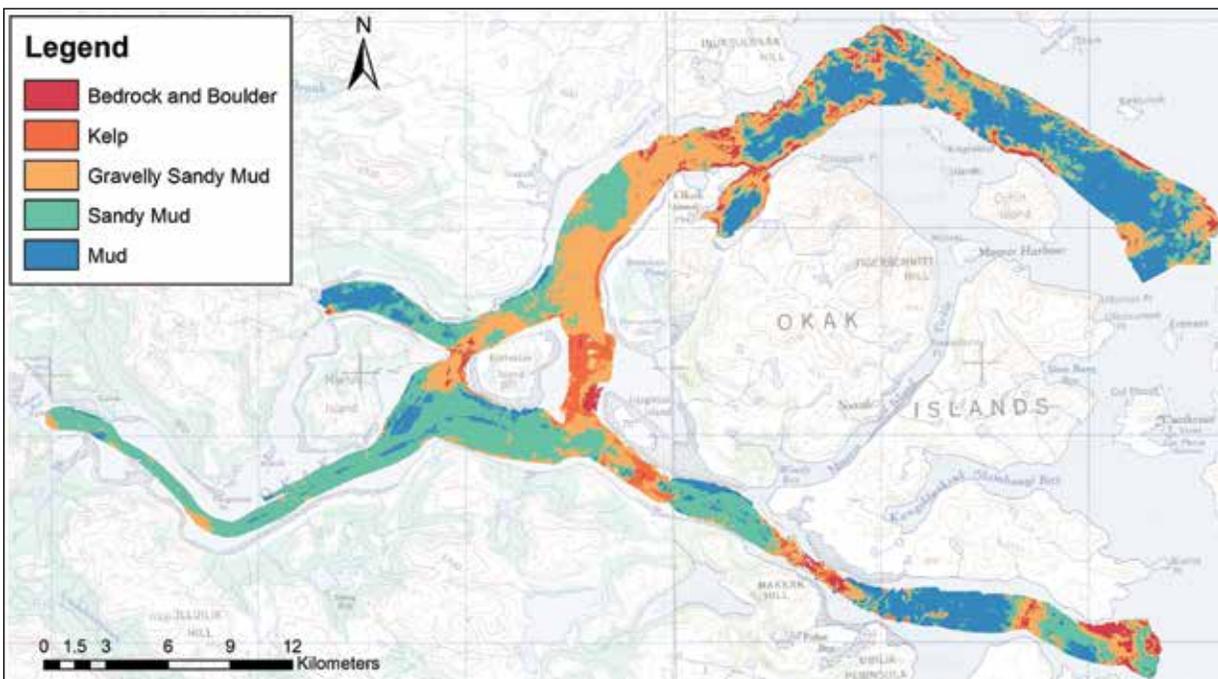


Figure 18. Habitat map of Okak Bay. Five colour-coded benthic habitats are distinguished on the basis of substrate type, benthic assemblage, backscatter and depth.

Biodiversity gradients differ between fjords and fjards. Rather than one gentle gradient towards high biodiversity in the outer fjord, in a fjard the areas of biodiversity are centralized and confined to specific bathymetric features. This holds important implications for future mapping activities in Anaktalak, where the inlet bathymetry is similar to Okak Bay.

10.7.3 Future Objectives

The next steps include completion of the habitat classification and mapping in the three northern inlets and data acquisition and sampling in the southernmost inlet (Anaktalak Bay). Once all mapping is completed, important comparisons between the regions can be drawn and habitats important for ecosystem functioning identified.

10.8 Zooplankton

Zooplankton are an important component of the Arctic marine food web, channeling energy from primary production to fish and marine mammal resources at the higher trophic levels. Their pivotal role in the food web make zooplankton an excellent indicator of the state of a marine ecosystem. The present study gives a general description of the zooplankton communities in the fjords and fjards of Labrador, including the species composition and biomass estimation of the zooplankton in each fjord. During 2006-2007 three inlets were studied: Nachvak Fjord, Saglek Fjord and Anaktalak Bay and in 2009-2010 a fourth inlet (Okak Bay) was included. Sampling was conducted at 8 stations; two stations in each fjord and fjard located at the head and mouth (Figure 1). The opportunity for annual sampling of zooplankton permits the establishment of baseline conditions to be used for future monitoring and recent climate change detection. Samples were collected in vertical, stratified hauls with a Hydrobios Multinet (Figure 19), equipped with a 200- μm -mesh net. Vertical hauls were taken at two to five intervals depending on the station depth.

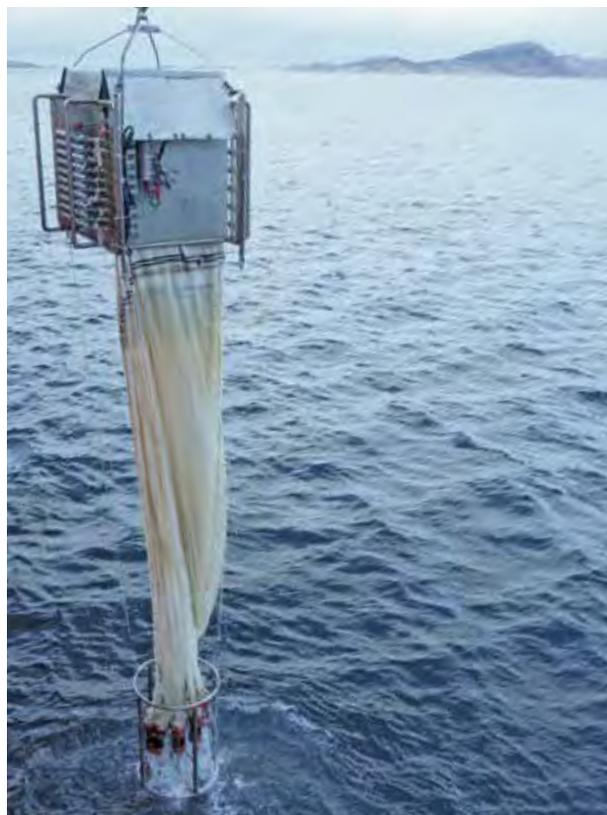


Figure 19. *Vertical hydrobios multinet.*

10.8.1 What We Have Learned

The zooplankton community in the fjords is largely dominated by copepods. In terms of abundance, the most common species recorded are the calanoid copepods of the genus *Pseudocalanus* (mainly *P. minutus* and *P. elongatus* and in less proportion *P. acuspes*) and the cyclopoid copepod *Oithona similis* (Figure 20). Similar Arctic studies found that *Pseudocalanus* sp. and *O. similis* were also the most common species in other areas, such as the southeastern Beaufort Sea (Darnis et al. 2008).

The species with the highest biomass contribution in the zooplankton are the calanoid copepods, especially the large *Calanus hyperboreus* and *Calanus glacialis* and the chaetognath *Parasagitta elegans*. Nachvak was the most productive inlet in the study with biomass values

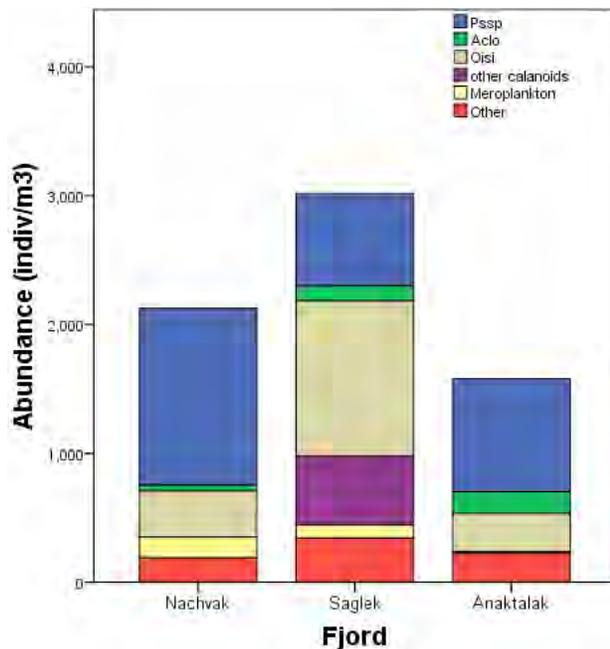


Figure 20. Mean values of species abundance in each inlet over the study period. Legend abbreviations: Pssp= *Pseudocalanus sp.*, Oisi= *Oithona similis*, Aclo= *Acartia longiremis*.

ranging from 6 to 27 g C m⁻². The least productive inlet was Anaktalak, with biomass values ranging from 0.3 to 17 g C m⁻².

10.8.2 Future Objectives

Our next goal in this study is to identify how the variation in water conditions, such as temperature, salinity and food availability, are influencing the zooplankton populations of the fjords and fjards. This will help us understand how climate change in the region may affect the marine ecosystems.

10.9 Phytoplankton

Primary producers play a key role in the oceans as they supply organic matter (food) to the higher trophic levels, including zooplankton, fish larvae and benthic animals. Marine polar ecosystems are particularly sensitive to any

changes in primary production due to their low number of trophic links (Grebmeier et al. 2006, Moline et al. 2008, Post et al. 2009; Wassmann et al. 2011). Arctic and Sub-arctic marine environments are changing as evidenced by the decrease in sea-ice thickness and extent (Stroeve et al. 2007, Kwok et al. 2009), the early melt and late freeze-up of sea-ice (Markus et al. 2009) and the enhancement of the hydrological cycle (Peterson et al. 2006; Serreze et al. 2006). These environmental changes have already altered the taxonomic composition and production of marine phytoplankton in the Canadian High Arctic (Li et al. 2009, Arrigo and van Dijken 2011, Comeau et al. 2011, Tremblay et al. 2011). In this context, the objectives of the study in Nunatsiavut are to: (1) determine the spatial and temporal variability in phytoplankton production, biomass, cell-size structure and community composition of northern Labrador fjords and fjards, and (2) assess the role of environmental factors on the phytoplankton dynamics and its variability. This is the first study on phytoplankton dynamics in Nunatsiavut fjord and fjard ecosystems.

Field sampling was conducted in Nachvak Fjord, Saglek Fjord and Anaktalak Bay during fall 2006 and summer 2007 and in Nachvak Fjord, Saglek Fjord, Okak Bay and Anaktalak Bay during fall 2009 and 2010. Sampling was carried out at the inner and outer parts of each fjord and fjard (Figure 1). At each station, we determined the vertical profiles of irradiance, temperature, salinity, nitrate concentration, transmissiometry and chlorophyll *in vivo* fluorescence, using probes attached to a CTD-rosette system. Water samples were collected at different depths in the euphotic zone with 12 L Niskin-type bottles for the determination of protist > 2 µm taxonomic composition (inverted light microscopy), picophytoplankton (≤ 2 µm) and nanophytoplankton (2-20 µm) abundances (flow cytometric method), phytoplankton chlorophyll a biomass (fluorometric method) and primary production (¹⁴C-assimilation method using *in situ* simulated incubations in 2007 and 2010 and photosynthesis-irradiance curves in 2009). Methods used during this study are described in detail in Ardyna et al. (2011). The results presented here are from data collected during summer 2007 and fall 2009 and 2010 only.

10.9.1 What We Have Learned

During the summer of 2007, a total of 86 protist taxa were observed in the euphotic zone of the three study inlets (i.e. Nachvak Fjord, Saglek Fjord and Anaktalak Bay), including 41 flagellate taxa, 24 centric diatom taxa, 14 dinoflagellate taxa, and 7 pennate diatom taxa. Thirty-one taxa were common to all three fjords, and most of them were flagellates. The most abundant protists belonged to the genera *Chaetoceros* (a centric diatom) and *Chrysochromulina* (a prymnesiophyte). The number of protist species, an index of species diversity, was 66 in Nachvak Fjord, 61 in Saglek Fjord and 65 in Anaktalak Bay. Hence, the species diversity was similar in the three fjords during summer.

During the fall of 2009 and 2010, the number of protist taxa ranged from 67 in Okak to 117 in Saglek, with a mean value of 92. The number of species ranged from 38 in Okak to 70 in Anaktalak, with a mean value of 54 (Figure 21). The number of taxa and species generally decreased from the inner to the outer part of each inlet, except in Saglek in 2009. The difference in protist diversity was relatively small between the inlets and sampling years. Maximum diversities, however, were observed at the outer station of Saglek Fjord and Anaktalak Bay during fall 2010 (Figure 21b). The community was composed of typical autumnal taxa, notably photosynthetic flagellates (e.g. *Prymnesiophyceae*) and heterotrophic flagellates (e.g. *Choanoflagellidea*).

The highest and lowest abundances of eukaryotic phytoplankton (0.2-20 µm) were recorded at the inner stations of Anaktalak Bay (summer 2007) and Okak Bay (fall 2009; Figure 22). Picoeukaryotes (≤ 2 µm) were the most abundant algal cells throughout the study period, making up on average 70-89 % of the total phytoplankton abundance (0.2-20 µm). Pico- and nanophytoplankton (2-20 µm) were always more abundant at the outer stations, except in Anaktalak Bay for picoeukaryotes and in Nachvak Fjord for nanoeukaryotes during summer 2007. Picophytoplankton were more abundant during sum-

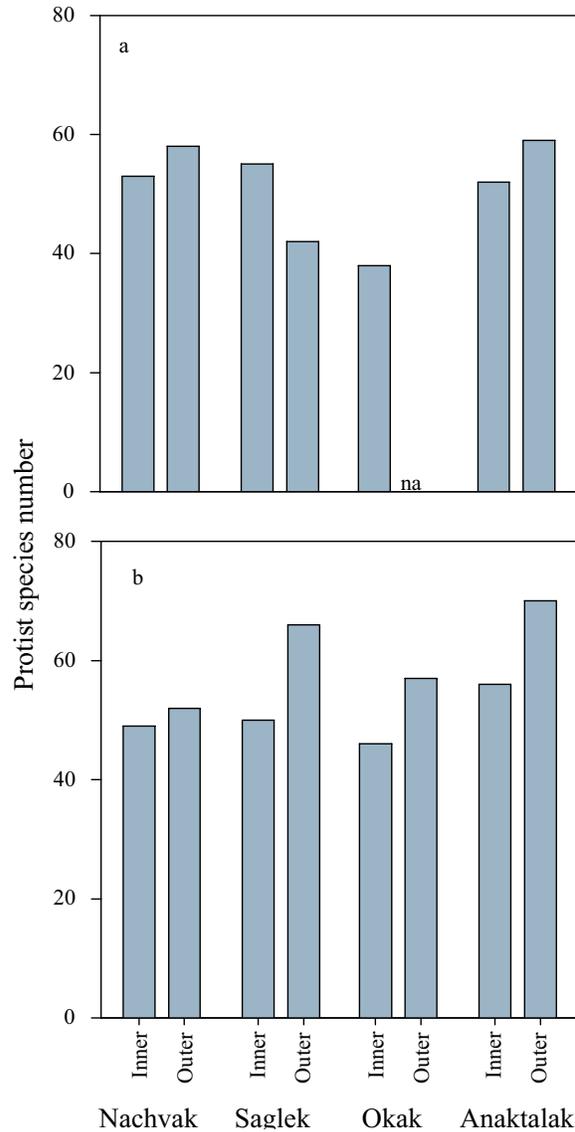


Figure 21. Number of protist species > 2 µm in the four Labrador inlets during (a) fall 2009 and (b) fall 2010. Protists are eukaryotic unicellular organisms. na: data not available.

mer 2007 and fall 2010 than during fall 2009, whereas nanophytoplankton were more numerous during summer 2007 than during the other two sampling periods. Overall, spatial and temporal patterns in phytoplankton abundance and cell-size structure were relatively similar between inlets.

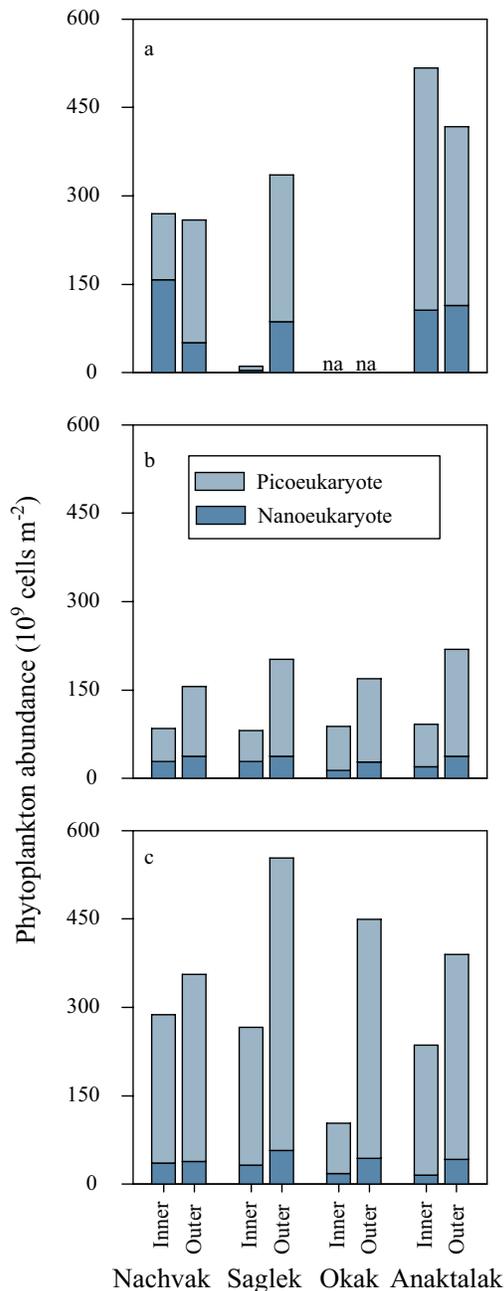


Figure 22. Total abundance of eukaryotic pico- and nanophytoplankton integrated across the upper 100 m of the water column (or entire water column in <100 m water depth) in four Labrador inlets during (a) summer 2007, (b) fall 2009, and (c) fall 2010. na: data not available.

During the sampling period, the phytoplankton biomass integrated over the euphotic zone ranged from 8.6 mg chl *a* m⁻² at the inner station of Okak Bay to 96.5 mg chl *a* m⁻² at the outer station of Anaktalak Bay (Figure 23). The phytoplankton biomass was consistently higher at the inner stations than at the outer stations in Nachvak Fjord and Anaktalak Bay, whereas the opposite pattern was observed in Saglek Fjord. The biomass was, on average, 3 times higher during summer 2007 than during fall 2009 and 2010. During summer 2007, the biomass was generally dominated by large cells (> 5 μm), in contrast to fall 2009 and 2010 when phytoplankton biomass was consistently dominated by small cells (0.7-5 μm), particularly at outer stations in Nachvak Fjord and Okak Bay and at both stations in Anaktalak Bay. Saglek Fjord was the exception to this trend with large cells dominating. The elevated biomass value (i.e. 98.3 mg chl *a* m⁻²; Figure 23b) measured at the outer station of Saglek Fjord during the 2009 expedition suggests that fall a phytoplankton bloom composed of large-sized cells may occur in northern Labrador fjords.

During summer 2007, the outer fjord stations were extremely productive (primary production >1000 mg C m⁻² d⁻¹), with rates decreasing from the northernmost to the southernmost inlet (Figure 24a). Primary production was, on average, 8 times lower during fall 2010 than summer 2007 (Figure 24b). During fall 2010, production rates were consistently higher at inner stations than outer stations. In addition, rates were lower in Anaktalak Bay than in the other inlets. Large phytoplankton made up, on average, 34 and 18% of the total primary production in summer 2007 and fall 2010, respectively. During summer, the contribution of large phytoplankton cells to total production (range = 27-46%, mean 34%) was generally lower than their share of total biomass (range = 62-71%, mean 67%). This suggests either the preferential removal of small phytoplankton cells by microzooplankton grazing or accumulation of large cells in the euphotic zone (Tremblay and Legendre 1994). Both interpretations imply that the phytoplankton carbon produced at the outer stations during summer was mainly retained in the euphotic zone rather than being exported to depth.

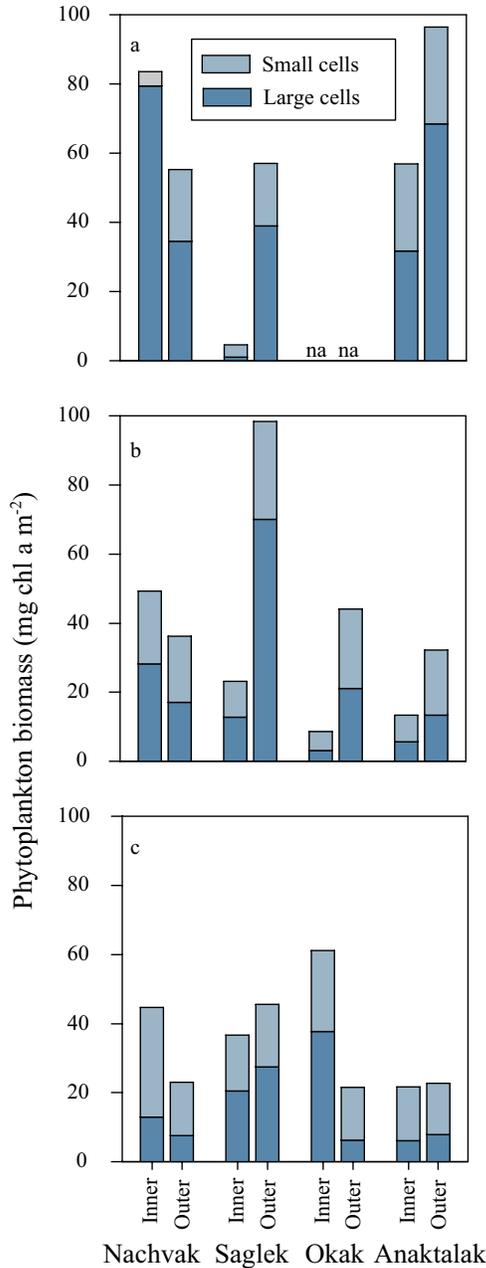


Figure 23. Variation of phytoplankton (chlorophyll a) biomass integrated over the euphotic zone in the four Labrador study inlets during (a) summer 2007, (b) fall 2009, and (c) fall 2010. Biomass of large (> 5 μm) and small algal cells (0.7-5 μm) is shown. na: data not available.

10.9.2 Future Objectives

Our next goal is to assess the role of abiotic (e.g. water column stratification, light availability and nutrients supply) and biotic (e.g. grazing) factors on the production and fate of the phytoplankton communities in the various

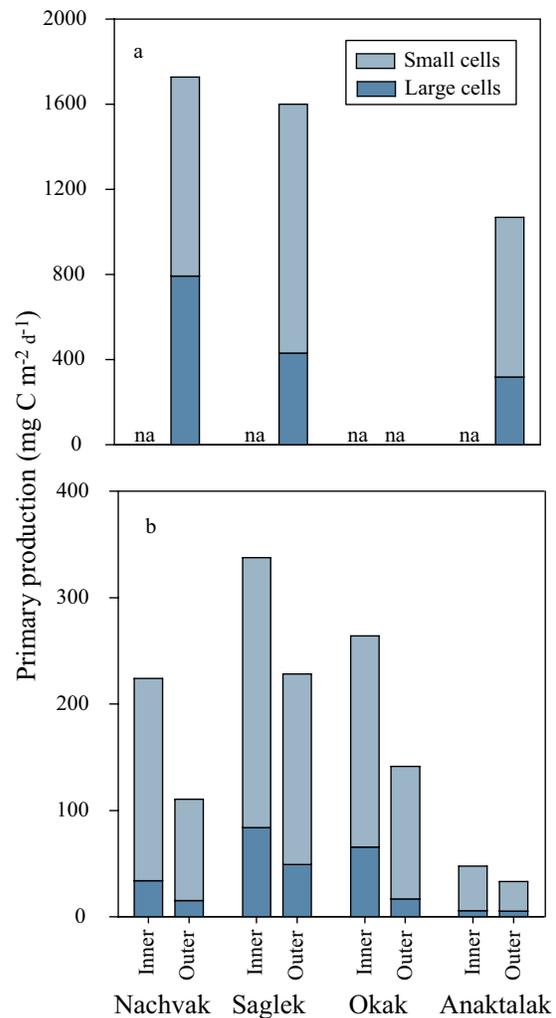


Figure 24. Variation of primary production in the euphotic zone of four Labrador inlets during (a) summer 2007 and (b) fall 2010. Production rates for large (> 5 μm) and small algal cells (0.7-5 μm) are shown. na: data not available.

fjords. This information will help us to understand how climate change may affect the functioning and structure of the planktonic communities in Subarctic fjord ecosystems.

10.10 Knowledge to date

This biological and physical study of fjords and fjards of northern Labrador is providing new insights into these critical but poorly understood areas. There has been a significant reduction in the duration of sea-ice cover across the marine inlets of northern Labrador over the past 50 years, with recent extreme lows in coverage, accompanied by reduced salinity. On a shorter timescale, over the past 10 years, there has also been an increase in marine productivity along a north to south gradient in Labrador. Although the biological significance of these changes will vary, it is expected that their continuation will result in

a general increase in species abundance as well as the northward expansion of geographical ranges of lower latitude species; such responses could alter energy transfer throughout physical and biological (including Inuit) systems and affect contaminant movement in more significant ways than present.

Ice-associated marine mammals, such as ringed seals, may be particularly vulnerable to the reduction in the duration of sea-ice cover because they depend on the ice for the successful rearing of their young. Furthermore, changes in prey availability and distribution could affect ringed seal nutritional status, reproductive success, and geographic range that may lead to changes in the species distribution and contaminant load. The ringed seal coastal food-web and telemetry studies are providing important insights into species distribution, foraging pattern and



diet. Telemetry data suggests localized feeding behavior in some seals and results of the coastal food-web study suggest there may be differences in feeding patterns (i.e. diet) of ringed seals across the four inlets that may have potential implications for the transfer of contaminants to this species.

The Saglek case study illustrates how high energy marine ecosystems along the coast of Labrador can demonstrate substantial resilience and recovery from anthropogenic disturbances, if managed in a sustainable and progressive manner. The legacies of local sources of contamination, however, continue to impact coastal marine systems in Labrador, as elevated levels of contaminants (PCBs) continue to be found in some ringed seals (approximately 10-15%) captured from the coast. Despite this fact, ringed seals still remain a healthy source of nutrition, and con-

taminant levels in Inuit from Nunatsiavut are generally lower than the rest of the Arctic due to overall diet choices.

The research conducted to date in these fjords and fjards provides a foundation for further research in these environments and for monitoring environmental change in Subarctic and Arctic coastal areas. Changes in the physical properties of these ecosystems as a result of climate change alone are expected based on conditions predicted by climate models and trends observed over the past 50 years. Major scientific unknowns relate to the impacts of climate change and industrialization on coastal marine fauna and flora interactions and ecosystem structure and function. Continued research and monitoring of these ecosystems will provide great value to understanding environmental changes.



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