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We would also like to thank all those who participated in this assessment for their support and contributions to its successful development.

Canada 



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Foreword

Earth's climate is changing at an unprecedented rate. As predicted by scientists a hundred years ago, rising temperatures are affecting, first and foremost, the Arctic regions of the planet. The ongoing decrease in sea-ice extent and transformation of the tundra have substantial implications for marine and terrestrial ecosystems and the services they provide. Pathways of contaminants to the Arctic are being altered. Permafrost destabilization is affecting infrastructure from homes to airports. The opening of new sea routes may increase vessel traffic and access to oil and gas and mineral deposits. For local communities, climate change is compromising the availability of traditional foods and water supplies with consequences for health and wellbeing. These and many related effects are significant and potentially irreversible. Concurrently, the modernization of the Arctic introduces profound socio-economic and education issues for Northern populations. Monitoring and understanding its changing Arctic territories, seas and communities are essential to ensure Canada has the best information available for effective management and policy-making.

ArcticNet, a Canadian Network of Centres of Excellence, is helping to prepare for the impacts of change in the Canadian Arctic. The Network is jointly funded by the three Canadian science granting councils: the Natural Sciences and Engineering Research Council, the Social Sciences and Humanities Research Council, and the Canadian Institutes of Health Research. Its central objective is to generate the knowledge and expertise required to document and evaluate the changes taking place and their consequences for the Arctic environment and its peoples. The results of these extensive efforts are integrated into assessment reports. These assessments and their recommendations are essential tools in the creation of effective adaptation strategies for sustainable communities and development in the Canadian Arctic and Subarctic. ArcticNet's vision is a future in which

scientists, Northerners and Inuit jointly build the capacity to lessen the negative impacts and maximize the positive outcomes of change.

The ArcticNet IRIS (Integrated Regional Impact Study) approach provides a unique opportunity to further develop linkages among Northerners, Inuit experts and academic specialists in the natural, health and social Arctic sciences. ArcticNet's ultimate ambition is to transform its current IRIS Reports into dynamic, web-based documents that are continuously updated by contributors with ongoing feedback from users. The first step is the publication of an initial Report for each of the four ArcticNet IRIS regions. We gratefully acknowledge the support and input of all Network Investigators, students, other researchers, colleagues and partners in the colossal task of formulating the IRIS Reports. We wish to express our sincere appreciation to the Eastern Arctic IRIS Steering Committee and the dedicated editorial team for bringing the IRIS 2 (Eastern Canadian Arctic) Report through to completion. Finally, we hope that the expertise, capability and communication network created during the preparation of this Report will continue to support Arctic communities as they adapt to their changing environment.

*Prof. Louis Fortier,
Scientific Director of ArcticNet*

*Ms. Leah Braithwaite
Executive Director of ArcticNet*

Preface

ArcticNet Inc. is a Network of Centres of Excellence of Canada that brings together scientists in the natural, human health and social sciences with their partners from Inuit organizations, northern communities, federal and provincial agencies and the private sector to study the impacts of climate change and modernization in the coastal Canadian Arctic. The research program of ArcticNet spans the entire coastal Canadian Arctic and includes both land and sea. Within the research program there are five main themes: marine systems; terrestrial systems; Inuit health, education and adaptation; northern policy and development; and knowledge transfer.

ArcticNet's research projects contribute to four Integrated Regional Impact Studies (IRIS) that correspond to one of the main political-physiographic-oceanographic regions of the coastal Canadian Arctic: 1) the Western and Central Arctic (including the Inuvialuit Settlement Region (ISR), the Yukon North Slope and Herschel Island, and the Kitikmeot region of Nunavut); 2) the Eastern Arctic (including the Qikiqtaaluk and Kivalliq regions of Nunavut); 3) Hudson Bay; and 4) the Eastern Subarctic (including Nunavik and Nunatsiavut) (see Figure right). Each IRIS supports an Integrated Regional Impact Assessment

(IRIA) that is structured to highlight current knowledge on the impacts of climate change and modernization and assist policy and decision-makers in developing strategies to mitigate and adapt to these impacts. The IRIA for the Eastern Arctic ("IRIS 2") was led by Dr. Trevor Bell, and coordinated by Philippe Leblanc (2011-2013), Dr. Kathleen Parewick (2013-2014) and Dr. Tanya Brown (2014-2017), with the support of ArcticNet and Memorial University of Newfoundland. Inuit Research Advisors (Stephanie MacDonald, Kiah Hachey, and Romani Makkik) assisted with IRIS coordination and communications in the region.

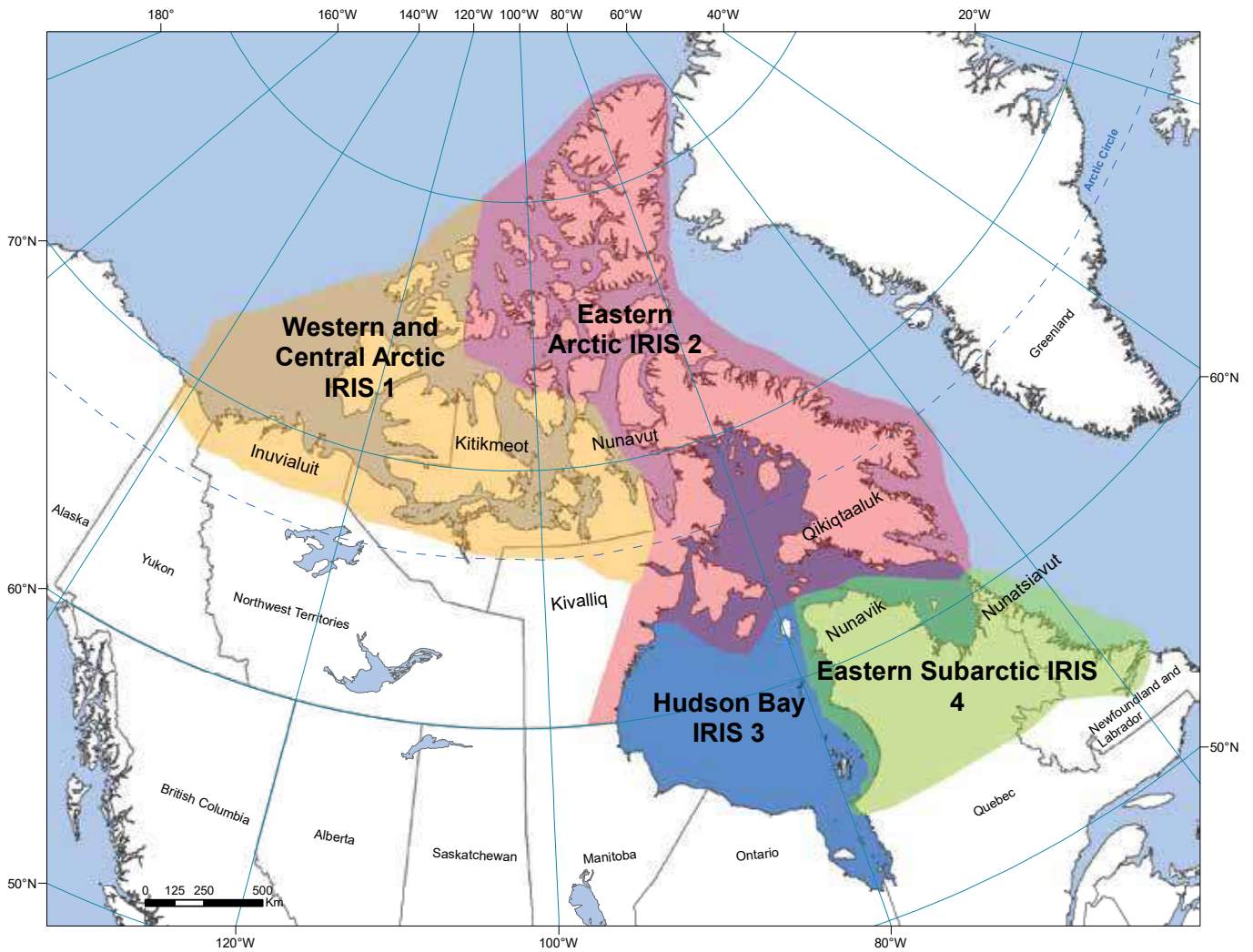
The IRIS 2 Steering Committee guided the development and production of the Eastern Arctic IRIA in a collaborative process to help ensure that the information and recommendations were relevant to decision makers and stakeholders within the region. The committee was composed of representatives from the Nunavut Research Institute, Nunavut Tunngavik Inc., Inuit Tapiriit Kanatami, Indigenous and Northern Affairs Canada, Government of Nunavut Climate Change Secretariat, and ArcticNet. In addition to newsletters, presentations and conference calls, face-to-face meetings were held in the region and at targeted Arctic-themed meetings in southern Canada, including:

- International Polar Year 2012 Conference, Montreal (April 22-27, 2012);
- ArcticNet Regional Science Meeting, Iqaluit (November 6-8, 2012);
- ArcticNet Annual Scientific Meetings (2012-2016);
- IRIS 2 Workshop, Arctic Change, Ottawa (December 8, 2014);
- IRIS 2 Regional Workshop, Iqaluit (October 3-4, 2017)

The editors thank all past and present IRIS 2 Steering Committee members, supporters and observers, as well as network investigators, students, researchers, reviewers, and partners for contributing to this IRIA for the Eastern Canadian Arctic.



JACQUELINE VERSTEGE/ARCTICNET



Map of the four ArcticNet IRIS regions covering the coastal Canadian Arctic.

Introduction

The Eastern Canadian Arctic is currently experiencing some of the most rapid climate warming in the North. This warming is associated with significant changes in snow and ice cover, shrinking glaciers and ice caps, and thawing permafrost, which in turn are triggering landscape, hydrological and ecosystem changes. These climate-associated changes are compromising the accessibility, availability, and quality of traditional foods and water supplies throughout the region.

For generations, Inuit have been documenting and adapting to change in the Eastern Canadian Arctic. Environmental and societal changes, however, have intensified in recent decades, increasing stress on Inuit communities as they try to cope and adapt. Extensive traditional and scientific-based research over the last decade has documented climate-related changes in the Arctic. The objectives of the Integrated Regional Impact Assessment are to summarize this research for the IRIS 2 region and present it in an accessible format to help mitigate negative impacts and identify opportunities associated with these changes.

This IRIS 2 Report is the culmination of research synthesis and engagement activities in the region and consists of two parts:

- 1) The *Synthesis and Recommendations* summarize the key findings, associated recommendations, and knowledge gaps arising from the assessment. This stand-alone document (available in English, French and Inuktitut) is intended as a reference guide to assist managers, policy analysts and decision makers develop adaptation strategies and programs that support productive ecosystems and thriving communities in a changing Arctic. The document provides a succinct overview of what we know about changing climate and environment in the region, followed by key messages and recommendations on how these changes are affecting priority issues. The document concludes with a listing of the knowledge gaps identified through the assessment process.



ISABELLE DUBOIS / ARCTICNET

- 2) The full report (in English only) includes both the *Synthesis and Recommendations* and the *Integrated Regional Impact Assessment*, the latter arranged in three parts. Part I describes the regional geography and the demographic and socio-economic context of the Eastern Canadian Arctic. Part II provides background information on mostly environmental “drivers” that are causing change in the region, including climate variability, melting glaciers and ice-shelves, thawing permafrost, shifting marine, freshwater and terrestrial ecosystems, dynamic coastal processes, and emerging educational priorities. Part III is divided into 14 chapters that focus more explicitly on responses to the ongoing change (e.g., effects, outlooks, adaptation) in the region and demonstrate how research and knowledge can be used to inform priority issues in the context of environmental and societal changes. Each chapter deals with a specific issue of importance to the IRIS 2 region: Contaminants; Travel and hunting; Human health; Food security; Water security; Permafrost and infrastructure; Managed wildlife; Marine biodiversity; Commercial fisheries; Mining and communities; Shipping; Cruise tourism; High school education; and Postsecondary education.

Synthesis and Recommendations

The Eastern Canadian Arctic IRIS Steering Committee together with invited representatives of regional government and non-government organizations provided input on the key findings and recommendations arising from the IRIS 2 report chapters. By involving regional experts and decision makers, our goal was to more effectively communicate the implications of the scientific knowledge for varied audiences across the region.

We have structured the document to provide first a succinct overview of key messages on current and future climate and environmental trends, as reported in Part II chapters of the IRIS 2 report. These chapters incorporate both science observations/projections and Inuit knowledge. The processes dictating these trends are driving changes in the environment and society of the region. Following the advice of our steering committee, we have collapsed the key messages and recommendations from the bulk of our report under three cross-cutting issues: Health, Food security, and Sustainable communities. Although these three broad integrative themes do not incorporate all the challenges facing society in the region, they do reflect the cumulative impacts of a wide range of environmental, socio-economic and political factors, and in one way or another affect all dimensions of life in the region today. The remaining key messages and recommendations from

the report are grouped under three other themes: Education, Socio-economic and resource development, and Ecosystem changes. By adopting this structure we do not claim an exhaustive treatment of each issue, rather we have mobilized the scientific knowledge generated in the report to optimize its contribution to these key societal issues.

In the final section we present in summary form the key knowledge gaps identified by chapter authors, grouped by rationale: Monitoring for climate change impacts and responses; Surveys for evidence-based decision making; Modelling for future climate change impacts; and Community based monitoring and incorporation of *Inuit Qaujimaqatuqangit*. These recommendations for future research and monitoring are intended to improve our understanding of the impacts of changing environment and society in the IRIS 2 region.



DAVID GASPARD/ARCTICNET

Recent and Future Climate Trends

What do we know about recent climate change in the IRIS 2 region?

- The region is currently experiencing some of the most rapid climate warming in the Arctic, particularly during the fall/winter season.
- The warming pattern shows evidence of a number of coastal “hot spots” in Hudson Strait and Foxe Basin where recent fall/winter season warming exceeds 1.7 °C per decade.
- Warming has been associated with significant changes in snow and ice cover, such that current conditions are likely unprecedented in many millennia.
- Warmer summer temperatures are shrinking glaciers and ice caps in the region at an accelerating rate.
- Arctic ice shelves that uniquely occur along the northern edge of the region have decreased in area by approximately half over the past decade.
- Permafrost in the region is warming between 0.3 and 0.5 °C per decade, and the seasonally thawed surface layer is deepening, triggering landscape, hydrological and ecosystem changes.
- Shallow ponds are shrinking and drying up because of a growing imbalance between precipitation (rainfall and snowfall) and evaporation (loss of moisture into the atmosphere).



PIERRE COUPEL/ARCTICNET

What can we say about future climate change in the IRIS 2 region?

- Climate change projections for 2050 show a continuation of observed trends with the greatest warming (4 to 8 °C) in the fall and winter seasons.
- Precipitation is projected to increase over most of the region by about 15-20% with the largest changes in the fall/winter season and over coastal and more southern areas.
- Projected increased snowfall (15-35%) will occur during a shorter snow cover season (a month or so shorter by 2050) with only slight changes in overall maximum snow depth.
- Large reductions in snow accumulation on the ground are projected during the fall and spring from a later start to the snow season and earlier melt.
- Nunavut lakes will warm faster than the global average.
- Projected changes in lake ice cover by 2050 indicate earlier break-up by 10-15 days and later freeze up by 5-10 days, with a 10-30 cm decrease in maximum ice thickness.
- The duration, thickness and concentration of sea ice are projected to decrease over most of the region.
- Within several decades Arctic ice shelves may no longer exist.
- Rivers are projected to have higher peak flows and longer flow duration.



DARCY MCNICHELL/ARCTICNET

Human Health

Human health is the subject of one chapter in our IRIS 2 report, from which we synthesize here major health trends of the 2007-08 Inuit Health Survey for the region. Associated recommendations focus on supporting existing programs and initiatives that promote individual and community wellbeing, and help build a strong public health system. Because environmental contaminants have implications for human health, we include here some of the key messages and recommendations from that chapter too.

Key Findings:

- Those who experience food insecurity (69% of the population) are more likely to feel unhealthy, be prone to infection, experience stress, as well as have chronic health problems, mental health challenges, and a lower learning capacity.
- Almost three-quarters (73%) of the adult population of the Eastern Canadian Arctic smoke on average 12 cigarettes a day and began smoking at 15 years of age. Second-hand smoke occurs in about 90% of households.
- Smoking is a major problem for many reasons. One is that smoking exposes Inuit to high levels of cadmium. Blood levels of cadmium were high in the Inuit Health Survey, and the main source of cadmium was cigarette smoking.
- The Inuit Health Survey highlighted some concerns with the health of children. More children than expected were at a high body weight, and some children experienced anemia (20%). Most children were found to have low levels of vitamin D (79%) and many children experience tooth decay.
- Almost half of Nunavummiut report having experienced suicidal thoughts at some point in their lives and 29% have reported a non-fatal suicide attempt, with younger adults aged 18-49 years reporting the highest percentage of suicide attempts.
- Generally, the nutritional benefits of eating country foods far outweigh the risks from contaminant exposure.



RODD LAING

For certain groups of people, such as pregnant women, special considerations exist.

- Concentrations of many persistent organic pollutants (POPs) have declined in the environment due to the implementation of international bans on their use.

Recommendations:

- Continue to promote smoking cessation through community-based support groups, counselling and online programs.
- Continue to promote the consumption of country foods. Country foods offer many benefits, including providing a rich source of nutrients, such as iron, vitamin D and healthy fats.
- Women of childbearing age should choose healthy country foods such as caribou or char, which have lower mercury concentrations and important nutrients and vitamins.
- Over the past several years, Nunavut has recommended that women of childbearing age eat ringed seal meat, instead of ringed seal liver, because seal meat is lower in mercury. The Government of Nunavut Department of Health is currently revisiting this recommendation.
- Support the provision of healthy store-bought foods to help reduce the consumption of high sugar and fat foods.
- Continue to promote supportive mental health services in communities to reduce suicidal ideation.



DAVID GASPARD/ARCTICNET

Food Security

One chapter in the IRIS 2 report focuses exclusively on Food security. In keeping with the cross-cutting nature of this key issue, we use environmental and socio-economic determinants to draw together from a range of report chapters the key findings that influence food security (accessibility, availability, quality) in the region.

Key Findings:

- Nunavut has the highest rates (69%) of food insecurity in the country, six times the Canadian average and the highest rate for any Indigenous population in an industrialized nation.
- Approximately 70% of children in Nunavut aged 3-5 years live in food insecure homes.
- Children, women and the elderly are most vulnerable to food insecurity.
- Food insecurity has implications for health and nutrition, with lower intakes of vitamins C and D, folate, iron, zinc, magnesium, and calcium being reported by food insecure individuals.
- Determinants of food insecurity are closely linked with socio-economic and environmental changes in the region.
- Climate change acts as a risk multiplier to existing food security challenges.
- Rapidly warming lakes will affect biological productivity and fish species composition and stocks.
- The expansion of boreal forest and shrubland farther north will likely reduce food availability for caribou while attracting more moose.
- More frequent freezing rain and thaw events restrict caribou foraging, potentially impacting their health and migration patterns.
- Loss of wetlands associated with thawing permafrost and increased evaporation may result in significant loss of habitat for harvestable bird species (e.g., ducks and geese).



RODD LAING

- Berry production may decline due to drier soil conditions and competition from other plants.
- Greater amounts of freshwater, lower productivity and potential for ocean acidification in the marine environment may ultimately impact fish and seal populations.
- Increased shipping near communities may affect migration patterns and availability of harvestable marine mammals.
- Extreme high tides in Iqaluit have flooded shoreline subsistence infrastructure, temporarily impacting local food security.

Recommendations:

- Support the work of the Nunavut Food Security Coalition and recommendations made in the Nunavut Food Security Strategy.
- Integrate climate change projections and impacts into food security strategies.
 - Continue to promote the health benefits of consuming country foods.
 - Increase accessibility and affordability of country and healthy store-bought foods.
 - Promote food sharing and social food networks within communities.
 - Enhance harvester-support and community freezer programs.
 - Encourage harvesting and food preparation skills transmission between generations.
 - Evaluate how adaptation can be integrated into food programming and policy.



Sustainable Communities

Under this Sustainable communities cross-cutting theme, we have compiled key messages and recommendations from a range of report chapters, including Permafrost, Coastal dynamics, Travel and hunting, Water security, and Permafrost and infrastructure.

Key Findings:

- Changes in ice and snow conditions are compromising traveller safety on trails, and limiting land and sea-ice access by Inuit.
- Changing weather conditions have resulted in hunters and Elders being less able (and more hesitant) to accurately predict weather.
- The near-absence of weather stations along community trails in the region severely restricts travel planning.
- More frequent and intense storms have increased travel risks throughout the year.
- Many communities have drinking water systems that require infrastructure improvements and improved operational capacity.
- Permafrost degradation and thermo-erosion processes are likely to continue to disturb the landscape, drain ponds and ultimately transform the hydrology,



RODD LAING

biogeochemistry, and ecosystems of surface waters in the Eastern Arctic.

- With the exception of bedrock, frozen ground can no longer be considered a permanently stable foundation for infrastructure in the region.
- Projected ground warming will increase permafrost thaw, compromise terrain stability and alter drainage patterns.
- Permafrost thaw and degradation will impact potable water quality, with possible changes in bacterial flora and load, and the emergence of potentially dangerous water-borne pathogens.
- Permafrost thaw and associated ground instability may compromise the structural integrity and shorten the life-cycle of community infrastructure.
- Increased coastal erosion rates are anticipated in areas of stable or rising sea levels, with more open water and wave energy in and close to communities.
- Higher coastal flooding, or enhanced wave run-up, will impact waterfront infrastructure in areas of present or future sea-level rise.

Recommendations:

- Document, maintain, and improve traditional knowledge sharing between generations, specifically with regards to weather and the environment.
- Improve weather forecasts at the community level and increase the number of weather stations along travel routes.
- Increase affordability and accessibility of safety equipment and continue to support services for travellers to help them adapt to unpredictable and dangerous travel conditions.
- Improve drinking water source protection and continue to promote multibarrier approaches to drinking water protection.
- Increase the frequency and scope of drinking water testing in communities.



- Promote programs and policies that support adequate and sufficient drinking water quantity for each person in the region to encourage better health outcomes.
- Climate-adapted planning in communities should account for areas most susceptible to climate impacts (e.g., permafrost degradation, flooding) and identify suitable land uses and related infrastructure design adaptations.
- Cost-benefit analyses for housing foundations must be used to assist decision-makers in choosing appropriate cost-effective mitigation solutions.
- Establish regulatory frameworks and appropriate governance for infrastructure design and construction to ensure safe and sustainable community development.
- Integrate and coordinate climate adaptation strategies across all decision levels for infrastructure design, construction and maintenance in communities.
- Upgrade telecommunication infrastructure to meet the Canadian national standard.



Education

Education is a fundamental issue underpinning Inuit society in the region. IRIS 2 report chapters deal specifically with the formal education system at the secondary and post-secondary levels.

Key Findings:

- High school graduation rates in Nunavut have increased more than 85% since 1999, but remain the lowest in Canada.
- Students who speak Inuktitut at home are less likely to succeed at school, which suggests the school system is not well adapted to the Inuktitut speaker.
- Only 2% of Inuit hold post-secondary diplomas and degrees, compared with 47% of non-Inuit in the region.
- The lack of housing is associated with reduced postsecondary education participation.
- Inuit youth are spending less time on the land, disrupting traditional knowledge transmission and placing future generations at risk of reduced land skills.

Recommendations:

- Continue to foster a school system in the region that encourages parental, teacher, and administrator engagement and is rooted in *Inuit Qaujimagatuqangit*.
- Integrate Inuit languages and land skills in school curricula.
- Create more postsecondary educational options for Inuit that are relevant and supportive of student cultural and learning needs.
- Increase access to skill-based training programs, especially in technology, to increase Inuit employment rates in the industrial economic sector.
- Recognize educational progress and success as a foundational action in climate change adaptation planning for the region.

Socio-economic and Resource Development

Under this broad development theme we include key messages and recommendations from report chapters on Mining, Shipping, Cruise tourism and Commercial fisheries.

Key Findings:

- Nunavut has 5 and 15% of Canada's known reserves of oil and natural gas, respectively, with the marine offshore having very high potential for undiscovered oil reserves.
- The mining industry constitutes a growing proportion of the region's economy, despite recent rapid and unpredictable changes in global commodity prices.
- Communities often feel they have not been properly consulted nor told how they will benefit from oil and gas and mineral exploration and development.
- Destinal (stopping in) ship traffic has already expanded significantly (2.8-fold from 2005 to 2016) in the region, but transit (passing through) traffic is likely to remain limited.
- Cruise tourism voyages grew two-fold from 2007 to 2014, but a significant increase is less likely without the future development of marine infrastructure.
- The ice regime within the Canadian Arctic Archipelago is likely to remain a hazard for shipping throughout the 21st Century.
- Ice shelves and floating glacier tongues are producing large ice islands and icebergs that can provide significant hazards to offshore oil exploration and shipping.
- Projected lower marine productivity could decrease future commercial fishery yields in the region.
- Characterized by low biological productivity and slow growth rates, marine waters are susceptible to overfishing and habitat disruptions.

Recommendations:

- Inuit must be included in monitoring and decision-making processes regarding resource development, tourism and shipping to help minimize environmental and socio-cultural impacts and maximize benefits to communities.
- Provide communities with the expertise and infrastructure to participate in community based monitoring activities.
- Building of maritime and tourism infrastructure will likely promote cruise ship activity in the region, which in turn may favour better economic return for communities.
- Implement fishing gear restrictions and modifications to limit the ecological impact of expanding fishing efforts and to protect important fish stocks in the region (e.g., Arctic char).
- Explore and support locally-based socio-economic opportunities (e.g., film, arts).



TANYA BROWN

Ecosystem Changes

Under Ecosystem changes we have combined key messages and recommendations from various chapters on Terrestrial, Marine and Freshwater environments, as well as those focused on Contaminants, Wildlife, Biodiversity and Conservation. Where appropriate, we have incorporated key messages relevant to the cross-cutting themes of Health and Food security into their respective sections.

Key Findings:

- Continued mass loss for glaciers and ice caps is expected for the remainder of this century, resulting in the complete disappearance of many small ice masses.
- Complete melt of some ice features (e.g., ice shelves) will result in loss of biodiversity and the complete extinction of globally unique ecosystems.
- Warmer lakes will affect ice cover duration, water mixing, biological productivity, greenhouse gas fluxes and species composition.
- Habitat loss associated with a reduction in the thickness, extent and duration of sea-ice coverage in the region will potentially reduce body condition, reproduction rates, and population size of polar bears.
- Greater summer stratification from increased freshwater input and sea-ice melt may limit marine productivity.
- The surface freshwater layer is more vulnerable to ocean acidification, which may alter lower trophic food-web structure and ultimately fish populations and their predators.
- A total of 29 Ecologically and Biologically Significant Areas, based mostly on large upper trophic levels animals, have been identified in the marine environment.
- Most legacy POPs appear to be declining with time in marine mammals; however, some of these compounds (e.g., PCBs, chlordanes) have shown little to no change, which may be related to continued emission or release from global environmental reservoirs (e.g., soils, snow, ice).
- Mercury concentrations in anadromous (sea-run) Arctic char have generally increased with time but are still very low. Marine mammals have shown little to no change in mercury levels.
- Contaminant burdens of legacy POPs and mercury in marine mammals appear to be increasing with rising temperatures, declining summer sea-ice extent and earlier sea-ice breakup.



MARTIN FORTIER/ARCTICNET

Recommendations:

- Support the development of a network of Marine Protected Areas that will enhance ecological resilience to anthropogenic disturbance and increase social and economic benefits for communities and sustainable fisheries.
- Protect important habitats such as wetlands and polynyas at scales that preserve functional connectivity, ecosystem resilience and facilitate adaptation to climate change.
- Support Inuit-led management and include traditional knowledge in conservation initiatives.
- Adopt proactive planning approaches which support community environmental stewardship.



DAVID BOERTMANN



PIERRE COUPEL/ARCTICNET

IRIS 2 Knowledge Gaps

The authors of the IRIS 2 report identified knowledge gaps where future research efforts might play an important role in understanding and responding to climate change and resource development impacts in the region. Opportunities to fill knowledge gaps by both science programs and community based monitoring are summarized below by theme.

Monitoring for climate change impacts and responses:

- The processes contributing to areas of locally enhanced warming, particularly where such “hot spots” occur close to communities or ecologically sensitive areas.
- The mass balance of glaciers.
- The current distribution, thermal state and properties of permafrost.
- Permafrost degradation processes and associated greenhouse gas sinks/sources.
- Glacier-ocean interactions.
- Water quantity, water quality and aquatic ecology.
- Lake and river ice.
- Shoreline stability.
- Co-located GPS stations and tide gauges for projecting future relative sea-level changes.
- The biological condition of fishes and bycatch (incidental fish caught) composition.
- Contaminant levels in Arctic biota, especially traditionally harvested foods.

Surveys for evidence-based decision making:

- University and post-secondary programs to help improve access to post-secondary education.
- Knowledge transmission from Elders to youth at the high school level.
- The chosen careers or education paths of young Inuit.
- High-resolution digital elevation data to assess flooding risk in communities.
- Baseline and impact monitoring of resource development, shipping and tourism.
- Harvestable species to assess their potential yield and temporal changes.
- Stock structure and distribution and the location and size of harvests for improved char fishery management.
- Distribution and abundance of forage fishes (e.g., capelin) to better understand energy transfers between plankton and commercially harvested species.
- Biodiversity and potential fishery resources in inshore waters.
- POPs to track environmental responses following implementation of the Stockholm Convention.
- Emerging contaminants to identify new candidates for inclusion in the Stockholm Convention.
- The costs of climate change impacts on people, communities and governments in the region.
- Food security strategies and pilot interventions.
- How socioeconomic-demographic trends will affect how communities experience a changing climate.
- The effectiveness, durability, cost and socio-economic and ecological implications of climate change adaptive strategies.

Modelling for future climate change impacts:

- Analytical permafrost modelling integrated with high-resolution regional climate modelling.
- Relative sea-level projections need to be available for all northern communities and updated as understanding, models, and future climate projections improve.
- Changes in water supply and quality with linkages to community and industry needs.
- Downscaling of climate impacts to examine how projected changes might interact with human systems and to assess how socio-economic-demographic trends will affect how communities experience a changing climate.
- Projected rates of change in key environmental indicators (e.g., sea ice) relevant to northern livelihoods.
- Potential future vulnerability in light of projected climate and socioeconomic trends.

Community Based Monitoring and incorporation of *Inuit Qaujimagatuqangit* (IQ)

- Comprehensive IQ integration in research and monitoring programs.
- Impacts of changing environment on drinking water quality.
- Shallow coastal monitoring (e.g., intertidal).
- Understanding of the issues facing Nunavut schools.
- Fisheries assessments and ecosystem monitoring for more sustainable management.



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A close-up, high-resolution photograph of a grey owl's head, showing its textured feathers and a bright yellow eye. The owl is looking towards the right. The background is a soft, out-of-focus natural setting with green and brown tones.

PART I

REGIONAL SETTING



Chapter 1 Regional Geography of the Eastern Canadian Arctic

Lead authors

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Abstract

The Qikiqtaaluk and Kivalliq regions are the two most populated regions in Nunavut, with over 29 000 people in 20 communities. These two regions are part of the Integrated Regional Impact Study (IRIS) 2 region, otherwise referred to as the Eastern Canadian Arctic. This region is characterized by few terrestrial and marine mammals and avian fauna relative to the species-rich benthic marine fauna. Low annual productivity is characteristic of most of the region, except for areas which tend to be ice free in the winter. The region is faced with many social and cultural challenges, which include inadequate housing, food insecurity, health and education issues, and efforts to support the retention of Inuit language and culture. The region is experiencing some of the most rapid warming in the Canadian Arctic, posing a serious threat for safety and well-being of Inuit and the wildlife upon which they depend. This chapter provides a description and overview of the IRIS 2 region and introduces many of the organizations that are responsible for protecting the region's people, culture, environment (land, air, water), and wildlife. These organizations, in collaboration with others, are involved in gathering traditional and scientific knowledge that will help the region adapt to and mitigate the impacts of climate change.

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1.1 IRIS 2 region delineated

The terrestrial areas of the IRIS 2 region encompass Ward Hunt Island, Ellesmere Island, the Sverdrup Islands (including Axel Heiberg, Ellef Ringnes, and Amund Ringnes Islands), some of the Parry Islands (including Melville, Bathurst, and Cornwallis Islands), Devon Island, some of Somerset and Prince of Wales Islands, Bylot Island, Baffin Island, Igloolik Island, Melville peninsula, Southampton Island, Coats Island, and the western coast of Hudson Bay (Figure 1). The marine part of the region includes Davis Strait and Baffin Bay, the Labrador Sea, Hudson Strait, Ungava Bay, Foxe Basin, Prince Regent Inlet, Lancaster Sound, Jones Sound, Kane Basin, Nares Strait, and Fury and Hecla Strait.

1.2 Communities and demographics

The IRIS 2 region includes the Qikiqtaaluk or Qikiqtani (formerly Baffin) administrative region of easternmost Nunavut, situated within the Eastern Canadian Arctic and part of the Kivalliq (formerly Keewatin) administrative region. The Qikiqtaaluk region covers an area of 1 040 418 km² and is Nunavut’s largest administrative district. This region is comprised mainly of the islands of the Canadian Arctic Archipelago (CAA). The communities within the Qikiqtaaluk region are Resolute on Cornwallis Island; Grise Fiord on Ellesmere Island; Arctic Bay, Pond Inlet, Clyde River, Qikiqtarjuaq, Pangnirtung, Iqaluit, Kimmirut, and Cape Dorset on Baffin Island; Igloolik

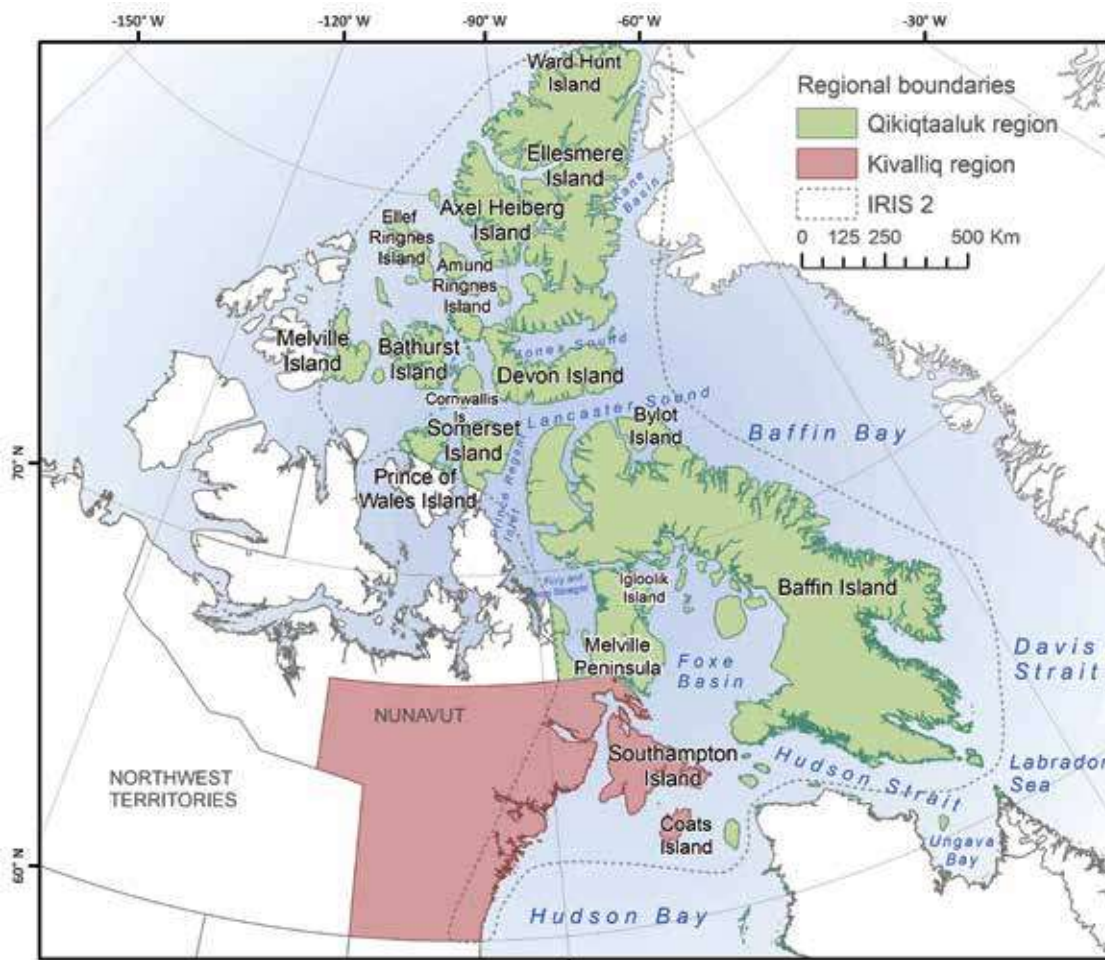


FIGURE 1. The IRIS 2 marine and terrestrial regions. Note the extent of the Qikiqtaaluk and Kivalliq administrative region outside the IRIS 2 region.

in Foxe Basin; Hall Beach located south of Igloolik and Sanikiluaq located in the Belcher Islands in Hudson Bay (Figure 2). The Kivalliq region, covers an area of 445 109 km² and is the smallest district in the territory. The Kivalliq region consists of the mainland to the west of Hudson Bay along with Southampton Island and Coats Island. The communities within the Kivalliq region are Nauyasat (formerly Repulse Bay), Igluligaarjuk (Chesterfield Inlet), Kangiqiniq (Rankin Inlet), Tikirarjuaq (Whale Cove), and Arviat on the shores of Hudson Bay; Qamani'tuaq (Baker Lake) located 320 km inland from Hudson Bay; and Salliq (Coral Harbour) on Southampton Island; (Figure 2). All 13 and 7 communities in the Qikiqtaaluk and Kivalliq regions, respectively,

are officially municipalities, and each has its own elected hamlet council and mayor. The territory's other region is Kitikmeot and is part of the IRIS 1 (western and central Canadian Arctic) region

The Qikiqtaaluk region is the most populated region of Nunavut, with 18 988 people living there, according to the most recent (2016) population estimate (Nunavut Bureau of Statistics 2017). Iqaluit, Nunavut's capital, is the largest community, with 7740 inhabitants counted in 2016. Grise Fiord and Resolute have the smallest populations, with 129 and 198 individuals, respectively. The Kivalliq region is the second most populated region of Nunavut, with 10 413 people living there (Nunavut Bureau of Statistics 2017).

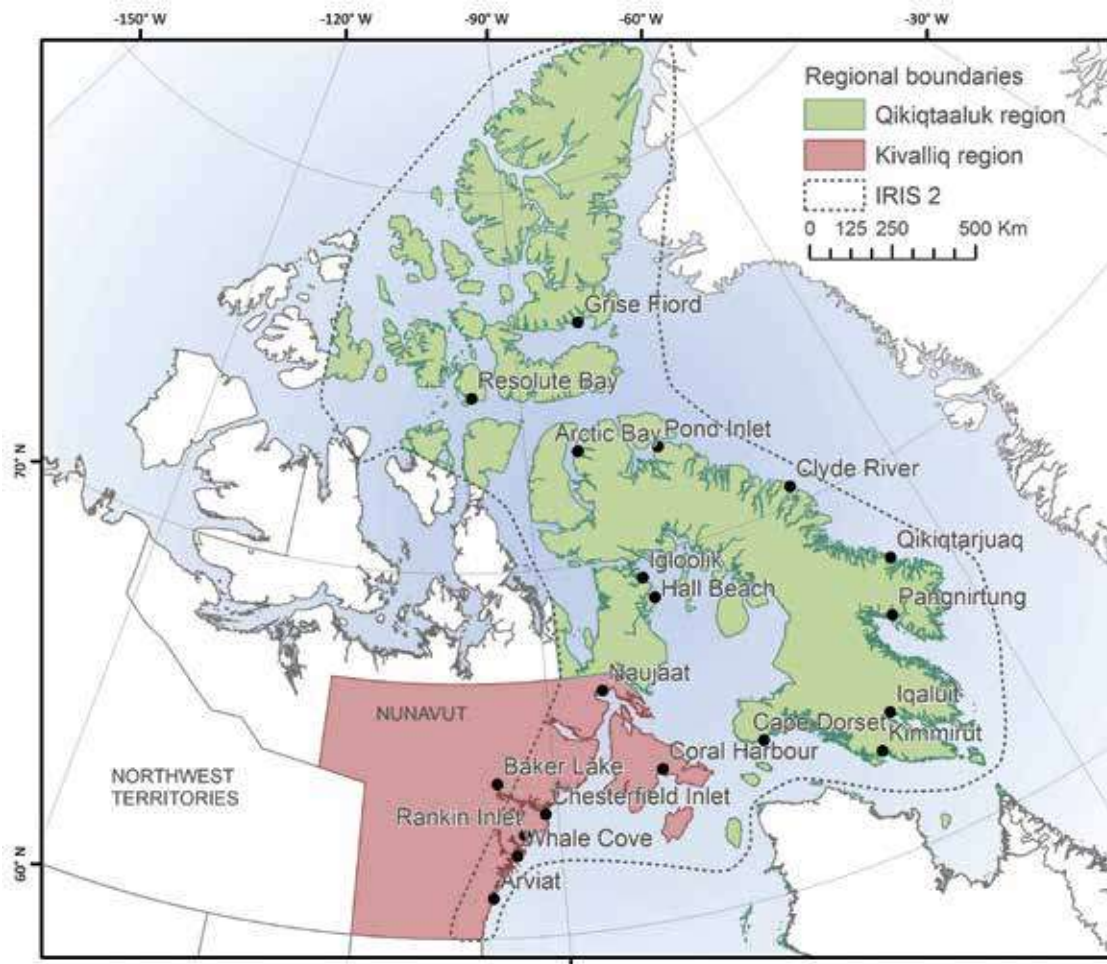


FIGURE 2. Communities in the Qikiqtaaluk and Kivalliq regions of Nunavut.

Rankin and Arviat have the second and third largest populations in Nunavut, with 2842 and 2657 individuals, respectively. Figure 3 illustrates the population distribution by sex and age groups in the Qikiqtaaluk and Kivalliq regions. The percentage of individuals under the age of fifteen years in the Qikiqtaaluk region (31%) and Kivalliq region (36%) is similar to the rest of Nunavut (33%) but higher than the rest of Canada (17%).

Signed by the Prime Minister of Canada on May 25, 1993, the Nunavut Land Claim Agreement (NLCA) made Nunavut the largest indigenous land claim settlement in

Canadian history (350 000 km²). Nunavut was officially made a territory in 1999. The goals of the NLCA are (1) to provide for certainty and clarity of rights to ownership and use of lands and resources, and of rights for Inuit to participate in decision-making concerning the use, management, and conservation of land, water, and resources, including the offshore; (2) to provide Inuit with wildlife-harvesting rights and rights to participate in decision-making concerning wildlife harvesting; (3) to provide Inuit with financial compensation and means of participating in economic opportunities; and (4) to encourage self-reliance and the cultural and social well-being of Inuit.

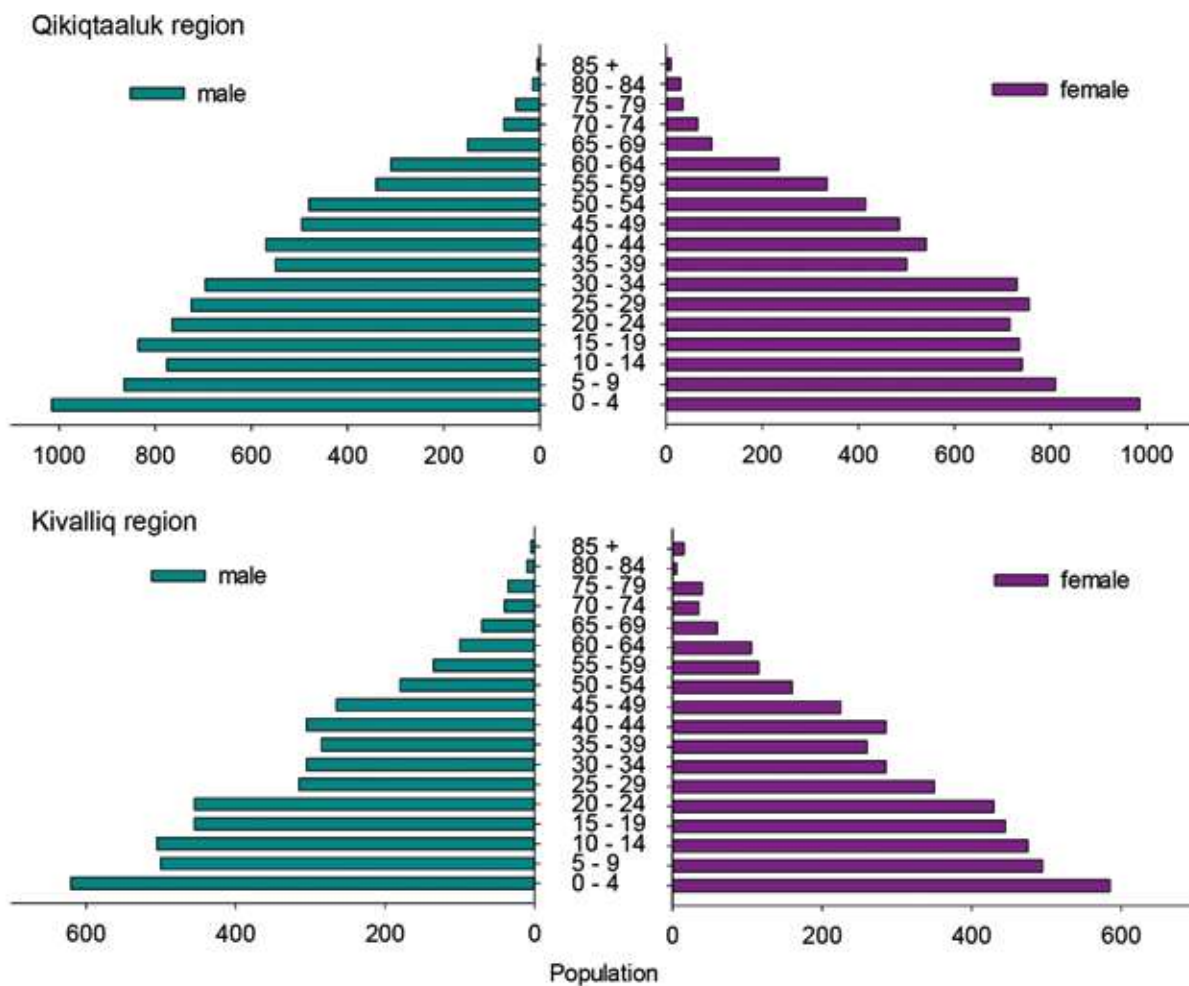


FIGURE 3. Number of individuals in the Qikiqtaaluk and Kivalliq regions in 2011, classified by sex and age groups. [Data from Statistics Canada.]

1.3 Language

Both Inuktitut and English are commonly spoken throughout the Qikiqtaaluk and Kivalliq regions. Within Qikiqtaaluk region, there are four recognized Inuktituk dialects: North Baffin (Qikiqtaaluk uannangani), Central Baffin (Qikiqtaalup kanannanga), South Baffin (Qikiqtaalup nigiani), and Sanikiluarmiut in Sanikiluaq. The Qikiqtaaluk uannangani dialect is spoken in Resolute, Grise Fiord, Pond Inlet, and Arctic Bay. Qikiqtaalup kanannanga is spoken in Clyde River, Qikiqtarjuaq, and Pangnirtung. Qikiqtaalup nigiani is spoken in Iqaluit, Kimmirut, and Cape Dorset. Within Kivalliq region, there are three recognized Inuktituk dialects: Kivallirmiut, Paallirmiut, and Aivilingmiut. The Kivallirmiut dialect is spoken in Baker Lake and Rankin Inlet. The Paallirmiut dialect is spoken in Whale Cove and Arviat. Aivilingmiut dialect is spoken in Repulse Bay, Chesterfield Inlet, Coral Harbour and Rankin Inlet. Despite the various dialects, fluent Inuktitut speakers within the region generally understand one another with only minor difficulties.

1.4 Economic sectors and employment

The Qikiqtaaluk and Kivalliq regions consist of a mixed economy consisting of wage economy, government transfer payments, and subsistence harvesting. Government and private sector jobs (e.g., tourism, mineral exploration, construction, transportation) comprise the wage economy. As of 2011, the employment and unemployment rates in the Qikiqtaaluk and Kivalliq regions were (55% and 9%) and (50% and 20%), respectively. These rates were similar to Nunavut's (52% and 11%, respectively) but differed from the national rates (61% and 5%, respectively) (Statistics Canada 2011). Traditional activities such as hunting, trapping, fishing, and gathering, as well as arts and crafts, are important for providing households with food, income, and a connection with the environment (Stern and Gaden 2015).

1.5 Resource utilization - living resources

1.5.1 Hunting

Hunting is an important part of providing households with food and is an essential part of the culture and well-being of people of Nunavut. Currently there are only two total allowable harvests (TAHs) in Nunavut which consist of 1600 for Southampton Island caribou and 250 for Baffin Island caribou. Three species of seal (ringed, harp, and bearded) are hunted without regulation. For walrus, no TAH has been established. However, the species is generally managed under an individual quota of four walrus per Inuk per year unless a community quota has been put in place. Polar bears are also harvested and are regulated by quotas, which in 2011–12 were set at 249 and 70 total for the Qikiqtaaluk and Kivalliq regions, respectively. For bowhead whales, the annual TAH in Nunavut is five, of which the Qikiqtaaluk region has a TAH of two. The Canadian beluga and narwhal fisheries are regulated by the Fisheries Act and are co-managed by Fisheries and Oceans Canada, the Nunavut Wildlife Management Board, regional wildlife organizations, and Hunter and Trappers Organizations (for details see Chapter 16). A TAH for beluga whale stocks in Nunavut has not been established; however, the only beluga population hunted in Nunavut is the Cumberland Sound population, for which there is a quota of 41 belugas per year. For narwhals, the TAH, which was established in 2012, is 1320. The catch of some other cetaceans (e.g., minke, harbor porpoise, pilot whales) is unregulated.

1.5.2 Fisheries

Fisheries play an important role in the economy of Nunavut (see Chapter 18). Off Nunavut, commercial fisheries are rapidly expanding, and have increased in value from CAD 38 million to CAD 86 million between 2006 and 2014. In 2012, Greenland halibut *Reinhardtius hippoglossoides* was the third most important export good for Nunavut (Lambert-Racine 2013). Very little fishing takes place north of 72 °N. The offshore fisheries of the region are currently dominated by bottom trawling for Greenland halibut and

northern shrimp (*Pandalus borealis* and *P. montagui*). Since the 1980s, a number of communities along the east coast of Baffin Island have explored the potential for inshore Greenland halibut fisheries. Inshore fisheries are largely limited to Greenland halibut and Arctic char (*Salvelinus alpinus*) in Cumberland Sound. Nunavut's largest fish processing plant is in Pangnirtung (Pangnirtung Fisheries Ltd.), with a smaller operation in Iqaluit (Iqaluit Enterprises Ltd.) (Government of Nunavut 2007a). Both fisheries normally operate between April and December. Iqaluit Enterprises concentrates on Arctic char, while Pangnirtung Fisheries concentrates heavily on turbot (the Nunavut name for Greenland halibut), with more limited production of char (or in some years, none).

None of the offshore shrimp is caught by Nunavut vessels, and none is processed in Nunavut. There is potential for the development of a commercial fishery for clams, scallops, and crabs in Nunavut in the future (Brubacher Development Strategies Inc. 2004). There is interest and growth by some communities in the region in inshore harvesting of invertebrates (e.g., clams, shrimp and whelk) (see Chapter 18).

1.6 Resource utilization: non-living resources

1.6.1 Minerals

The economic and socio-cultural history of the Eastern Canadian Arctic has been linked in part to nonrenewable resources – notably lead, zinc, nickel, copper, iron, rubies, gold, oil and gas, and diamonds. Mineral development dates back to the late 1950s, but by the early 2000s there were no active mines (see Chapter 19). Large-scale mining developments in the Qikiqtaaluk region have existed, such as the lead–zinc mines in Nanisivik on North Baffin Island (opened in 1976, Canada's first High Arctic mine) and the Polaris zinc mine on Little Cornwallis Island (opened in 1982). These mines were operational until 2002 (Chapter 19). One major mine, the Mary River iron mine on North Baffin Island, started production in 2014 and is currently still in operation (Baffinland Iron Mines Co.). In more recent years, the Kivalliq area has had a number of major

exploration projects, mainly to do with gold, uranium, and diamonds. The Repulse Bay area in particular has ongoing exploration activity pertaining to gold and diamonds. The Kivalliq region has a long history of mining, with two past-producing mines which include the North Rankin Nickel Mine at Rankin Inlet and the Cullaton-Shear Lake gold mine north of Nueltin Lake. There is one operational mine, the Meadowbank gold mine located 80 km north of Baker Lake. This mine opened in 2010 and since 2015 the open pit mine has been in continuous operation. Mining continues to be seen as one of the most important sectors for growth in Nunavut, and in 2014 it represented 18% of the territory's gross domestic product (GDP). Construction, some of it related to mining, represented an additional 16% of GDP. Exploration expenditures have increased substantially over the past 15 years (see Chapter 19).

1.6.2 Oil and gas

The marine part of the IRIS 2 region is among those Arctic areas with a very high potential for undiscovered oil reserves (Gauthier et al. 2009). Nunavut has 5% and 15% of Canada's known reserves of oil and natural gas, respectively (Government of Nunavut 2007b). Starting in the late 1960s, significant exploration was undertaken in Nunavut's Sverdrup Basin (MacIsaac 2015), which sprawls beneath the northern Canadian Arctic islands. While activity over the past 20 years in this region has been limited to seismic testing and geologic fieldwork, it is still considered to be a potential future production site and is estimated to hold nearly 2 billion barrels of crude oil and 27 trillion cubic feet (Tcf) of natural gas. The Parry Islands Fold Belt Basin, an area adjacent to the Sverdrup Basin, is estimated to hold between 2 and 10 billion barrels of oil and between 14 and 51 TCF of natural gas. The Lancaster Sound Basin also has high petroleum potential. In 1974 drilling was approved in this area; however, no well was drilled due to a moratorium that was put in place following an environmental review in 1978. Oil and gas companies remain interested in Lancaster Sound, but the boundary for a national marine conservation area has recently been announced for this area (see Chapter 17). The Bent Horn site on Cameron Island produced a

high-quality oil from 1985 to 1996 – most of which was used to supply energy to the Polaris mine.

Increasing global gas prices are increasing the likelihood that development of Nunavut's reserves will become feasible. These reserves are estimated to contain ultimate initial marketable gas at 16.7 Tcf and ultimate recoverable oil at 0.8 billion barrels (Barnes 2015). The oil and gas industry has expressed an ongoing interest in Nunavut. However, exploration in the region has been limited to only seismic testing and geologic fieldwork. Currently, there is one Husky Energy gas project south of Baffin Island and one major Royal Dutch Shell exploration project north of Bylot Island. There is concern in the region regarding offshore oil and gas developments and their potential environmental impacts. Compared to onshore developments, offshore developments are seen as being potentially more damaging to the subsistence activities of local Indigenous communities. In addition, communities feel they have not been properly consulted nor told how they will benefit from oil and gas development (Varga 2014).

1.7 Infrastructure

Sea and air are the dominant modes of transportation, as very few communities are connected by roads. Sea ice, moreover, inhibits shipping in large parts of the region in

winter and spring. However, sea ice also provides a means of transportation, at least when stable and solid. Dog sledging is the traditional way of traveling in the winter, and motorized vehicles (e.g., snowmobiles, automobiles, and aircraft) predominate today. Consequently, many socioeconomic activities rely greatly on airports, especially during the sea-ice season. Food is available year-round and comes in by ship during open water periods and by air throughout the year. Fuel for heating and transportation, as well as construction materials for housing and basic infrastructure, are always shipped in during the ice-free summer season. See Chapter 15 for discussion on infrastructure in the region, and Chapter 20 which discusses shipping.

1.8 Land and Sea

1.8.1 Climate

The IRIS 2 region is situated within the Arctic climate zone. The Arctic climate zone is divided into the Low Arctic, where the July mean temperature is 5–10 °C, and the High Arctic, where the July mean temperature is <5 °C (Figure 4). In Figure 5, subzones D and E constitute the Low Arctic; subzones A, B, and C constitute the High Arctic. The true Arctic climate zones are treeless, with open tundra in flat areas. For example, in subzone A (Figure 5; Table 1), the vegetation is extremely sparse, with



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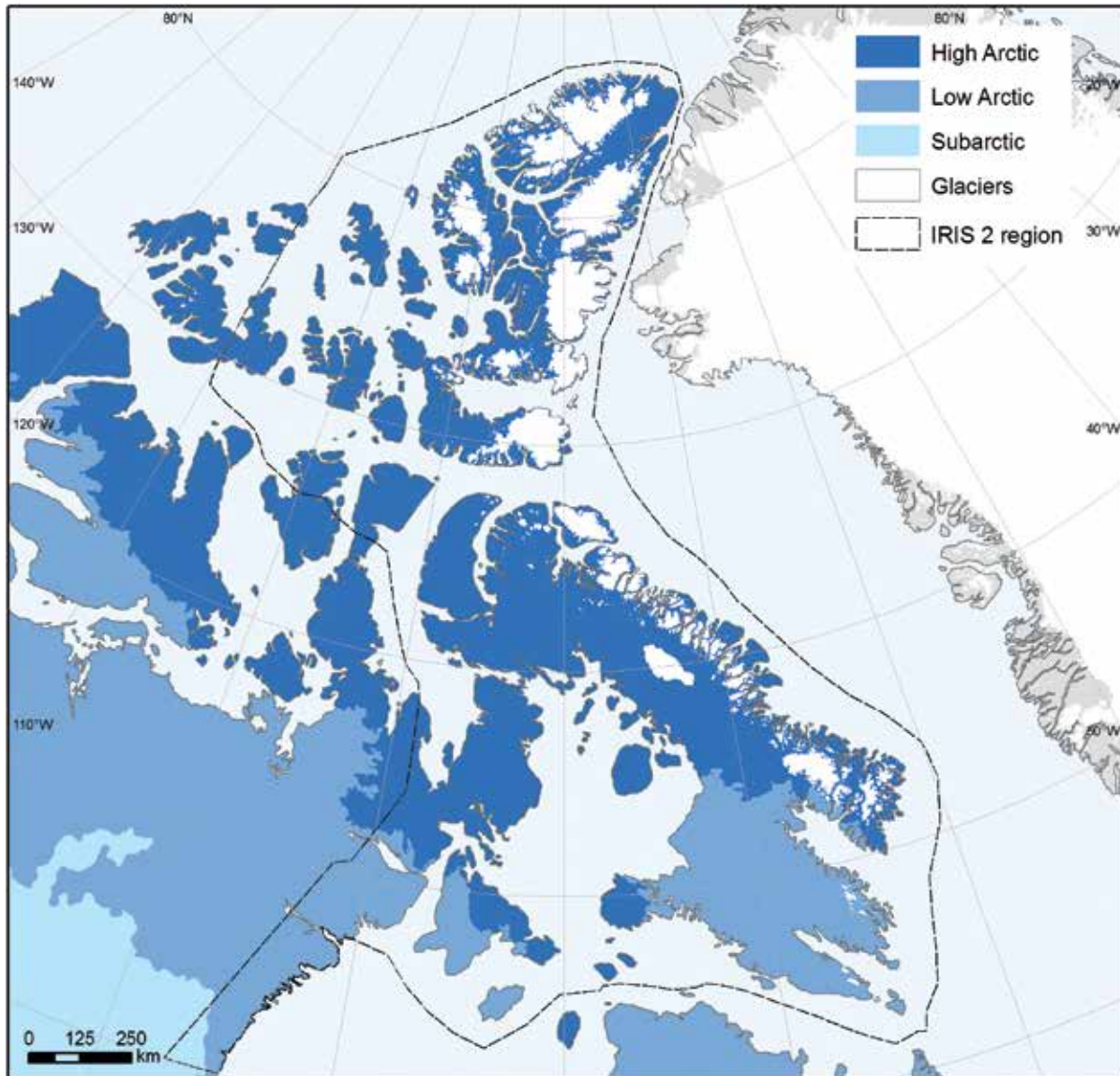


FIGURE 4. The IRIS 2 region lies mostly within the Low Arctic and High Arctic climate zones; only a small area in southwestern Hudson Bay is Subarctic. Adapted from CAVM Team (2003) data set.

<5% cover and only scattered plants in the almost barren coastal lands. However, in moist and fertile places, vegetation cover may be locally higher – for instance, below snowdrifts and in wetlands. In the Low Arctic, the dominant plant growth consists of low shrubs, and dwarf shrub heath in some areas (subzone E), willow and birch may form dense thickets with 80–100% vegetation cover (Young 1971, Chernov and Matveyeva 1998; Table 1).

1.8.2 The terrestrial environment

1.8.2.1 *Geology and physiography*

The regional geology is dominated in the south by Precambrian hard rocks of the Canadian Shield. These are primarily crystalline (intrusive) and metamorphic rocks of the Churchill Province (Harrison et al. 2011, Wheeler et al. 1996), exposed along much of the Kivalliq coastal

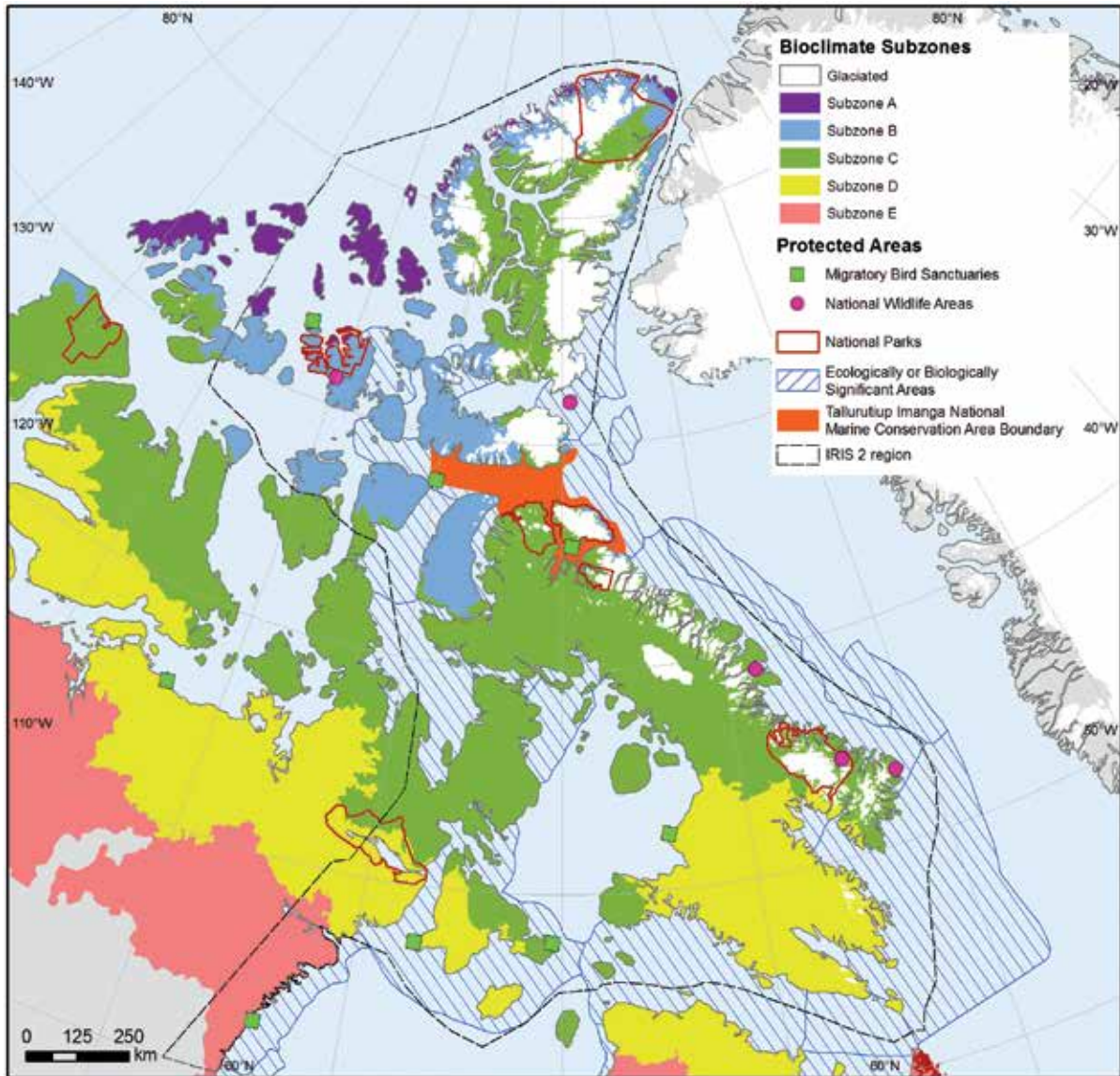


FIGURE 5. Bioclimate subzones and protected areas in the vicinity of the IRIS 2 region. The protected areas include ecologically or biologically significant marine areas (EBSAs), bird protection areas, wildlife protection areas, national parks, and marine protected areas. Adapted from CAVM Team (2003) data set, DFO (2011), Parks Canada (2013), and Environment Canada (2016).

region and small mainland parts of Qikiqtaaluk, most of Baffin Island, Bylot Island, eastern Devon Island, and part of southeastern Ellesmere Island (Figure 6).

Flat-lying or mildly deformed Paleozoic sedimentary rocks of the Arctic Platform underlie much of the central Arctic, including Foxe Basin, northwestern Baffin Island, northern

Somerset Island, Prince of Wales Island, eastern Bathurst Island, Cornwallis Island, and central and western Devon Island (Figure 6). A large proportion of these rocks are Ordovician to Devonian shallow-water shelf carbonates (limestone and related lithologies), merging northward into deeper basin sedimentary lithologies with resedimented carbonates (NOG 1995).

TABLE 1. Vegetation properties of the bioclimate subzones (from Walker et al. 2016). (The subzone colors in the table match the colors on the Figure 5).

Subzone	Mean July temperature ¹ (°C)	Summer warmth index ² (°C)	Vertical structure of plant cover ³	Horizontal structure of plant cover ³	Number of vascular plant species in local floras ⁴
A (High Arctic)	0–3	<6	Mostly barren. In favorable microsites, one lichen or moss layer <2 cm tall, widely scattered vascular plants that are barely taller than the moss layer.	<5% cover of vascular plants, up to 40% cover by mosses and lichens	<50
B (High Arctic)	3–5	6–9	Two layers: moss layer 1–3 cm thick and herbaceous layer 5–10 cm tall. Prostrate dwarf shrubs <5 cm tall.	5–25% cover of vascular plants, up to 60% cover of cryptogams	50–100
C (High Arctic)	5–7	9–12	Two layers: moss layer 3–5 cm thick and herbaceous layer 5–10 cm tall. Prostrate and semi-prostrate dwarf shrubs <15 cm tall.	5–50% cover of vascular plants, open patchy vegetation	75–150
D (Low Arctic)	7–9	12–20	Two layers: moss layer 5–10 cm thick and herbaceous and dwarf-shrub layer 10–40 cm tall.	50–80% cover of vascular plants, interrupted closed vegetation	125–250
E (Low Arctic)	9–12	20–35	Two to three layers: moss layer 5–10 cm thick, herbaceous/dwarf-shrub layer 20–50 cm tall, sometimes with low-shrub layer to 80 cm.	80–100% cover of vascular plants, closed canopy	200–500

¹Based on Edlund (1990) and Matveyeva (1998).

²Annual sum of mean monthly temperatures greater than 0 °C, modified from Young (1971).

³Chernov and Matveyeva (1998).

⁴Number of vascular species in local floras based mainly on Young (1971).

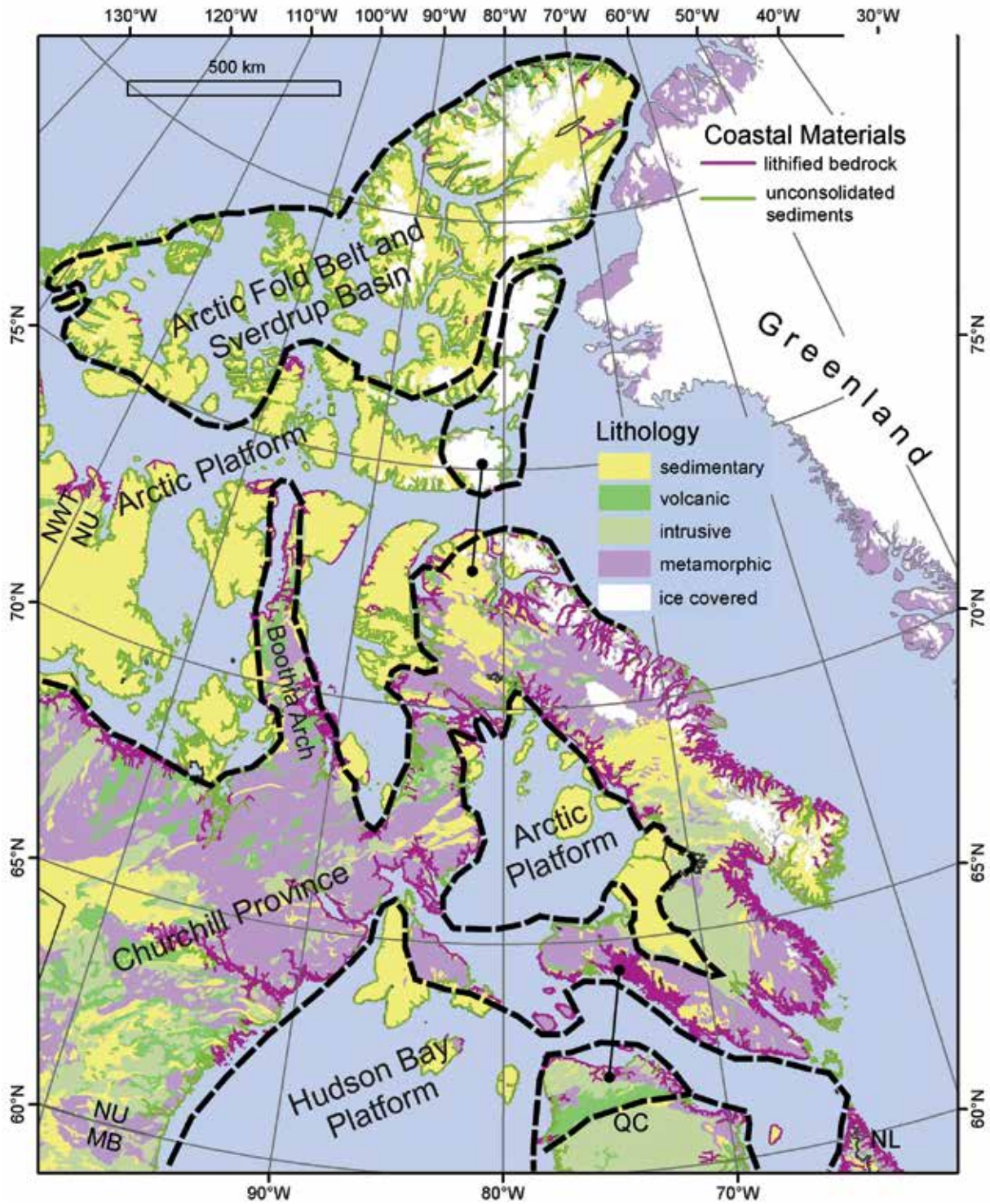


FIGURE 6. Geological provinces of the IRIS 2 region of Nunavut and adjacent areas, with distribution of rock and non-rock shores, from CanCoast data base [geology from Wheeler et al. 1996, NOG 1995]

To the north and west, the islands falling within the Arctic Fold Belt and Sverdrup Basin include a range of sedimentary formations with varying relief, cementation, and deformation. Folded Arctic Platform rocks of the Ellesmerian Orogen extend from northeastern Ellesmere Island southwest to the Parry Islands Fold Belt in western Bathurst and southern Melville Island (Harrison 2016).

Younger Carboniferous to Cenozoic formations of the successor Sverdrup Basin include mostly flat-lying, poorly lithified, or unlithified deposits of the low-relief islands in the northwest. Within Nunavut, these include slivers

of Borden and Mackenzie King islands, Sabine Peninsula (northeastern Melville Island) and Cameron, Lougheed, King Christian, Amund and Ellef Ringnes, Cornwall, and Meighen islands (Harrison 2005, NOG 1995).

The physiography of the region reflects its tectonic history, including mountain uplift in eastern Baffin, Devon, and Ellesmere islands related to Baffin Bay rifting (Keen et al. 1974, 2012). The lower-relief Arctic Platform rocks are dissected by the Arctic Island channels, forming extensive cliff exposures (Figure 7), which locally provide important seabird nesting habitat. The flat-lying and



FIGURE 7. (a) Cliffs in sedimentary rocks of the Arctic Plateau and raised beach sequences at Cape Ricketts, with Radstock Bay in right background, southwest Devon Island, August 2009 (DLF). (b) Wide gravel beach and emergent backshore at base of the talus-banked Gull Rock cliff on southeast Lowther Island, with ATVs for scale, August 2006 (DLF). (c) Raised gravel beaches and stream outlet, southwest Lowther Island, August 2009 (DLF). (d) Ice-scarred mud coast on Christopher Formation shale, Lougheed Island, August 1986 (DLF).

poorly lithified Sverdrup Basin sediments of northwestern Qikiqtaaluk have low relief (Figure 7d). The mountains of the eastern archipelago support numerous extensive ice caps and mountain glaciers, with tidewater ice-fronts in some bays and fiords. Extensive but rapidly diminishing ice shelves extend beyond the mouths of some fiords along the north coast of Ellesmere Island (Mueller et al. 2008, Vincent et al. 2001).

The coastal geology reflects the geological provinces, tectonic history, glaciation (primarily glacial erosion), and general relief. The highest cliffs (to 1500 m) are associated with fiords cut through the eastern cordilleran range. In the Arctic Platform province, cliffs on southwestern Devon Island or Lowther Island (Figure 7a,b) are typically a few hundred metres high. By contrast, backshore slopes in the Sverdrup Basin can be extremely gentle, with perennial sea ice virtually eliminating hydrodynamic shore processes, except those related to direct impacts of ice moving onshore (Figure 7d; Taylor and Forbes 1987).

1.8.2.2 Snow and permafrost

Snow cover and its duration, stability, and thickness is critical for terrestrial biodiversity in the region. A late snowmelt, for example, prevents ground-nesting birds (e.g., shorebirds) from establishing nests. For lemming winter survival, a stable and thick snow layer is required. Midwinter thaws may create ice crust on the snow, thus preventing muskoxen (*Ovibos moschatus*) and caribou (*Rangifer tarandus*) from finding food (for details on snow trends see Chapter 2; for details on the implications for wildlife see Chapter 16).

Permafrost is being increasingly affected by rising ambient temperatures, which in turn causes changes in hydrology, snow drift patterns, and landscape stability (see Chapters 4 and 15). Land instability results in problems for the residential, municipal, and transportation infrastructure placed on the permafrost. Moreover, the infrastructure itself often becomes an additional driving factor that can greatly exacerbate the impact of climate change on permafrost stability.

Many permafrost infrastructure issues originate from infrastructure that was built on sediment deposits prior to climate warming in the region. In addition, permafrost stability was poorly understood at the time and construction projects were often implemented without sufficient knowledge of ground conditions (e.g., amount of ground ice). Consequently, the construction designs of many buildings and other infrastructure in the region are not appropriate for the underlying permafrost conditions (see Chapter 15).

1.8.2.3 Vegetation

The plant communities in the region are dominated by dwarf shrub heath and grassland on dry lands and by widespread marshes with grasses and sedges in moist areas and wet areas. In more protected areas, low shrubs can be found, and on sloping hillsides with stable water supply (e.g., from snow drifts), herb slopes can develop with relatively high species richness. At higher elevations and in exposed sites where the soil is dynamic due to solifluction, vegetation (herbaceous plants and dwarf shrubs) becomes scarce and the soil is covered by a dark layer of lichens and mosses. Soil coverage in some areas (e.g., Brodeur, Cornwallis Island, parts of Devon Island) can be even less, where it is composed of only bare gravel. For details on vegetation see Chapter 7.

The large herbivores of the region – caribou and muskoxen – utilize the grasslands and dwarf shrubs to a wide degree, and geese are also dependent on areas with dense vegetation for feeding. The human use of the vegetation is limited to the gathering of berries in the heath lands. Berry picking represents an important activity and a source of healthy food in the region (see Chapter 7).

1.8.2.4 Fauna

The terrestrial fauna is relatively species poor compared to the marine fauna. Mammal species include the Arctic fox (*Alopex lagopus*), hare (*Lepus arcticus*), wolverine (*Gulo gulo*), two sub-species of wolves (tundra/timber wolf, *Canis lupus occidentalis* and the high arctic wolf, *Canis lupus*



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arctos), grizzly bears (*Ursus arctos* ssp.), muskoxen (*Ovibos moschatus*), two species of lemming (*Lemus* spp.), and caribou (*Rangifer tarandus*). Caribou herds are heavily utilized – so much so that a moratorium on harvesting caribou on Baffin Island was established in 2015. In addition, there are over 100 species of birds in the region, nearly all of which are migratory.

1.8.2.5 Protected areas, National Wildlife Areas, and Migratory Bird Sanctuaries

Within the region there are 12 protected areas, with each site protecting both marine and terrestrial environments (Figure 5). Five are National Wildlife Areas (NWAs) and seven are Migratory Bird Sanctuaries (MBSs). Environment and Climate Change Canada, directly and/or through partnerships, establishes and manages these protected areas.

There are currently five national parks in the IRIS 2 region, four in the Qikiqtaaluk region: Quttinirpaaq National Park (Ellesmere Island), Auyuittuq National Park (Baffin Island), Qausuittuq National Park (Bathurst Island), Sirmilik National Park (Bylot Island, Oliver Sound, and the Borden Peninsula), and one in the Kivalliq region: Ukkusiksalik National Park (northwestern Hudson Bay)

(Figure 5). Quttinirpaaq National Park, on the northeastern corner of Ellesmere Island, is the second largest park in Canada. It was established in 1989 as Ellesmere Island National Park Reserve, and in 2000, the reserve became a national park. Quttinirpaaq is dominated by hundreds of glaciers and includes the highest mountain (2616 m) in Eastern North America. Auyuittuq National Park, on Baffin Island's Cumberland Peninsula, features many terrains of Arctic wilderness, such as fiords, glaciers, and ice fields. Auyuittuq was established as a national park reserve in 1976, then upgraded to a national park in 2000. Qausuittuq National Park, located on northwest Bathurst Island was established in 2015. This national park represents a high Arctic environment that is home to the endangered Peary caribou and has been an important traditional hunting and fishing area for Inuit of Resolute Bay since the time of their relocation in the 1950's. Sirmilik National Park comprises three areas: most of Bylot Island, Oliver Sound, and Baffin Island's Borden Peninsula. This national park was established in 1999 and is amidst a landscape of glaciers, valleys, and nesting areas for many birds. Ukkusiksalik National Park was established in 2003 and surrounds Wager Bay, a 100 km long saltwater inlet located on the northwest coast of Hudson Bay, south of the community of Nauyasat (Repulse Bay). Ukkusiksalik features over 500 archaeological sites and has terrain consisting mainly of tundra and coastal mudflats that are thriving with wildlife.

1.8.3 The marine environment

The marine environment of the IRIS 2 region is shaped by a number of factors, including large-scale and regional ocean currents, ocean temperatures, sea ice, and glacial ice (see Chapter 5). The oceanographic system encompasses Lancaster Sound, Baffin Bay, Davis Strait, and the northern Labrador Sea. Here, large southward flows of water (Arctic Ocean outflow), sea ice, and glacial ice converge along the eastern Canadian coastline. Much of this water originates from the Pacific Ocean and spends more than a decade transiting the High Arctic, where it is modified by ice growth and decay, precipitation, river discharge, and biological activity (Azetsu-Scott et al. 2010). The West

Greenland Current flows northward along the west coast of Greenland and most of the water within arcs westward and then southward in northern Baffin Bay (Figure 8). This regional circulation affects the physical and chemical properties of waters in the IRIS 2 region and is responsible for transporting organisms from the North and the South. Further, the circulation has a profound influence on the climate in coastal areas with high Arctic conditions found on Baffin Island to as far south as 65° N (Figure 4).

A polynya is a geographically fixed region of open water that is surrounded by sea ice (Hannah et al. 2009). Polynyas are an important component of the IRIS 2

marine system because their open waters create a refuge for marine mammals and seabirds to feed, breathe, and rest. In addition, spring time primary production is able to start much earlier in polynyas than in ice-covered waters (see Chapter 5). Twenty polynyas recur in the same position each year in the region (Figure 8). The Pikialasorsuaq/North Water Polynya (NOW), which lies between Greenland and Canada in northern Baffin Bay, is the region's largest polynya. With one of the most productive food webs in the Arctic Ocean, the NOW attracts numerous marine mammals and millions of seabirds (Stirling 1980, Dunbar 1981, Deming et al. 2002, Egevang et al. 2003, Boertmann and Mosbech 2011, DFO 2015). Because

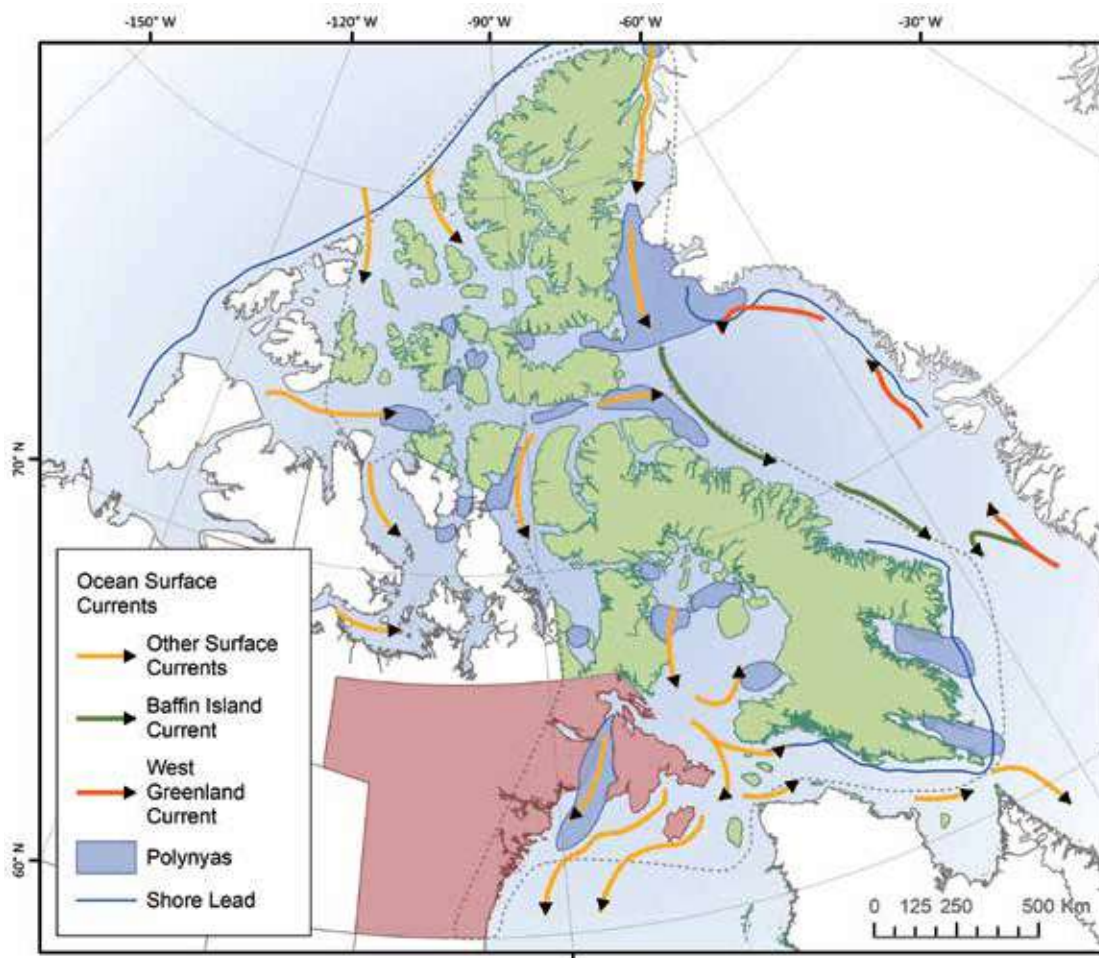


FIGURE 8. Major surface ocean currents (black lines) and known polynyas in the IRIS 2 region. "NOW" indicates the North Water Polynya. Adapted from AMAP (1998), Stirling (1980), Barber and Massom (2007), and Hannah et al. (2009).

of its year-round open-water conditions and its abundance of marine mammals, this polynya has also attracted Inuit hunting communities and 19th-century whaling and exploring expeditions.

1.8.3.1 Ice

Most of the IRIS 2 region is covered by sea ice in winter. The sea ice of the IRIS 2 region is mainly first-year drift ice of local origin; only small amounts of Arctic Ocean pack ice are transported in through Nares Strait. This means that Baffin Bay and Davis Strait become free of ice each summer, but ice may linger in adjacent areas. Especially along Baffin Island's east coast, the ice remains until late July; among the High Arctic Canadian islands, ice may persist throughout the summer – e.g., in Foxe Basin. The trend, though, is that these permanently ice-covered areas are diminishing (see Chapter 5). Fast ice (ice that is anchored to land or the seabed) occurs in fiords and bays and in the waters between the High Arctic Canadian islands. Another characteristic feature is the presence of icebergs, which originate either from glaciers on West Greenland or from East Greenland glaciers, to then be carried by currents into the IRIS 2 region.

1.8.3.2 Flora and fauna

The marine mammal and avian fauna of the Eastern Canadian Arctic are characterized by relatively few species, but these species are well adapted to conditions in the region (see Chapter 16). Approximately 189 fish species inhabit the Canadian Arctic (Archambault et al. 2010). The benthic fauna is an exception, in that it is characterized by a very high number of species. For example, approximately 947 benthic species or taxonomic groups have been documented at various stations across the Canadian Arctic (Archambault et al. 2010) and it is likely that more species are present, given Piepenburg et al. (2005) estimate of 1100 species for the Beaufort Sea alone. Low annual primary productivity is characteristic of most of the IRIS 2 region (see Chapter 5). However, increased production is found in the areas that are more or less ice-free in winter (e.g., polynyas). The primary production in these areas

sustains aggregations of zooplankton, especially the very important species of copepods of the genus *Calanus*. These multi-year copepods accumulate lipids for hibernation, and these lipids constitute an extremely important resource for organisms higher up in the food web. Fish, seabirds, and large baleen whales are dependent on these copepods, to a degree that the fatty acids from *Calanus* lipids can be traced to the top predators of the Arctic (Dahl et al. 2000). The open water in polynyas and shear zones attracts seabirds and marine mammals, which both forage and surface in these areas. Some marine mammal and seabird species move out of the region when winter restricts food availability, while others overwinter in ice-covered waters – e.g., narwhals (*Monodon monoceros*) in the drift ice of Baffin Bay and ringed seals (*Pusa hispida*) in drift ice areas and in waters with shore-fast ice – where they can maintain breathing holes in the ice.

1.8.3.2.1 Marine mammals

The IRIS 2 regions hosts a number of marine mammals year-round, with all species more or less associated with the sea ice. Bowhead whales (*Balaena mysticetus*) move between winter quarters in the Labrador Sea and summer quarters in the Canadian Archipelago, traveling in early spring along the marginal ice zone in Davis Strait and Baffin Bay and congregating in the Disko Bay waters of central West Greenland. Beluga whales (also known as white whales, *Delphinapterus leucas*) move from summer habitats in the Canadian Archipelago to winter habitats in the North Water Polynya and along the West Greenland coast. Narwhals from several discrete summer populations congregate in the Baffin Bay drift ice in winter. Polar bears (*Ursus maritimus*) occur in relatively high numbers on the drift ice of Davis Strait, Baffin Bay, and in the High Arctic Canadian islands, as they follow the annual movements of sea ice. Hooded seals (*Cystophora cristata*) whelp on the ice in central Davis Strait in late winter and then disperse to the open waters of the entire region in summer; harp seals (*Phoca groenlandica*) are numerous in open water areas throughout the year. Two discrete populations of walrus (*Odobenus rosmarus*) move between habitats in the Eastern Canadian Arctic and west Greenland. Additional



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resident species include ringed seal and bearded seal (*Erignathus barbatus*). The region is also a summer habitat for many migrating species of marine mammals, such as large baleen whales – minke whale (*Balaenoptera acutorostrata*), blue whale (*B. musculus*), fin whale (*B. physalus*), sei whale (*B. borealis*), and humpback whale (*Megaptera novaeangliae*) – and also sperm whales (*Physeter macrocephalus*) and pilot whales (*Globicephala melas*). All migrate into the Eastern Canadian Arctic from southern latitudes. The harbour porpoise (*Phocoena phocoena*), a small toothed whale, inhabits the ice-free water year-round. For details see Chapter 16.

Most of the marine mammals are harvested by Inuit in the region. Seals constitute the basis of the hunt, due to their high abundance and the fact that they provide both meat and skin (which today is almost unsalable on international markets but remains important for traditional uses including clothing). Beluga whale and narwhal provide meat and mattaq (thick skin). These animals are important to hunters

in some but not all of communities. Walrus also provide large quantities of meat. Both walrus and narwhal provide ivory for carving and art making. Finally, the baleen whales provide large quantities of meat and blubber, which has been marketed on a national scale.

1.8.3.2.2 Seabirds

Seabirds are very numerous in the Eastern Canadian Arctic during the summer. The most important seabirds – in terms of numbers – are Northern fulmar (*Fulmarus glacialis*), Little auk (*Alle alle*), Thick-billed murre (*Uria lomvia*), Arctic tern (*Sterna paradisaea*), and Common eider (*Somateria mollissima*). Several species of gulls also occur. Less numerous seabird species of conservation concern include Ross's gull (*Rhodostethia rosea*), Atlantic puffin (*Fratercula arctica*), and Ivory gull (*Pagophila eburnea*). The King eiders (*Somateria spectabilis*) move in numbers of hundreds of thousands from breeding areas on the Canadian tundra to molting and wintering habitats on the

shelves and along the coasts of Greenland. The North Water Polynya is extremely important to breeding seabirds.

1.8.3.2.3 Fish and invertebrates

Approximately 189 fish species inhabit Canadian Arctic waters (Archambault et al. 2010), and most of these live on or near the seabed. The number of species decreases with latitude. Important species, in an ecological context, are the schooling fish such as capelin (*Mallotus villosus*), sand eel (*Ammodytes dubius*), and Arctic cod (*Boreogadus saida*). These species are key species because they serve as essential food resources for higher levels of the food web, including seabirds, seals, and whales. The most important species for commercial fisheries in the region is the Greenland halibut (*Reinhardtius hippoglossoides*). Many other species are utilized on a subsistence basis. As mentioned above, the benthic fauna is species rich in the region. A few species are utilized on a commercial basis – primarily northern shrimp (*Pandalus borealis*) and, locally, snow crab (*Chionoecetes opilio*) and scallops (*Chlamys islandica*). Blue mussels (*Mytilus edulis*) are also utilized in some communities but only on a subsistence basis.

The Arctic Biodiversity Assessment of the Conservation of Arctic Flora and Fauna working group (CAFF 2013) has identified threats to Arctic biodiversity, including within the IRIS 2 region. One of their key findings was that climate change is by far the most serious threat to Arctic biodiversity and that the ice-associated organisms will be most impacted – for example, walrus, narwhal, and ringed seal. Other threats to the biodiversity of the region are the long-range transport of contaminants (see Chapter 10) and threats on the winter grounds of migratory species, such as many of the seabirds.

Several marine mammals of the IRIS 2 region are included on the International Union for Conservation of Nature (IUCN) list of threatened species (“red list”). The polar bear is listed as Vulnerable; the beluga whale as Near Threatened; narwhal, Near Threatened; fin whale, Endangered; and blue whale, Endangered. Among birds, the ivory gull is classified as Near Threatened (IUCN 2016).

1.8.3.3 Marine conservation areas

Over the past few decades, national and international organizations have been working toward protecting ocean resources as global pressures on those resources increase. The Government of Canada is working with the provinces and territories to protect Canada’s marine ecosystems through the development of a national network of marine protected areas (MPAs) (see Chapter 17). Canada’s network of MPAs will be composed of 13 bioregional networks – twelve within Canada’s oceans and one in the Great Lakes. Each network will be designed to suit its own unique geography, management tools, and ecological and socio-economic objectives.

In October 2012, the Convention on Biological Diversity proposed seven scientific criteria for identifying “ecologically or biologically significant areas” (EBSAs; Dunn et al. 2014; Chapter 17) in need of protection in open-waters and deep-sea habitats: (1) uniqueness or rarity, (2) special importance for life history stages of species, (3) importance for threatened, endangered, or declining species and/or habitats, (4) vulnerability, fragility, sensitivity, or slow recovery, (5) biological productivity, (6) biological diversity, and (7) naturalness. A total of 61 EBSAs have been identified in the Canadian Arctic within the five marine biogeographic regions in the Canadian Arctic; 29 of these are located in the Eastern Canadian Arctic (IRIS 2 region; see Figure 5). Included in these 29 EBSAs are the Hatton Basin and the entrance to Hudson Strait, the South Baffin Bay narwhal overwintering area, Lancaster Sound, and the North Water Polynya (for details see Chapter 17).

As noted above, the North Water Polynya and to some extent Lancaster Sound are among the Arctic’s most productive marine areas. Lancaster Sound is characterized by two polynyas that are kept open from ice by winds and currents (Figure 8). One is located along the northern coast of Lancaster Sound, and the other is at the eastern outflow of the sound (Barber and Massom 2007). This area’s high productivity supports high benthic abundance, biomass, and diversity, as well as the Arctic’s highest density of marine mammals and seabirds.

Parks Canada is working with provinces and territories to develop a system of MPAs called the National Marine Conservation Areas (NMCAs). An NMCA is managed and used in an ecologically sustainable way, and each one includes zones that fully protect special features and sensitive ecosystem elements. The Eastern Canadian Arctic overlaps with five of the Parks Canada marine regions: Arctic Archipelago, Lancaster Sound, Baffin Island Shelf, Foxe Basin, and Hudson Strait. Since 2009, Parks Canada, the Government of Nunavut, and the Qikiqtani Inuit Association (QIA) have been working toward the creation of an NMCA in Lancaster Sound (called Tallurutiup Imanga, in Inuktitut). In 2017, the final boundary for the national marine conservation area was announced (see Figure 5).

As stated in the Terrestrial Environment section, there are five NWA and seven MBSs located in the IRIS 2 region (Figure 5) that are managed by Environment and Climate Change Canada. Fisheries and Oceans Canada (DFO) also establishes, under the Oceans Act, MPAs to protect and conserve important fish and marine mammal habitats, endangered marine species, unique features, and areas of high biological productivity or biodiversity. To date, no Oceans Act MPAs have been established in the region.

1.9 Climate change studies

The Arctic science community has been increasingly involved in climate-related studies since the early 1990s. The International Arctic Science Committee (IASC) has been engaged in Arctic climate research since it was founded in 1991 and continued to conduct regional Arctic impact studies through the 1990s. The Arctic Monitoring and Assessment Programme (AMAP) conducted its preliminary assessment of climate and UV impacts in the Arctic which was published in 1998 and has continued to produce numerous reports with respect to pollution and climate change issues in the Arctic. IASC, AMAP and CAFF proposed a comprehensive and circum-Arctic climate impact study in 1999 which later led to a joint project – the Arctic Climate Impact Assessment (ACIA) – between the Arctic Council and IASC in 2000. The ACIA which

was built on several regional and global climate change assessments was published in 2005 (ACIA 2005). In addition, a number of regional studies in the Arctic have been conducted in Canada (Maxwell 1997), the Mackenzie Basin (Cohen 1997a,b), the Barents Sea (Lange and the BASIS Consortium 2003, Lange et al. 1999), and Alaska (Weller et al. 1999). These helped form the baseline for the ACIA. The Intergovernmental Panel on Climate Change (IPCC) has produced the most comprehensive and world renowned assessments of climate change on a global basis (e.g., IPCC 1990, 1995, 2001a,b, 2007a,b, 2013, 2014).

Within Canada, an Integrated Regional Impact Study (IRIS) of climate change and modernization has been conducted for the 1) western and central Arctic (Stern and Gaden 2005), 2) the Eastern Arctic (this report), 3) Hudson Bay, and the 4) Eastern Subarctic (Allard and Lemay 2015). ArcticNet adopted the IRIS framework to present our current knowledge of climate change and modernization research in the Canadian Arctic. The intent of the information in these reports is that it is accessible to everyone, and in particular resource managers and decision-makers at all political levels.

The Northern Contaminants Program was established by Indigenous and Northern Affairs Canada (INAC) (formerly Indian and Northern Affairs Canada – INAC) in 1991 due to concerns that Inuit and northerners were being exposed to elevated levels of contaminants through their diet. The program was designed to research, monitor and communicate information on contaminant levels and trends in traditionally harvested food items (e.g., ringed seal, beluga whales, Arctic char) across the Canadian Arctic. The program funds human health research, environmental monitoring and research, education and communications, and national/regional coordination and aboriginal partnerships. Information from the program is used to provide national and international regulatory oversight of chemicals and to inform health authorities on the contaminant levels in country foods and the potential health and safety risks related to consuming traditionally harvested foods.

1.10 Management regimes

1.10.1 Nunavut Tunngavik Incorporated

Nunavut Tunngavik Inc. (NTI) promotes and advocates Inuit economic, social and cultural well-being through the implementation of the NLCA, which was signed in 1993. NTI along with Nunavut's three Regional Inuit Associations (Kitikmeot Inuit Association, Kivalliq Inuit Association, Qikiqtani Inuit Association) manage all Inuit owned land. NTI is governed by an 8 member board of directors and the organization consists of 10 departments.

1.10.2 Kivalliq and Qikiqtani Inuit associations

The Kivalliq Inuit Association (KIA) is a Designated Inuit Organization under the Nunavut Land Claims Agreement that represents the interests of Inuit living in the Kivalliq Region. These interests include the development, protection, administration and advancement of Inuit rights and benefits as indigenous people living in the region. KIA's mandate is to preserve Inuit heritage, culture and language; to manage Inuit owned lands in the region and provide information to and consult with land claim beneficiaries on land use; and to protect Arctic wildlife and the environment, so as to preserve traditional uses for current and future generations.

The Qikiqtani Inuit Association (QIA) is also a Designated Inuit Organization that represents the interests of Inuit of the Qikiqtani region. QIA began as a non-profit organization in 1986 and was registered as a society in 1997. Currently there are two Inuit organizations that work under QIA: the Kakivak Association, which is responsible for community economic development and small business development; and the Qikiqtaaluk Corporation, which is the regional development arm of QIA. Each of the 13 communities in the Qikiqtani region has a community director that sits on the QIA board of directors. In addition to the board there is a secretary-treasurer, vice president and president. There are seven departments within the QIA.

1.10.3 Nunavut Planning Commission

The Nunavut Planning Commission is a public land use agency that is responsible for the development, implementation and monitoring of land use plans. These plans are used to guide and direct resource use and development in the territory. The NPC roles and responsibilities are mandated by the NLCA. Under the NLCA "land" includes both surface and sub-surface land, freshwater, and renewable and non-renewable resources including wildlife. The NPC consults with government, Inuit organizations and many other organizations; however, it is the NPC that makes the final decisions on how land use plans will be developed and managed in Nunavut. NTI and RIAs are included in the approval process. A draft Nunavut Land Use Plan is available online at <http://www.nunavut.ca/en/downloads>. The land use plan provides for protection of caribou calving and post-calving grounds and critical bird habitat; identifies traditional ice travel routes and presents tools to protect them; and identifies areas of mineral potential, as well as areas with potential for tourism activities. A final public information session on the draft Nunavut Land Use Plan is scheduled for the fall 2017.

1.10.4 Nunavut Impact Review Board

The Nunavut Impact Review Board (NIRB) was created by the NLCA with a mandate to assess the potential impacts of proposed developments in the Nunavut Settlement Area. The NIRB provides recommendations regarding whether a project may proceed. The NIRB also establishes monitoring programs for projects that have been assessed and approved. The overarching goal of the NIRB is to protect and promote the existing and future well-being of the residents and communities and the ecosystem integrity of Nunavut. The NIRB requires that proposals for projects include the impacts of climate change within their environmental impact assessment.

1.10.5 Nunavut Water Board

The Nunavut Water Board (NWB) is an Institution of Public Government (IPG) that was created by the NLCA. The NWB holds the responsibilities and powers over the use,

management and regulation of inland waters in Nunavut. The primary role of the NWB is to license uses of water and deposits of waste. In doing so, the NWB considers any detrimental effects of the potential use of waters or a deposit of waste on other water users. The NWB does not hold enforcement powers over the licences it issues. Enforcement of licenses falls under the jurisdiction of Indigenous and Northern Affairs Canada (INAC). The NWB cooperates with the NPC to develop land use plans that affect water, and with the NIRB to assess environmental and socio-economic impacts of water-related project proposals.

1.10.6 Government of Nunavut, Department of Environment

The Department of Environment (DOE) has the lead responsibility in the Government of Nunavut to ensure protection, promotion, and sustainable use of natural resources in the territory through the management of the environment, wildlife and parks. Six divisions: Wildlife Management, Parks and Heritage, Fisheries and Sealing, Environmental Protection, Education and Outreach, and the Climate Change Secretariat within the Department of Environment are responsible for ensuring that all initiatives above are achieved. See Chapter 16 for legislated responsibilities governed by the Wildlife Management division and Fisheries and Sealing division. The Parks and Heritage division is responsible for planning, establishment, management, operation and promotion of territorial parks and places that are important destinations for Nunavummiut and visitors to the territory. These have been established based on *Inuit Qaujimagatuqangit* also known as ‘traditional knowledge’, local and scientific knowledge and geospatial information. The Environmental Protection division administers the Environmental Protection Act and is responsible for delivering a range of regulatory and operational program functions. The Education and Outreach division works closely with all DOE divisions to ensure that education and outreach initiatives, involving youth, community members, Elders and teachers, are integrated into all of the work conducted within the department. Lastly, the Climate Change Secretariat (CCS), established in November

2016, is responsible for developing programs, policies and partnerships that assist the territory in adapting to and mitigating the projected impacts of climate change. The CCS addresses climate change adaptation through initiatives and programs that respond to local needs, build local capacity, and increase local resilience to the effects of climate change. It also supports mitigation efforts through reduction in diesel consumption and greenhouse gas emissions. The CCS is responsible for running the Nunavut Climate Change Centre or NC³ (www.climatechangenunaut.ca) that provides a web-based resource to share and distribute climate change knowledge, research, and resources to the public.

1.10.7 Nunavut Research Institute

The Nunavut Research Institute (NRI) is the science division of Nunavut Arctic College. NRI administers licences, as required under Nunavut’s Scientists Act, for research in the health, natural, and social sciences. Other responsibilities include: (1) providing mentorship and support to scientists working throughout the territory, (2) the consultation and inclusion of Nunavummiut in research, (3) assisting broker research projects and partnerships that meet the needs and concerns of community residents, and (4) providing opportunities to Nunavummiut for hands-on skills, training and experience in applied science and research. NRI has a research centre in Iqaluit that offers dedicated teaching and research laboratories facilities, equipment rentals and storage, office and meeting space rentals, a research library and other resources. Research field support units are available in Iqaluit, Arviat and Igloodik. Accommodation and lab use is usually available in the summer period in Cambridge Bay and Rankin Inlet. NRI also runs a summer science camp and school science outreach program.

1.10.8 Federal agencies governing environmental protection

1.10.8.1 Department of Fisheries and Oceans

Fisheries and Oceans Canada (DFO) is a federal government agency that is responsible for developing and implementing policies and programs in support of Canada’s

economic, ecological and scientific interests in oceans and fresh waters. DFO's mandate is delivered under the authority of the Fisheries Act (for details concerning governing environmental protection and the management of wildlife and the environment see Chapter 16).

1.10.8.2 *Environment and Climate Change Canada*

Environment and Climate Change Canada is responsible for the protection of migratory birds through the implementation of the Migratory Birds Convention Act, the Migratory Birds Regulations, and the Migratory Birds Sanctuary Regulations. As mentioned previously, Environment and Climate Change Canada establishes and manages NWA and MBS for the conservation of significant marine and/or terrestrial areas that protect migratory birds, species at risk and other species of national importance and their habitat.

1.10.8.3 *Parks Canada*

Parks Canada manages National Parks, National Marine Conservation Areas, National Historic Sites and a National Landmark in Canada. Parks Canada is responsible for the protection of nationally significant natural and cultural heritage, and for fostering public understanding and appreciation in ways that ensure the ecological and commemorative integrity for present and future generations.

1.10.8.4 *Indigenous and Northern Affairs Canada*

Indigenous and Northern Affairs Canada (INAC) supports Indigenous peoples and northern peoples in their efforts to 1) improve social well-being and economic prosperity, 2) develop healthier, more sustainable communities, and 3) participate more fully in Canada's political, social and economic development to the benefit of all Canadians.

1.11 Conclusion

Nunavummiut in the Kivalliq and Qikiqtaaluk regions, in partnership with regional, territorial and federal governing bodies, are dedicated to protecting Inuit well-being and culture, the region's resources, environment (land, air, water),

and wildlife. The Eastern Canadian Arctic is undergoing some of the most rapid warming in the Canadian Arctic accompanied by significant reductions in snow and ice cover. These changes are impacting wildlife, the environment, and the Inuit way of life. Protection of Qikiqtaaluk and Kivalliq regions and its people will require strong partnerships and policies that are rooted in traditional and scientific knowledge and directed at assisting the regions in adapting to and mitigating the impacts of climate change.

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STEPHANIE COULOMBE

A large glacier flows from the background towards the foreground, its surface marked by numerous crevasses and striations. The glacier is set against a backdrop of a reddish-brown, conical mountain under a dramatic, cloudy sky. In the foreground, the glacier's edge meets a rocky, reddish-brown terrain with a small stream of water.

PART II

UNDERSTANDING CHANGE: DRIVERS, TRENDS, UNCERTAINTIES



Chapter 2 Climate Variability, Trends and Projected Change

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Key messages

- The Eastern Canadian Arctic is currently experiencing some of the most rapid climate warming in the Arctic, particularly during the fall/winter season in response to later ice formation. Warming is mainly confined to the period since 1993 and the warming pattern shows evidence of a number of coastal “hot spots” in Hudson Strait and Foxe Basin where recent fall/winter season warming exceeds 1.7 °C/decade.
- Warming has been associated with significant changes in snow and ice cover, particularly the later timing of snow cover, reduced overall snow depth, decreased summer sea-ice extent, declines in river and lake ice cover, and an increasingly negative mass balance of glaciers and ice caps. There is evidence that current snow and ice conditions are likely unprecedented in many millennia.
- Climate change projections for 2050 over the Eastern Canadian Arctic show a continuation of recent observed warming trends with the greatest warming (+4 to +8 °C) in the fall and winter seasons. Precipitation is projected to increase over most of the region by about 15-20% with the largest changes in the winter and fall. There is considerable regional variability in the projected changes with the largest values over coastal areas and more southern parts of the region.
- Major changes are projected in snow and ice cover over the region. Snow cover duration is projected to decrease by about one month by 2050, but annual maximum snow depth is projected to change only slightly due to increased snowfall (15-35%) offsetting the shorter snow accumulation period. Large reductions in snow accumulation on the ground are projected during the fall and spring from earlier melt and a later start to the snow season.
- Projected changes in lake ice cover for 2050 indicate earlier break-up by 10-15 days and later freeze up by 5-10 days, with 10-30 cm decreases in annual maximum ice thickness. The duration, thickness and concentration of sea ice are projected to decrease over most of the region. However, the ice regime within the Canadian Arctic Archipelago is likely to remain a hazard for shipping throughout the 21st Century.
- The current downward trend of glacier and ice cap ice mass in the region is projected to continue and is considered to be irreversible in the foreseeable future.

Abstract

Reliable and authoritative information on observed and projected climate change is needed for developing successful adaptation strategies for northern communities, decision makers and stakeholders. This chapter presents information on the climate regime of the Eastern Canadian Arctic, its variability and change, and projected changes from climate model scenarios out to the period 2050. The region is currently experiencing some of the most rapid warming in the Canadian Arctic with changes of ~ 1.0 °C/decade in annual mean surface air temperature since 1993. Climate station records show this rapid warming is linked to both natural climate variability and anthropogenic forcing. This recent warming is most pronounced in the fall and winter period with the coldest months warming at close to twice the rate of the warmest months. The warming pattern also shows a number of coastal “hot spots” where recent fall/winter season warming exceeds 1.7 °C/decade. The regional warming has been accompanied by significant reductions in snow and ice cover: Baffin Bay has experienced some of the largest decreases in summer sea ice in the Canadian Arctic with 20% losses during the period 1979-2008. Extensive reductions in river and lake ice cover have also been documented over the region with evidence that some high latitude lakes are shifting from perennial to seasonal ice cover for the first time in several millennia. There is also evidence that current mass loss from glaciers and ice caps is unprecedented in several millennia. Climate model projections show a continuation of currently observed trends with the largest warming in the winter and fall seasons with increases of ~ 4 -8 °C in air temperature and increases in precipitation of ~ 8 -26% by 2050. The spatial pattern of warming is quite variable with the largest changes typically seen over southern land areas. Snow cover duration is projected to decrease by about one month with the largest changes to the start date of snow cover. Annual maximum snow depth is projected to change only slightly due to increased snowfall (15-35%) offsetting the shorter snow accumulation period. However, snow accumulation in the May-October period is projected to undergo large reductions from earlier melt and a later start to the snow season. Simulations from the higher resolution CanRCM4 model show the largest decreases in snow cover are projected to occur in the coastal zone. Projected changes in sea ice from a high resolution coupled ice-ocean model over the Canadian Arctic Archipelago (CAA) show declining sea-ice concentration and thickness but no completely ice-free summers before 2100. Multi-year ice has undergone rapid decreases in recent years but is likely to remain a hazard for shipping for the foreseeable future. Projected changes in lake ice cover for 2050 indicate earlier break-up of 10-15 days and later freeze-up of 5-10 days, with 10-30 cm decreases in annual maximum ice thickness. Modelling studies of the future response of land ice in CAA suggest it is highly unlikely that the current glacier mass loss trend will reverse in the coming century, and that projected mass loss is irreversible in the foreseeable future.

2.1 Introduction

The Arctic is currently experiencing the most rapid warming anywhere on the planet in response to a number of processes and feedbacks that contribute to amplification of anthropogenic warming over polar regions (LeTreut et al. 2007, Screen and Simmonds 2010, Pithan and Mauritsen 2014). This warming is generating dramatic changes in the Arctic cryosphere (AMAP 2011) and vegetation (Zeng and Jia 2013) which contribute to a further series of mostly positive feedbacks to the climate system. For example, changing Arctic vegetation is driving changes in snow cover (enhanced snow trapping) and melt energetics (Marsh

et al. 2010) that impact the hydrological (Déry et al. 2009) and ground thermal regimes (Smith et al. 2010, Lantz et al. 2012). The impacts of a shortening snow and ice season and a thinner, less stable fastice regime have major impacts on the security and livelihood of northern residents (Laidler and Elee 2008, Ford et al. 2008).

The IRIS 2 region is currently experiencing some of the most rapid warming in the Canadian Arctic. Climate station records show this rapid warming began relatively recently ~ 1993 and has been associated with both natural climate variability (the Arctic Oscillation and Atlantic meridional overturning circulation are two of the most important

sources) and anthropogenic forcing (Way and Viau 2014). Documenting a changing climate and providing climate change scenarios for the region is a particular challenge as this region has the largest gradients in elevation, temperature and precipitation of the four IRIS regions. Current global climate models (resolutions ~100-250 km) and the regional climate model (45 km resolution) used in this study are unable to capture the detailed topography. It should therefore be stressed at the outset that the climate change scenarios presented here provide a physically plausible portrait of regional-scale changes but community-scale applications would require additional downscaling (Dibike et al. 2008).

This chapter presents information on the climate regime of the Eastern Canadian Arctic, its variability and change based on historical climate and related paleo- and proxy data, and climate model scenarios of plausible future pathways for climate out to the period 2050. The chapter assesses variability and change in a number of key climate and cryospheric variables including air temperature, precipitation, snow cover, sea ice, storms and land ice. The ground thermal regime is addressed in detail in Chapter 4. Knowledge of the current and projected rates of change in these variables and related indicators is important information for stake-holders, policy-makers and northern communities for developing adaptation strategies and policies.

The chapter is divided in two parts consisting of (1) a portrait of historical regional climate variability and trends based on the analysis of available datasets and the review of recent literature, and (2) projections of future climate change based on output from the Canadian Regional Climate Model (CRCM, de Elía and Côté 2010) driven with two different CMIP3 global climate models for emission scenario SRES A2 (Nakicenovic et al. 2000).

2.2 The climate

2.2.1 Data sources

This report used the 2013 updates of the second generation of the Adjusted and Homogenized Canadian Climate Data (AHCCD) (Vincent et al. 2012, Mekis and Vincent 2011) that take account of systematic errors related to observing

methods (temperature and precipitation) and station relocations (temperature). A total of 17 climate stations are located in the IRIS 2 region with long term surface air temperature (SAT) observations suitable for characterizing the recent climate (1981-2010 normal period) and trend over the period from 1950-2013, and 10 stations for precipitation (PCP) (Table A1). The locations and the temporal distribution of climate stations in the region are shown in Figures 1 and 2, respectively. The marked drop-off in the number of stations after 1990 (particularly for precipitation) is related to station closures and loss of manual precipitation measurement programs. The air temperature analysis was based on the daily version of the Vincent et al. (2012) dataset with missing data filled by interpolating observations from surrounding stations. This step was necessary to generate complete monthly series at stations: the Vincent et al. (2012) dataset follows the World Meteorological Organization guidelines for monthly statistics (no more than 5 missing days, or 3 consecutive days) which results in incomplete monthly data at many stations. Gap-filling was also necessary for computing daily temperature statistics such as freezing and melting degree-day totals. Gap-filling was not attempted for precipitation as the observations are more strongly affected by local-scale processes.

Information on surface snow cover (start/end date of continuous snow cover, snow cover duration, maximum depth and date of maximum depth) was obtained from daily snow depth observations made at climate stations. The start (end) dates of snow cover are defined as the first (last) date in the snow season with 14 consecutive days of snow depths \geq ($<$) 2 cm. Snow cover duration is defined as the number of days with \geq 2 cm snow on the ground. *In situ* observations of snow depth are usually made in open grassy terrain near airports that may not be representative of snow cover conditions in the prevailing land cover. Satellite-derived snow cover information from the NOAA-CDR dataset (Estilow et al. 2015) was also analyzed to obtain another independent source of information on snow cover trends over the region. Data on historical trends in sea ice over the region were obtained from the online regional summaries provided by the Canadian Ice Service (CIS). Information on fastice conditions (depth, freeze-up and break-up dates)

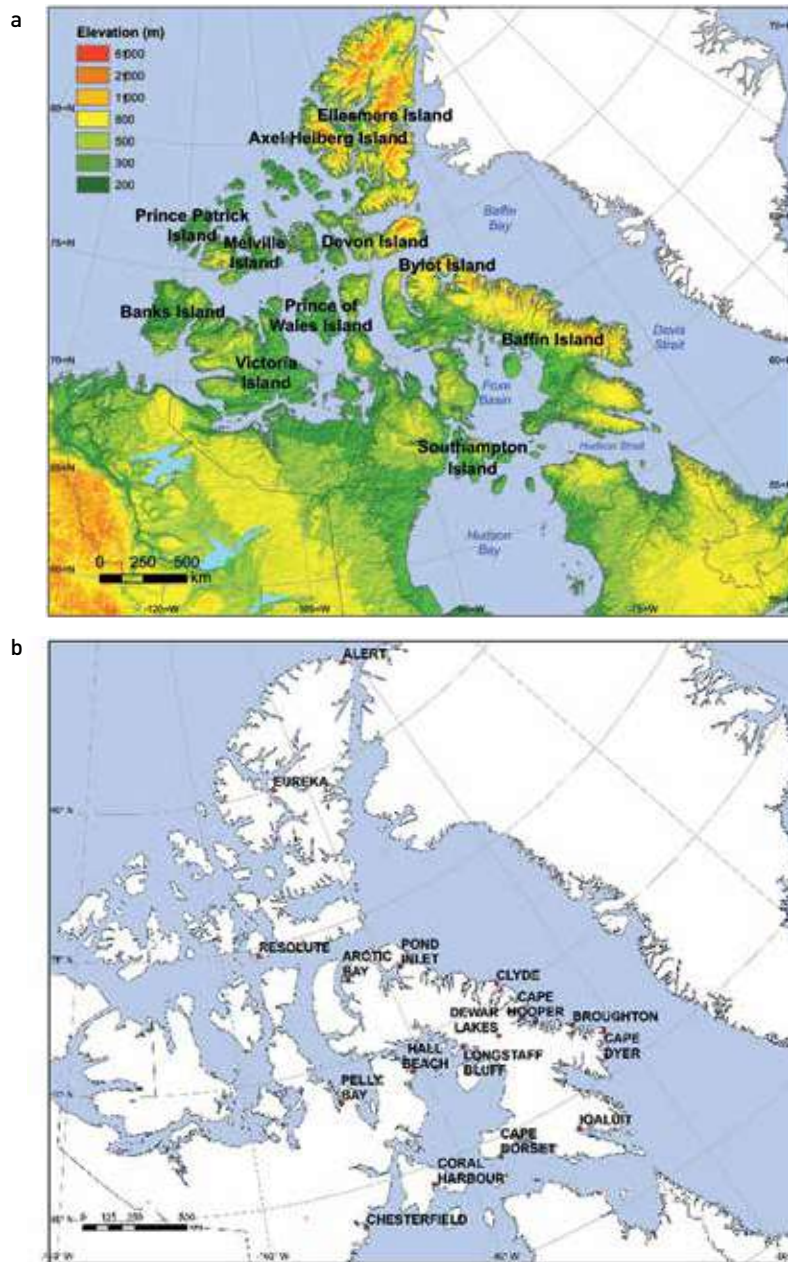


FIGURE 1. (a) Geography and elevation (meters) of the Canadian Arctic. (b) Location of climate stations used in the regional climate analysis.

was obtained from the weekly ice thickness data archived at CIS as well as from published summaries of ice thickness and freeze-up/break-up compiled by the CIS.

The climate station data analysis consisted of two parts: (1) calculation of climate normals for the 1981-2010 period, and

(2) calculation of trends over the main period of historical climate observations (1950-2013) and a more recent 30-year period of data (1984-2013). Regional anomaly series for the region were constructed using a 1981-2010 reference period with a confidence interval estimated from the mean inter-station correlation following Wigley et al. (1984).

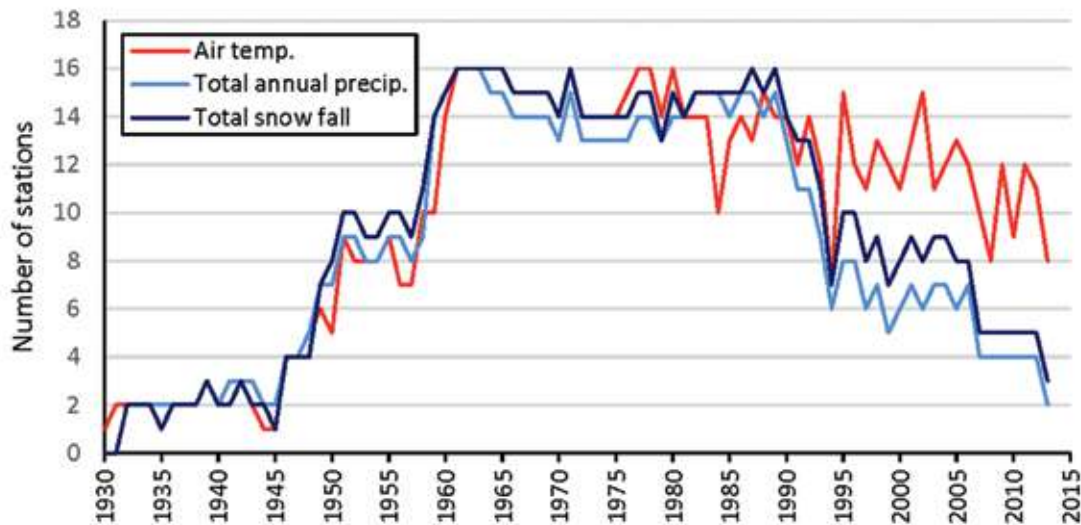


FIGURE 2. Number of stations in the IRIS 2 region with complete annual mean temperature, annual total precipitation and annual total snowfall from the 2013 updates of the Mekis and Vincent (2011) and Vincent et al. (2012) datasets.

2.2.2 General description and key characteristics

The IRIS 2 region covers over 20 degrees of latitude from southern Baffin Island and the northwest coast of Hudson Bay to the northern tip of Ellesmere Island and includes strong gradients in temperature and net radiation. For example, the average annual mean SAT for the period 1981-2010 at Alert (82.5 °N) is -17.4 °C compared to -8.8 °C at Iqaluit (63.8 °N) and Iqaluit has almost four months of above-freezing temperatures compared to two months at Alert (Tables A2 and A3). The climate of the region is dominated by snow and ice with seasonal snow and ice cover extending on average from October to June. The region is also characterized by strong north-south and east-west gradients in heat and moisture related to the frequent movement of cyclones up the east coast of Canada into Davis Strait and Baffin Island. This moisture contributes to the formation of ice caps and numerous valley glaciers over the higher elevation regions of Axel Heiberg, Ellesmere, Devon and Baffin Islands. Large ice shelves are distinctive features along the west coast of

Ellesmere Island that maintain some of the most unique aquatic ecosystems found north of 82° N (Müller and Vincent 2003). The numerous fiord systems and deep valley troughs found in the region, combined with the distinctive network of large water basins, sounds and narrow straits exert important physical controls on the climate and snow and ice regimes. The region also includes a number of polynyas (areas of persistent open water) such as the North Open Water (NOW, Barber et al. 2001) that have important impacts on local-regional climate. For example NOW is a significant winter moisture source for Devon Ice Cap (Boon 2010) and also for the Manson and Prince of Wales Icefields (Koerner 1979).

The climate of the region is strongly influenced at annual to decadal time scale by natural atmospheric and oceanic variability. Some of the major modes of atmospheric and oceanic variability known to influence the IRIS 2 region are: the Arctic Oscillation (Thompson and Wallace 1998) and the related North Atlantic Oscillation (NAO, Barnston and Livezey 1987), the Atlantic Multidecadal Oscillation (Kerr 2000), El-Niño/Southern Oscillation (Walker 1928)

the Quasi-biennial Oscillation (Holton and Lindzen 1972) and the Baffin Island-West Atlantic pattern (Shabbar et al. 1997). These modes of natural climate variability interact and vary over time (Moore et al. 2013, Raible et al. 2014) and have important impacts on climate and climate extremes (Way and Viau 2014), sea ice (Wang et al. 1994, Stern and Heide-Jørgensen 2003) as well as atmospheric processes such as ozone depletion (Li and Tung 2014). In the past decade, the atmospheric circulation over the region has been characterized by a shift to more frequent summer anticyclonic circulation (Overland et al. 2012) linked to sea-ice loss (Petrie et al. 2015) that is driving more intense and sustained summer melt of snow and ice (Bezeau et al. 2014, Sharp et al. 2014). Floating ice shelves in northern Ellesmere Island have been strongly affected by these recent changes with some fiords in the region now ice free for the first time in over 3000 years (Sharp

et al. 2014, White et al. 2014). The observed response of the atmospheric circulation to declining sea ice is only weakly replicated by CMIP5 climate models (Overland et al. 2012, Petrie et al. 2015).

2.3 Air Temperature

Air temperature is a key variable in Arctic regions with important influence on cryospheric variables and processes (Derksen et al. 2012). Air temperature is influenced by latitude, elevation, distance from coast, and sea-ice conditions. This gives rise to strong local-regional gradients in temperature over the region (see Figure 3). Figure 3 also shows the changing seasonal contrast between land/ocean temperatures over Baffin Island in June (land warms faster than oceans) and September (land also cools faster than ocean). Annual mean SAT at climate stations in the

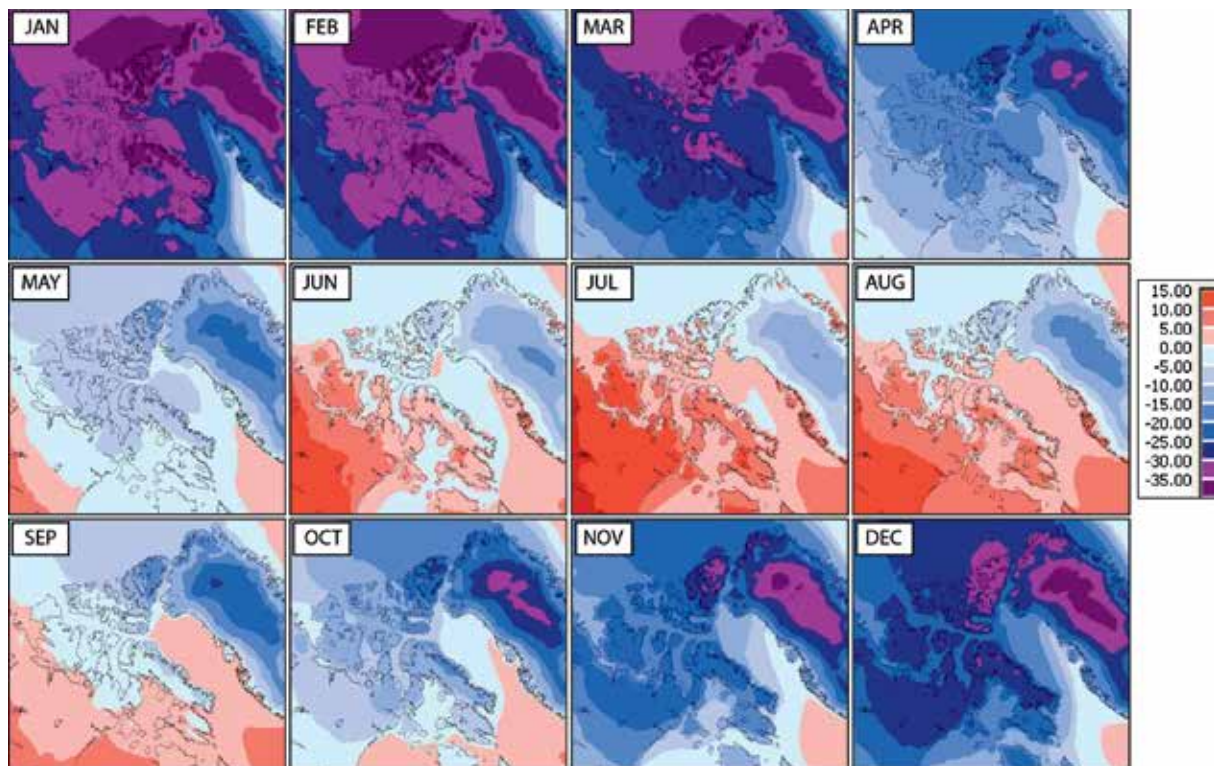


FIGURE 3. 1989-2009 monthly mean SAT (°C) from ERA-interim dynamically downscaled to a 0.22° resolution by the CanRCM4 regional climate model (www.cccma.ec.gc.ca/data/canrcm/CanRCM4/index_cordex.shtml).

region (Table A2) ranges from $-8.8\text{ }^{\circ}\text{C}$ at Iqaluit to $-18.7\text{ }^{\circ}\text{C}$ at Eureka which means the entire region lies within the zone of continuous permafrost which corresponds roughly with the $-8\text{ }^{\circ}\text{C}$ isotherm (Brown et al. 1998). The region is characterized by a short ~ 3 -month period of above freezing temperatures with monthly means of daily maximum temperatures in July-August ranging from $10\text{ }^{\circ}\text{C}$ in the south (Chesterfield Inlet, Coral Harbour) to less than $4\text{ }^{\circ}\text{C}$ at Alert in the north.

Observed variability in annual mean SAT over the region from 1950 (Figure 4a) estimated from the climate stations in Table A1 shows evidence of a gradual (but not statistically significant) cooling trend of $-0.16\text{ }^{\circ}\text{C}/\text{decade}$ from 1950 to 1992 followed by a significant warming trend of $0.9\text{ }^{\circ}\text{C}/\text{decade}$ between 1993 and 2013. This recent warming is most pronounced in the fall and winter period (Figure 5) and is observed over most of the Eastern Canadian Arctic and Subarctic regions (Figure 6) (Allard and Lemay 2012, Way and Viau 2014). In the period since 1993 the coldest months are warming at close to twice the rate of the warmest months ($1.42\text{ }^{\circ}\text{C}/\text{decade}$ versus $0.84\text{ }^{\circ}\text{C}/\text{decade}$). Air temperatures in the region

are characterized by strong interannual variability with visible evidence in Figure 4a of a marked 3-4 year oscillation in annual air temperatures consistent with NAO variability (Higuchi et al. 1999). 2010 was the warmest year in the historical climate record to 2013 and the decline in temperatures in subsequent years is consistent with the observed 3-4 year variability over the region and with observed multi-decadal variability in the Arctic climate system (Keenlyside et al. 2008, Semenov et al. 2010). The latest update of the Climate Research Unit CRUTEM4 (Jones et al. 2012) gridded air temperature dataset (not shown) indicates a continuation of the post-2010 cooling period into 2015 with 2015 having the coldest annual mean temperature since 1992. The recent cooling is mainly seen in the winter period and is consistent with a return to more positive values of NAO after the large negative anomalies experienced in 2010.

Long-term warming is observed at all stations in the region since the 1950s (Table A3) although the change is not significant everywhere. However the past 30-year period (1984-2013) shows significant warming trends in mean annual temperatures at all stations (Table A4)

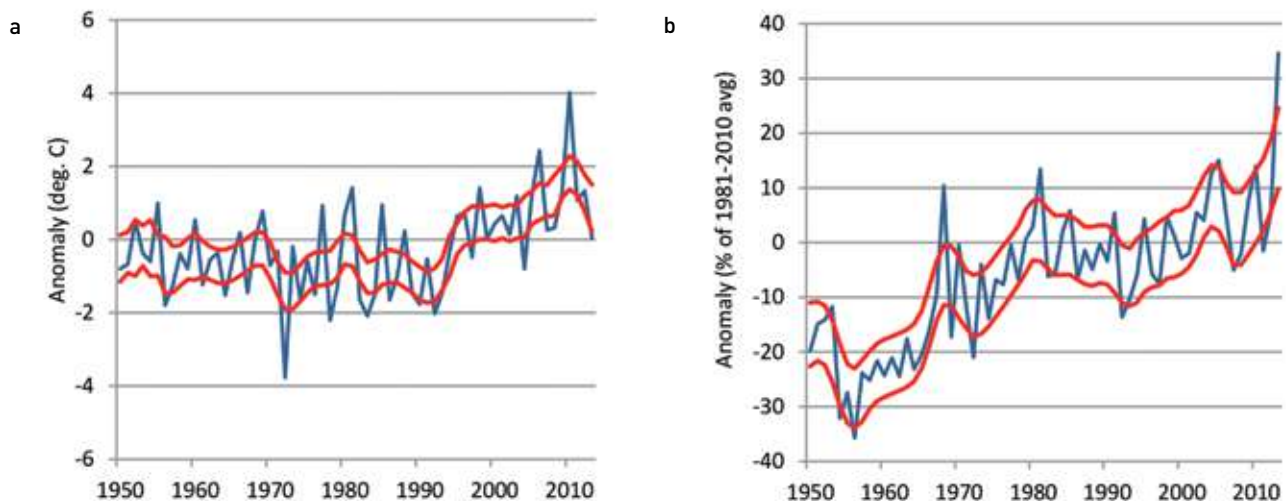


FIGURE 4. (a) Regionally-averaged anomalies (solid blue line) of annual mean SAT ($^{\circ}\text{C}$) and (b) annual total precipitation (%) with respect to a 1981-2010 reference period for climate stations in the region. The 9-term binomially filtered 95% confidence interval (red curves) are estimated from the between-station correlations following Wigley et al. (1984).

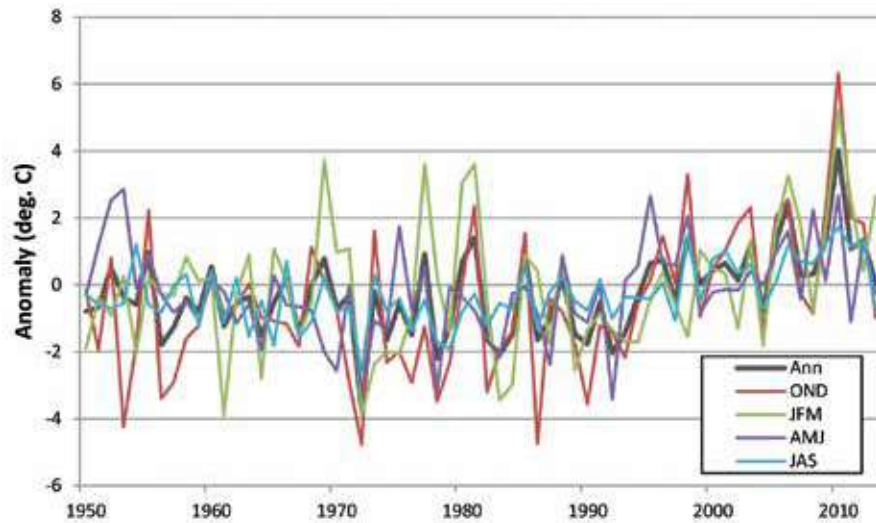


FIGURE 5. Regionally-averaged seasonal mean and annual mean SAT anomalies with respect to a 1981-2010 reference period for 17 climate stations in the region.

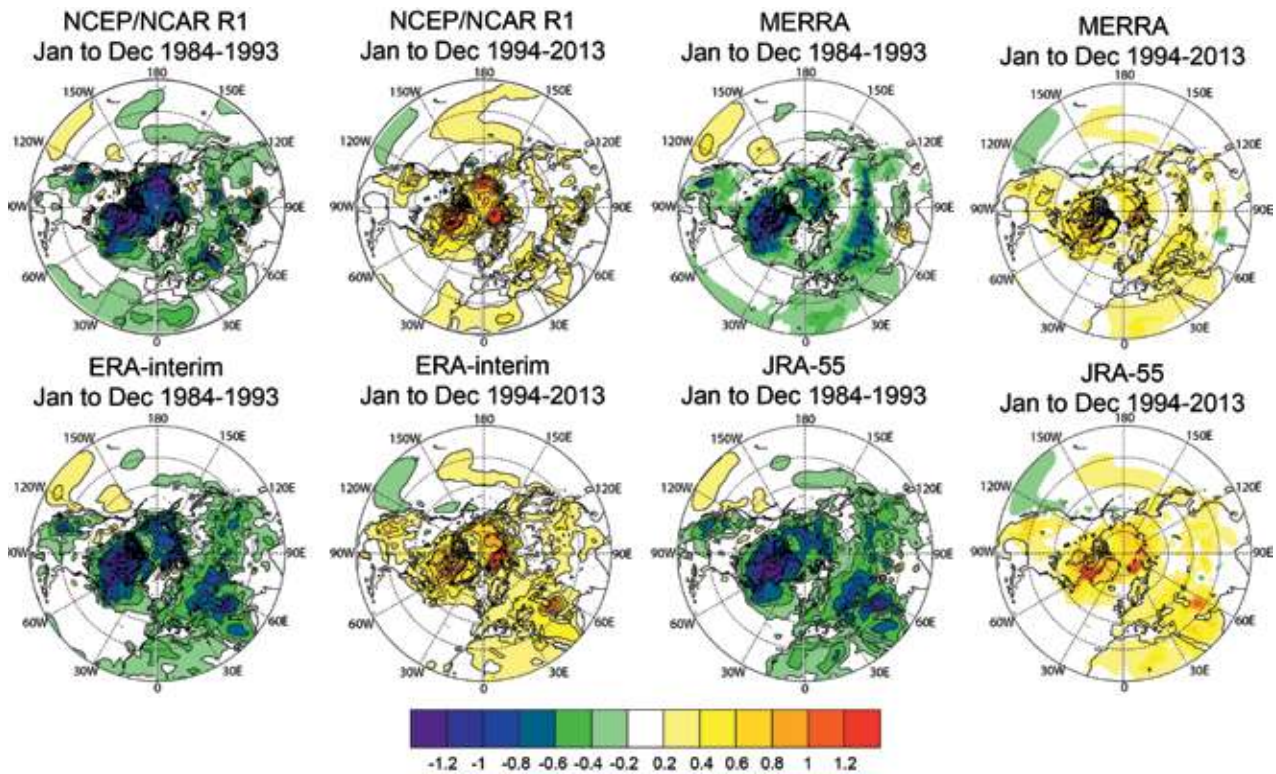


FIGURE 6. Comparison of NCEP, MERRA, ERA-interim and JRA55 2m air temperature anomaly patterns (K) for the recent warming period (1994-2013) versus the previous decade (1984-1993). The contrast between the two periods is striking. <http://www.esrl.noaa.gov/psd/cgi-bin/data/testdap/plot.comp.pl>. The plots were generated using the NOAA WRIT plotting tool which uses a fixed 1981-2010 reference period for anomalies.

with the coldest months warming at more than twice the rate of the warmest months consistent with the findings of Vincent et al. (2015). Few stations showed significant changes in thaw- or freeze-onset dates (related to the large interannual variability in these variables) but the regionally-average results are consistent with warming (earlier thaw-onset and later freeze-onset). The spatial pattern of recent warming over the region (Figure 7) shows evidence of a number of regional “hot spots” where seasonal warming has exceeded 5 °C/30y. The enhanced warming in these regions is associated with marked declines in sea-ice concentration which contributes a positive feedback particularly in the fall period due to later ice formation (Parmentier et al. 2013).

2.4 Precipitation

Information on the amount and phase (solid/liquid fraction) of precipitation is important for water resources, permafrost temperatures, ground stability and many biological aspects of northern environments. Precipitation over the region is characterized by a strong southeast to northwest gradient (from southern Baffin Island region to the north of Ellesmere Island) with strong gradients in snowfall along Baffin Bay coastlines (Figure 8). The mean annual total snowfall record from climate stations (Table A5) clearly shows a north-south gradient with the highest snowfall amounts observed at Cape Dorset and Iqaluit in the south (418 and 301 mm water equivalent respectively) compared to less than 90 mm at Eureka. The snowfall climate is characterized by frequent trace amounts with stations recording

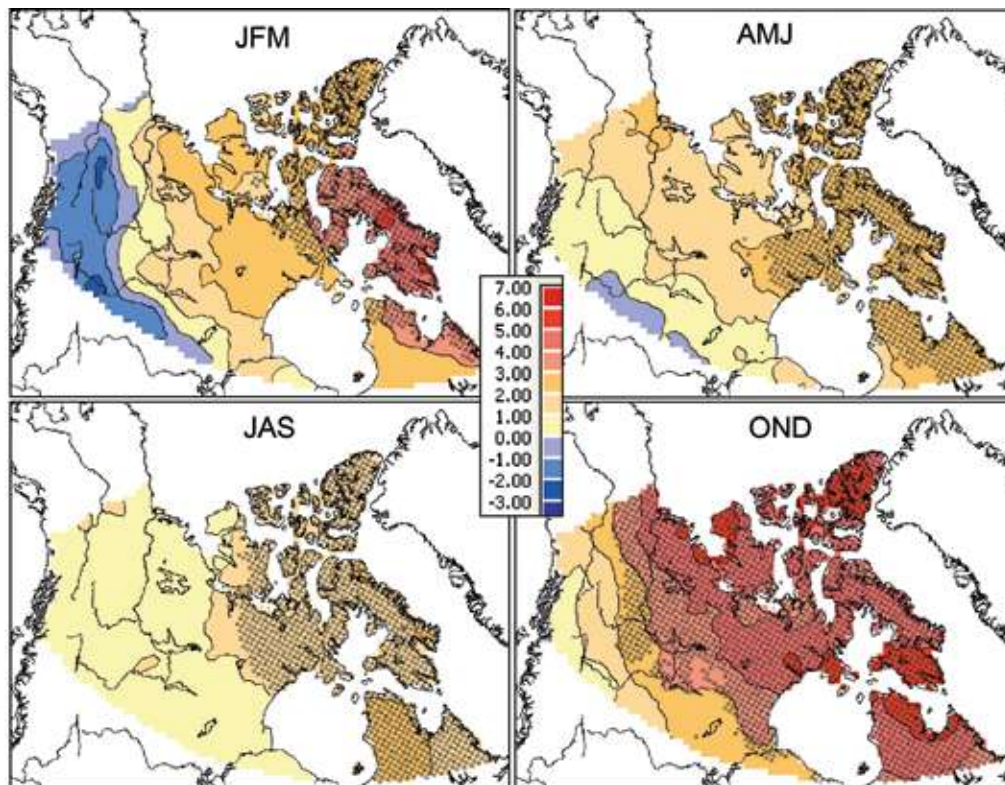


FIGURE 7. Seasonal patterns of 1981-2010 surface air temperature trend (°C/30y) in the CANGRD dataset. Grid points with locally significant trends are indicated with an “x”. Reproduced from Rapaic et al. (2015).

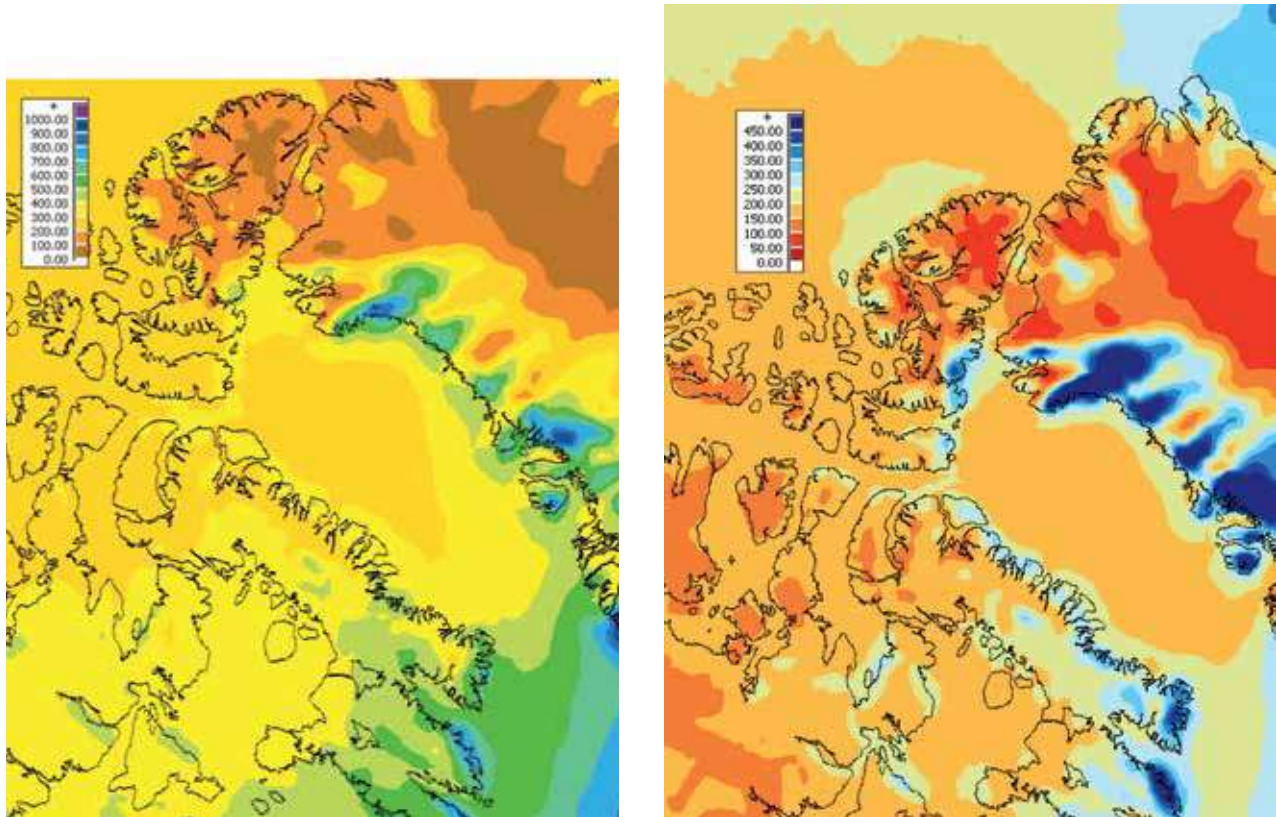


FIGURE 8. Annual total precipitation (mm - left) and snowfall (mm water equivalent -right) over the 1989-2009 period from ERA-interim dynamically downscaled to a 0.22° resolution by the CanRCM4 regional climate model (www.cccma.ec.gc.ca/data/canrcm/CanRCM4/index_cordex.shtml).

on average more than 100 trace snowfall amounts per year. Resolute and Eureka record the highest frequency of trace amounts with more than 170 trace events per year. These large numbers of trace events are a significant source of uncertainty for estimating precipitation amounts in Arctic environments from *in situ* observations (Mekis and Vincent 2011). About 65% of all precipitation falls in the summer and fall seasons (Figure 9).

The previously presented regionally-averaged precipitation series (Figure 4b) showed clear evidence of an increasing trend with significant increases in snowfall documented at six stations over the period from 1950-2013 (Table A6) consistent with the findings of Vincent et al. (2015). The

trend observed at Cape Dorset seems unrealistically high and appears to be related to a shift in the observing site in 1977. The 9-station regional average exhibited significant increases in rainfall and snowfall over the 1950-2013 period but part of this increase is related to abnormally low snowfall amounts in the period prior to 1965 (Figure 10). This period was also associated with anomalously low solid precipitation fraction values (below 60%) which contrasted with the rest of the period where the solid fraction of total precipitation was typically close to 70% (not shown). Excluding this period and Cape Dorset from the trend analysis still yielded significant increases in regionally-averaged precipitation of 5.3%/decade for rainfall and

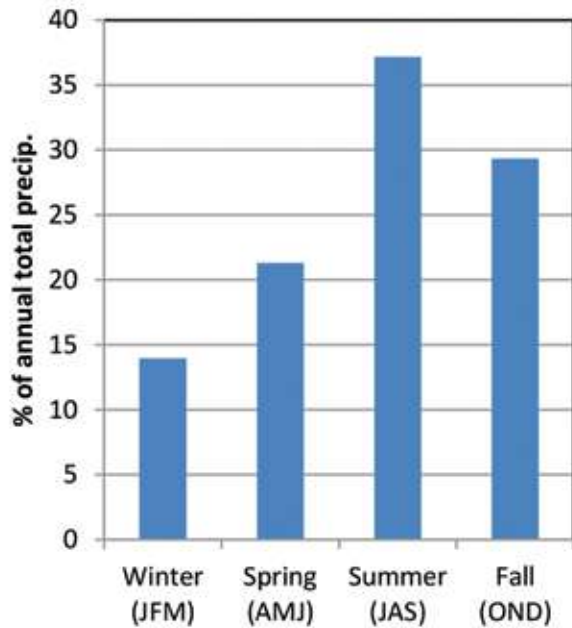


FIGURE 9. Average seasonal distribution of precipitation (% of annual total) in the region from climate station precipitation observations over the 1981-2010 period.

3.0%/decade for snowfall (% computed with respect to the 1981-2010 average). Where trends were able to be computed over the more recent 30-year period they were (apart from Hall Beach) not statistically significant (Table A6). The large increasing trend in snowfall at Hall Beach seems realistic as the snowfall series showed no evidence of any obvious discontinuities. Rapaic et al. (2015) looked at the consistency of precipitation trends over the Canadian Arctic in a number of gridded climate and reanalysis datasets and found a large spread in trends over much of the region with no consensus for significant increases. They also found that trends computed using the adjusted station data of Mekis and Vincent (2011) were about two times larger than those obtained from a multi-dataset estimate. These findings suggest that there is large uncertainty in trends in precipitation over the region.

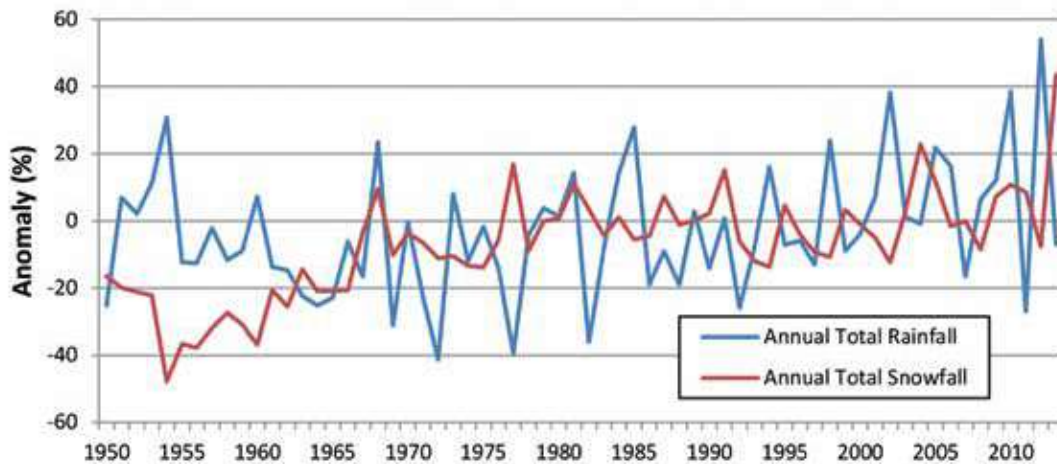


FIGURE 10. Regionally-averaged snowfall and rainfall anomalies (% of 1981-2010 average) from 10 stations in the region.

2.5 Snow cover

Snow is the dominant land surface in the Arctic and plays key roles in energy exchanges, the ground thermal regime, hydrology, and ecology through its high reflectivity, low thermal conductivity and water storage. Snow cover is also important for overland transport. Snow is present on average from early October to mid-June over much of the region with maximum snow depths varying considerably based on proximity to moisture sources, elevation, surface topography (exposure to wind), and the prevailing vegetation cover (Table A7). The joint effects of blowing snow and frequent trace snowfall events over the winter give rise to an almost linear evolution of the snowpack over the accumulation period, followed by rapid melt in the May-June period of high solar energy input (Figure 11a). Similar linear evolution of snow cover properties such as depth, snow water equivalent (SWE), and snowpack density are seen in bi-weekly snow survey observations (Figure 11b). Snow densities at the start of the snow season are higher in the region than in more southern latitudes due to wind packing, but do not increase much over the snow season because of depth hoar (also called sugar snow) formation within the snowpack (Sturm et al. 1995).

The regional pattern of snow cover extent derived from the NOAA IMS-24 km satellite-derived daily snow cover analysis (Helfrich et al. 2007) highlights the strong coastal gradient in snow cover around Baffin Bay (Figure 12) with permanent or quasi-permanent snow cover over higher elevations. The IMS snow season start dates agree closely with the station observations but are about two weeks later for snow-off. This difference is related to the different scales of these data sources (IMS integrates information over a larger footprint) and to cloud cover masking in the IMS product which is mainly based on visible satellite data. The regional pattern of seasonal snow accumulation is difficult to estimate reliably because of strong local controls on moisture availability and precipitation processes (e.g., topographic influences such as up-slope flow), but is likely to resemble the mean total snowfall distribution shown in Figure 8.

Evidence from surface observations (Table A8) and satellite data indicates significant decreases of ~3 weeks in

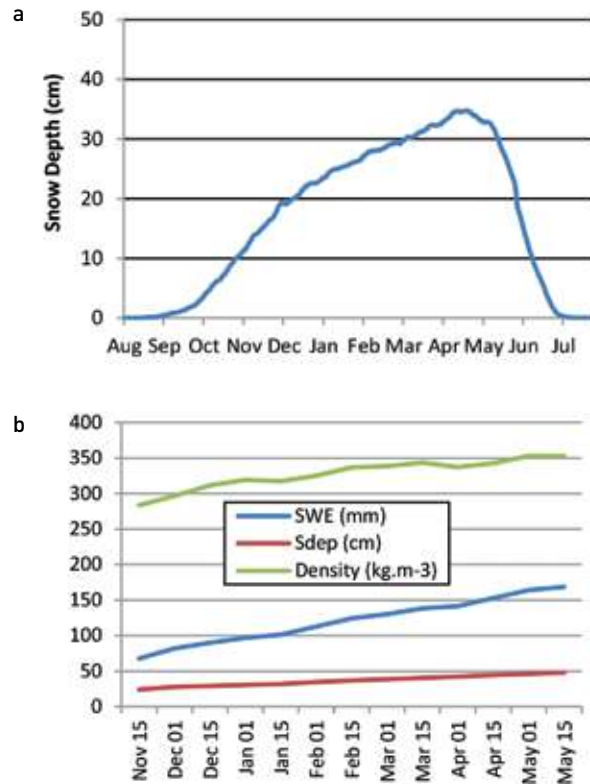


FIGURE 11. (a) Typical seasonal evolution of snow depth in the IRIS 2 region from the average of all *in situ* daily snow depth observations over 1971-2000 period (23 stations). (b) Typical seasonal evolution of snow depth (cm), SWE (mm) and snowpack density ($\text{kg}\cdot\text{m}^{-3}$) from all bi-weekly snow course observations in the region in the 1971-2000 period (11 snow courses). There were insufficient data after 2000 to compute 1981-2010 averages.

the period with snow on the ground over the 1950 -2013 period (Figure 13). These decreases are largely related to a later start to the snow cover season reflecting the enhanced warming observed in the fall season over the Canadian Arctic (Vincent et al. 2015, Stern and Gaden 2015). The larger response of snow cover in the snow-onset period is also observed in climate model projections and is likely linked to positive feedbacks driven by a shorter sea-ice season. The period since ~1980 is characterized by the increasing importance of earlier snow disappearance in the spring period. Maximum snow depths have decreased over

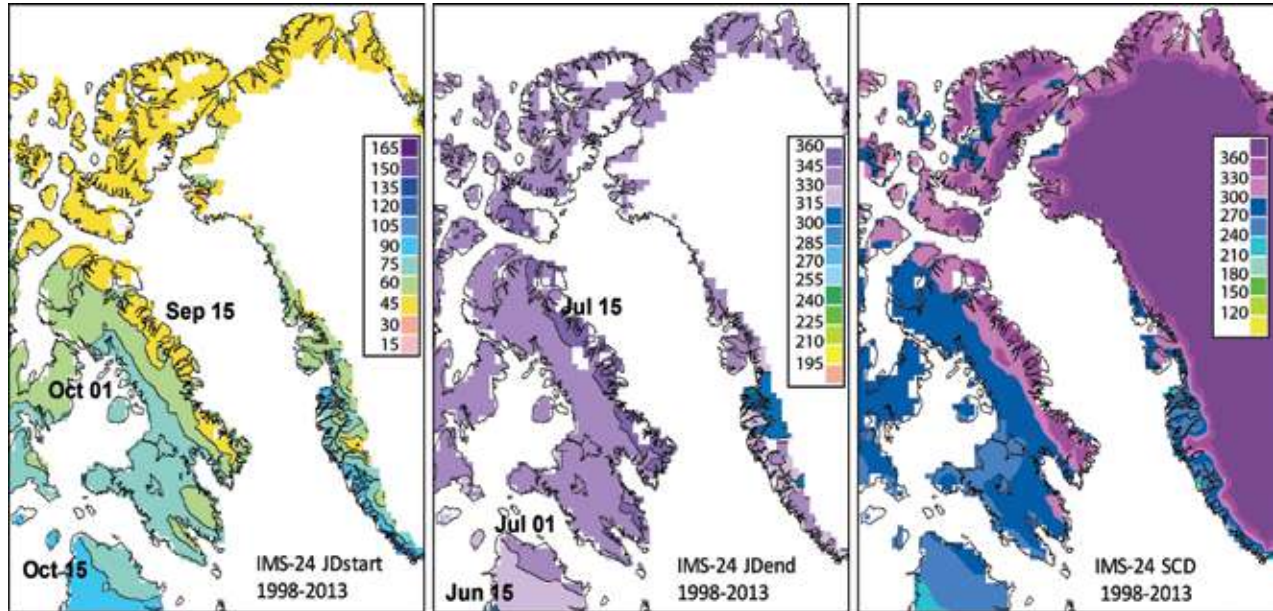


FIGURE 12. Median start (JDstart) and end (JDend) dates of continuous snow cover and the mean annual number of days with snow (SCD) from the NOAA IMS-24 km daily snow cover analysis over snow seasons 1998/99 to 2013/14. The legends for start and end date are the day in the snow year starting August 01 and ending July 31.

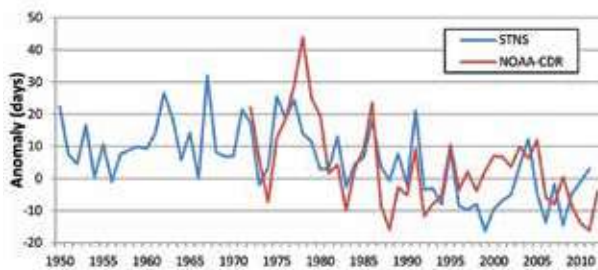


FIGURE 13. Regionally-averaged anomalies (days) in annual snow cover duration from surface stations (STNS) and the NOAA-CDR satellite dataset over snow seasons 1950/51 to 2012/13. Anomalies were computed as departures from the 1981-2010 reference period.

the region by an average of about 20% since 1950. However this may not reflect accumulation trends over vegetated areas as snow depth observations are made at climate stations in open terrain that may not be representative of snow conditions in the prevailing land cover. For example, observations of snow depth made at climate stations will not reflect the impact of the increasing shrub expansion

over tundra that has important impacts on snow accumulation, snowpack physical properties, energy exchanges and climate feedbacks (Marsh et al. 2010, Loranty and Goetz 2012). Estimates of trends in annual maximum SWE over Arctic land areas from satellite data (e.g. GlobSnow, Takala et al. 2011) and reanalysis-driven reconstructions (e.g., Liston and Hiemstra 2011) show trends of different signs over the region.

2.6 Ice cover

The ice cover of the region comprises sea ice and land-fast ice in marine environments, and river and lake ice in freshwater environments, and is a key feature of the winter environment affecting a wide range of climate sensitive ecosystem services and processes including over-ice transport, fishing and hunting (see Chapter 11), marine and aquatic ecosystems (see Chapter 5), coastal infrastructure (see Chapter 15), coastal erosion (see Chapter 8) and river stage and discharge (Prowse et al. 2011a,b, AMAP 2011,

Allard and Lemay 2012). Inuit society and culture is intimately intertwined with ice cover, and recent rapid declines in ice are challenging the adaptive capacity of communities (Laidler et al. 2009, Ford et al. 2009).

The sea-ice season in the region extends from approximately October to June with stronger regional variability in dates of break-up than freeze-up (Figure 14). For example, the northern part of Baffin Bay is the first area in the region to be ice-free related to the NOW polynya. Break-up dates range from mid-June to the end of August across northern Hudson Bay, Hudson Strait, Foxe Basin and Baffin Bay. Some northern areas of the region remain ice covered for most of the year e.g., Nares Strait, Kane Basin and the north coast of Ellesmere Island (Tivy et al. 2011). Multi-year ice (MYI) can be found in Hudson Bay and Baffin Bay from transport through Fox Basin, the eastern Parry Chanel and Kane Basin. The ice concentration in the region is generally at its lowest by mid-September.

The region has experienced some of the largest observed decreases in summer sea-ice extent in the Canadian Arctic with 20% losses in July-November sea-ice extent over the period 1981-2014 (Figure 15). Most of the change has occurred since 1998 with 2006 having the lowest ice cover in the period with regular satellite observations. The

observed declines in sea ice over the region are part of a pan-Arctic and pan-cryospheric response to warming (Derksen et al. 2012) that is underestimated in current climate models (Stroeve et al. 2012). Analysis of trends in ice concentration from passive microwave satellite data (Figure 16) show that the ice concentration has been decreasing in nearly all months in the region. Within the region, Baffin Bay, Hudson Strait and Davis Strait have experienced some of the largest decreases in summer sea

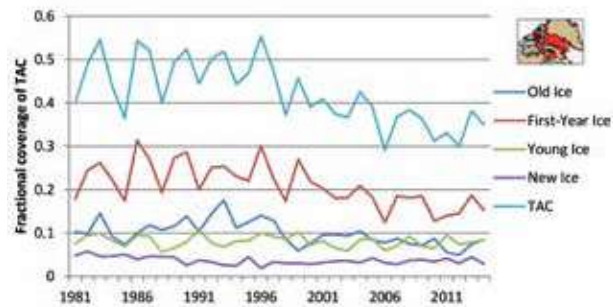


FIGURE 15. Annual variability in the ice season (June-November) fractional coverage of total accumulated ice (TAC) and the relative contributions of different ice types over the Eastern Arctic region (area in red in map insert) for the period 1981-2014. Data obtained from the Canadian Ice Service (<http://ice-glaces.ec.gc.ca/App/WsvPrdCanQry.cfm?CanID=11090&Lang=eng>).

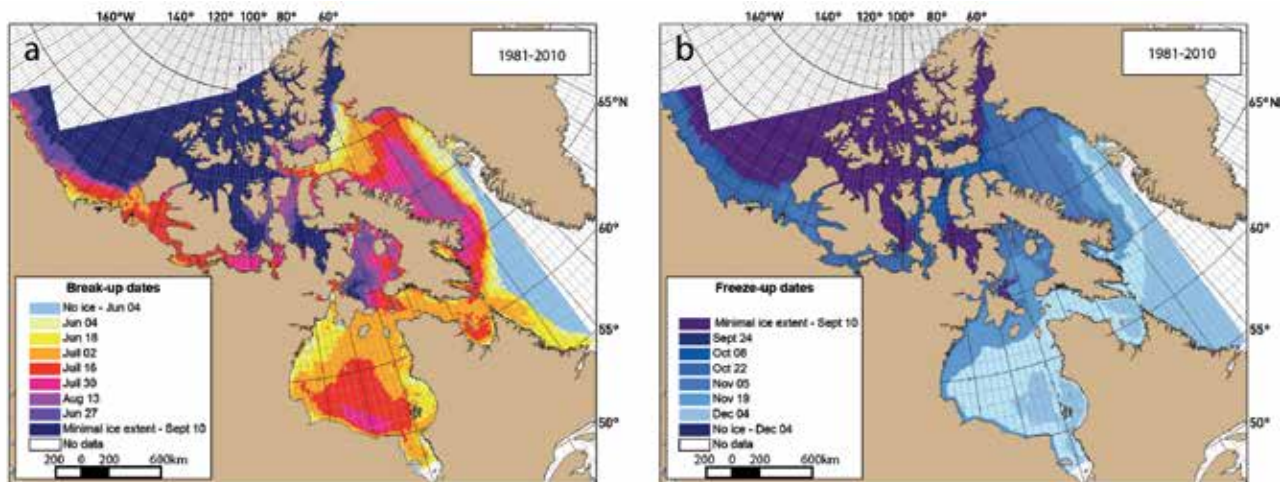


FIGURE 14. Sea-ice break-up (a) and freeze-up (b) dates averaged over 1981-2010 period for the Canadian Arctic. From the Canadian Ice Service (<http://iceweb1.cis.ec.gc.ca/30Atlas10/?lang=en>).

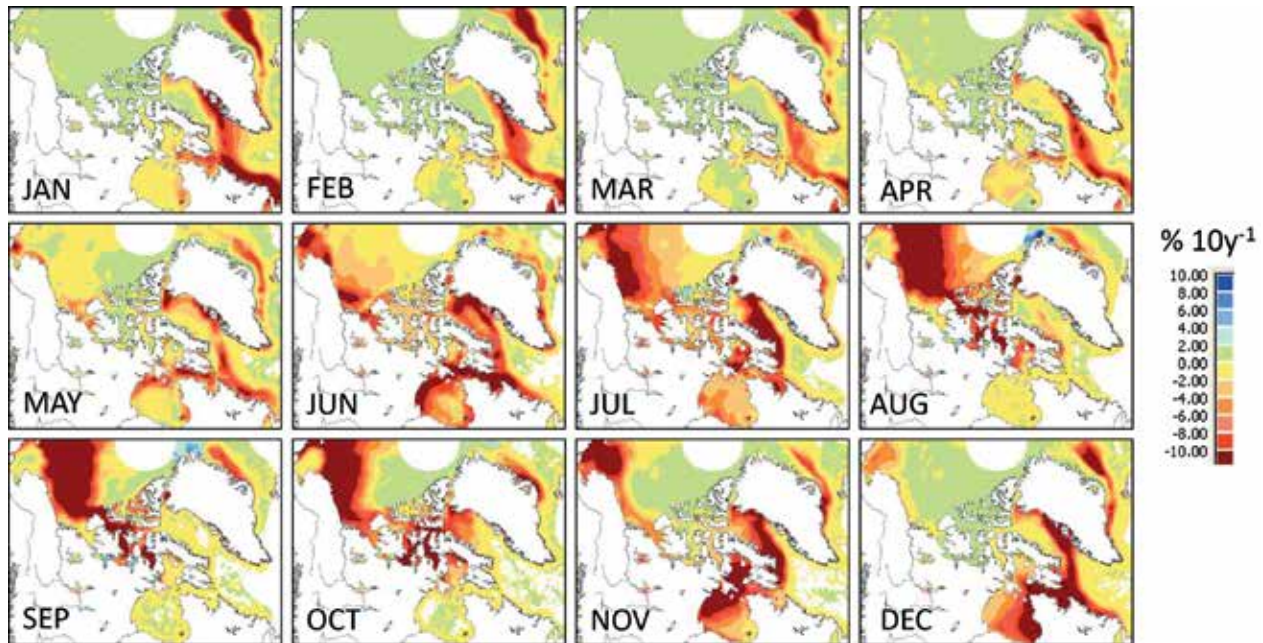


FIGURE 16. 1979-2012 trend (% per decade) in monthly average ice concentration (%) over the Canadian Arctic and adjacent waters based on the passive microwave satellite dataset of Cavalieri et al. (1996, updated to 2012). Reproduced from Rapaic et al. (2015).

ice total and MYI area in the Canadian Arctic (Howell et al. 2009, Tivy et al. 2011). These ice changes are reacting to (and providing positive feedbacks to) increasing surface air and sea-surface temperatures, and changes in atmospheric circulation (Overland et al. 2012, Sharp et al. 2014, Petrie et al. 2015) that are driving the rapid rates of climate change observed over the region in the past decade.

Documenting the climate of the landfast ice regime (e.g. thickness, freeze-up and break-up dates) is a challenge on a number of fronts: manual observations involve security risks to personnel, ice conditions can vary considerably over short distances, and landfast ice has a relatively small spatial footprint for satellite monitoring. Regular weekly measurements of ice thickness at coastal, river and lake sites close to communities were made at ~30 locations across the Canadian Arctic from the late-1950s to the mid-1990s (Canadian Ice Centre 1992a). The program was reinstated at 11 Arctic stations in the early-2000s with data archived at the CIS (formerly known as the Canadian Ice Centre until

the mid-1990s). The Canadian Ice Centre (1992a) published 1961-1990 period ice thickness climatologies for 135 stations in Canada including 11 stations located in the IRIS 2 region with more-or-less complete data in the 1961-1990 averaging period (Table A9). Corresponding information on ice cover state (freeze-up and break-up dates) for the 1961-1990 period was published by the Canadian Ice Centre (1992b) and is summarized in Table A10 for 8 sites in the region with 20 or more years of data in the 1961-1990 period. The 1961-1990 period was on average ~1 °C cooler than the recent 1984-2013 period. However, the CIS summaries still provide useful information on the variability in fastice conditions across the region as well as benchmarks for assessing change from other sources of ice cover information such as satellite data.

Analysis of the data presented in Table A9 shows that the thinnest ice in the region is observed at Cape Dorset in Hudson Strait (~1.4 m) with ice thickness increasing to over 2 m at Eureka. Latitude, longitude and the maximum on-ice

snow accumulation are able to explain over 75% of the spatial variation in maximum fastice thickness over the region. The role of snow at influencing fastice thickness (acts as an insulator to slow growth) was highlighted in Brown and Cote (1992). The average date of maximum ice thickness varies ~2 months over the region from mid-April at Cape Dorset, to mid-June at Alert and Resolute. The freeze-up/break-up summary (Table A10) shows a north-south gradient in the date of complete freeze over ranging from early September at Alert to mid-November at Iqaluit. The average date of water clear of ice varies more uniformly over the region (mid-July to early August). Ice is considered safe for traffic by observers' on average from approximately November to mid-June, with the largest variability where the ice may be considered unsafe during the spring period.

Trends in landfast ice are highly relevant to local communities as the coastal ice corridor has significant social, cultural, and economic importance. Analysis of U.S. National Ice Center weekly sea-ice charts from 1976 to 2007 by Yu et al. (2014) show that landfast ice extent around the Arctic Basin was relatively extensive from the early to mid-1980s but has since declined in many coastal regions of the Arctic, particularly after the early 1990s. Analysis of Canadian landfast ice conditions with CIS digital charts from 1983 to 2009 by Galley et al. (2012) showed significant decreases in landfast ice cover duration over the CAA from later freeze-up and/or earlier break-up. The study identified a number of Arctic communities where the landfast ice regime had undergone particularly large changes (Tuktoyaktuk, Kugluktuk, Cambridge Bay, Gjoa Haven, Arctic Bay, and Pond Inlet). Landfast sea-ice duration in the interior of the Northwest Passage was not observed to have undergone any statistically significant change over the period analyzed.

Ford et al. (2009) observed significant trends to later freeze-up over Turton Bay near Igloolik over the 1969-2006 with data from the CIS Digital Archive and local data collected by the Nunavut Research Institute (NRI) (1985-2006). The observed trends (both statistically significant at $p < 0.01$) were 7.0 days/decade for CIS and 8.3 days/decade for the NRI data. Laidler et al. (2009) documented a trend for

earlier ice break-up at Igloolik of 6.0 days/decade over the 1982-2005 period.

Analysis of weekly ice thickness data from six coastal communities in the region with long-term weekly ice thickness measurements from the late-1950s show maximum ice thicknesses experiencing a step decrease of ~20 cm after 2000 which represents about a 10% reduction in maximum thickness (Figure 17). The timing of the decrease matches the shift to lower sea-ice cover over the region seen in Figure 15. The regionally-averaged date of annual maximum ice thickness (not shown) advanced by ~3 weeks over the same period in response to earlier melt.

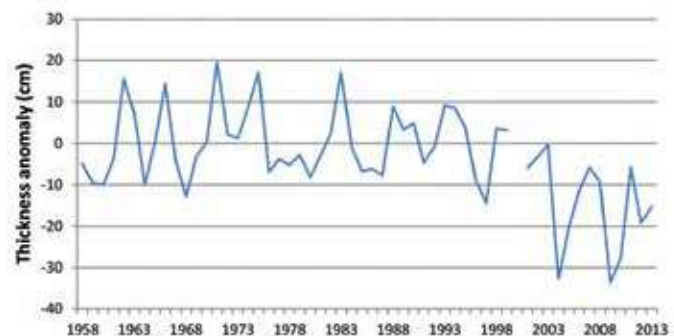


FIGURE 17. Regionally-averaged annual maximum ice thickness anomalies (with respect to the 1959-1987 average) from 6 stations in the region. Ice thickness data were obtained from the Canadian Ice Service.

Information on trends in lake and river ice cover is more difficult to obtain for the IRIS 2 region as there are few *in situ* records and satellite observations have various limitations related to resolution, frequency, consistency and length of coverage. Comprehensive assessments of Canadian *in situ* lake and river ice trends were provided by Lacroix et al. (2005) and Duguay et al. (2006) but with noticeably few observations over the region. Their results showed evidence of a widespread trend across the Canadian Arctic towards earlier breakup dates, with trends in freeze-up dates characterized by stronger regional variability. Improved spatial coverage over the Canadian Arctic was provided by Latifovic and Pouliot (2007) who

analyzed lake freeze-up/break-up trends over 1985-2004 from AVHRR satellite imagery. Their analysis included four lakes distributed across the region and showed evidence that these lakes were part of a consistent Canadian Arctic-wide trend to later freeze-up and earlier break-up. The average rates of change observed over the four lakes were 0.8 days/yr later freeze-up and 1.2 days/yr earlier break-up with Lake Hazen near Alert exhibiting the largest and the only statistically significant trends of the four lakes over the 20 year period.

Paquette (2015) provided evidence of recent significant changes at Ward Hunt Lake in northern Ellesmere Island from analysis of field records, aerial photographs, and satellite imagery. The records showed the summer perennial ice regime was relatively stable from 1953 to 2007 but experienced rapid thinning in 2008 and became ice free in 2011. Further evidence of rapid lake ice changes over the region was provided by Surdu (2015) who observed widespread decreases in lake ice cover over the CAA from analysis of RADARSAT data over the 1997-2011 period. There was also evidence that some lakes may be transitioning from perennial to seasonal ice regimes which has major consequences for freshwater ecosystems (Vincent et al. 2012).

2.7 Glaciers and ice caps

Glaciers are persistent masses of moving ice that develop when the annual snow accumulation exceeds the annual loss of mass by ablation over many years. They tend to be located in regions that are either cold or seasonally cold with high precipitation (e.g., mountains, maritime polar regions). Their response time to climate forcing depends on size and dynamics. For example small steep glaciers react quickly to changes (~1-2 years) while large cold ice caps and sheets have lags of centuries or more. Glaciers play important roles in global climate (e.g. albedo feedback, influences on atmospheric circulation and freshwater production) and sea level changes (Cazenave et al. 2009), and they can be locally important for freshwater supply. They can also release fine sediment, nutrients, organic matter and a range of contaminants into the broader environment.

In the region, glaciers are mostly found in the Queen Elizabeth Islands (QEI; Devon Island, Axel Heiberg Island and Ellesmere Island) and on Baffin and Bylot Islands (Figure 18). The Canadian Arctic contains the largest area of land ice (~150,000 km²) on Earth outside the ice sheets of Greenland and Antarctica, and recent estimates of mass loss make the CAA the single largest land ice contributor to sea-level rise outside Greenland and Antarctica (Gardner et al. 2011, Sharp et al. 2011, Gardner et al. 2013, Sharp et al. 2014, Way 2015). Glaciers of the region exist in low annual precipitation regimes (<400 mm.a⁻¹) with a high annual temperature range (difference between winter and summer temperature >40 °C) (Braithwaite 2005). The variability in mass balance in these environments is strongly controlled by variations in summer temperature and melt season duration (Sharp et al. 2011).

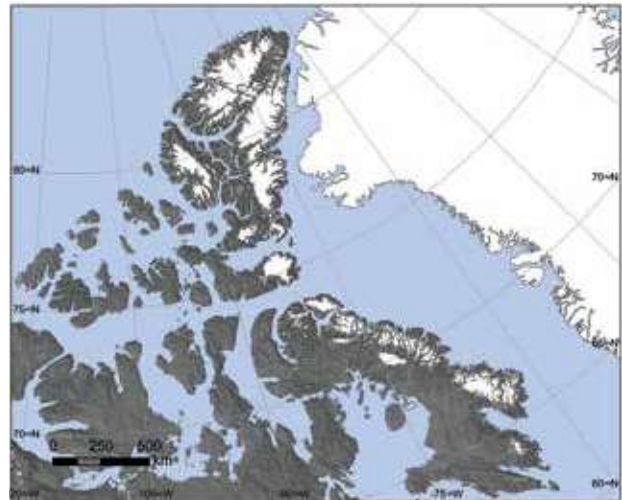


FIGURE 18. Land glaciers of the region. Land glaciers are derived from elevation data and correspond to data presented in Gardner et al. (2011).

Observations of glacier area, thickness, and mass since the late 1950s (including *in situ* measurements of glacier surface mass balance and satellite measurements of changes in the Earth's gravity field) show that the mass and area of land ice in the CAA have decreased over the past half century. This is a result of climate warming, which became more intense after 2007 as anticyclonic circulation became more frequent over the region in summer (Overland et al. 2012, Gascon et al. 2013, Bezeau et al. 2014, Sharp et al. 2014) (Figure 19). The observed glacier mass losses are dominated by melt/runoff with iceberg calving playing a

varying but apparently minor role (Williamson et al. 2008, Van Wychen et al. 2014). Attribution studies suggest that the signal of anthropogenic climate forcing (from land-use change, greenhouse gas emissions and anthropogenic aerosols) has been apparent (with high confidence) in the glacier mass balance records from the Queen Elizabeth Islands since ~1960 (Marzeion et al. 2014).

Zdanowicz et al. (2012) documented a post-1980 intensification of summer melt at Penny Ice Cap (the most southerly ice cap on Baffin Island) and concluded on the basis of the ice core record that the present ice cap thermal and mass balance state was probably unique in the past 3000 years or more. Fisher et al. (2012) found that ice core-derived melt series from the Canadian Arctic (latitude range of 67 to 81° N) show that the last quarter century has seen the highest melt in two millennia, while the Holocene-long melt record from Ellesmere Island's Agassiz Ice Cap shows the last 25 years had the highest melt rates in 4200 years. Melt rates on the Agassiz Ice Cap since the middle 1990s resemble those of the early Holocene thermal maximum over 9000 years ago - when incoming solar radiation was greater than it is today. Extensive ice bodies >6 m thick have formed in the near surface of the firn layer of the Devon Ice Cap as a result of the refreezing of percolating meltwater (Bezeau et al. 2013, Gascon et al. 2013). The upper part of the firn warmed by as much as 5.5 °C between 1971 and 2012 due primarily to latent heat release during freezing of percolating meltwater. Almost half of this warming occurred after 2004. See Chapter 3 for more on glaciers.

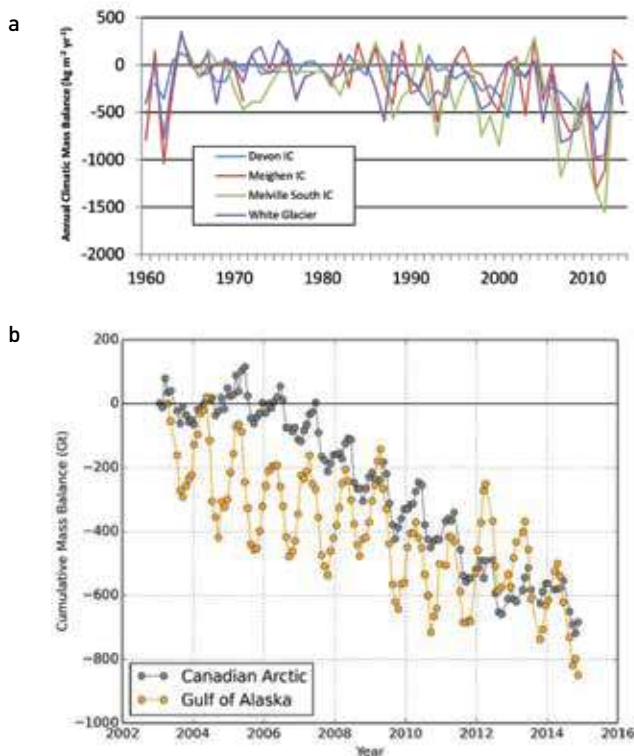


FIGURE 19. Observed trends in Arctic land ice mass balance. (a) Trend in annual surface mass balance for the Canadian Arctic reference mass balance glaciers (acknowledgements to R. Koerner, D. Burgess, P. Adams, G. Cogley and L. Copland for data collection)(Figure provided by M. Sharp). (b) Cumulative total mass balance (gigatonnes) of glaciers in the Canadian Arctic and the Gulf of Alaska region for 2003–15 from GRACE satellite gravimetry [Source: B.Wouters]. Reproduced from Sharp et al. (2015).

2.8 Cyclones, waves and coastal erosion

Knowledge of cyclone characteristics (frequency, location, intensity) and how they vary over time is important as they have significant impacts on coastal infrastructure through wind and wave loadings, coastal erosion, and storm surge (Melling et al. 2012, Perrie et al. 2012). Khon et al. (2014) anticipate an increase in significant wave height and their extremes over inner Arctic waters in the 21st Century in response to reduced sea-ice cover and regional wind intensification.

Cyclones are found all year round in the Arctic (Simmonds and Keay 2009) and the region is located in a zone of more frequent cyclones (Figure 20b) with preferred storm tracks over Hudson Bay to Foxe Basin, and up the east coast of Canada into Baffin Bay (Serreze and Barrett 2008). Cyclones arriving in the Canadian Archipelago tend to originate from northern Alaska and areas to the east of the Canadian Rockies (Sorteberg and Walsh 2008, Serreze and Barrett 2008) while cyclones affecting southern Baffin Island tend to originate from the Atlantic region (Savard et al. 2014). There are more cyclones in summer than winter (Figure 20a) and summer cyclones have longer durations. However, winter cyclones are generally more intense and their frequency is significantly correlated to the NAO (more storms in positive NAO years) (Wang et al. 2006).

There is a body of evidence indicating that significant changes have occurred in the cyclone climatology over the region. Over the 1953-2002 period Wang et al. (2006) found that cyclones in the lower part of the Canadian Arctic were more frequent, stronger and persistent. Over the Baffin Bay region for the 1948-2002 period Sepp and Jaagus (2010) showed significant increases in the frequency of cyclones crossing $\sim 70^\circ\text{N}$ and the number of cyclones forming in the bay. Possible mechanisms for these increases include more open water and increasing water temperatures (Forbes 2011) as well as decadal-scale cycles in cyclone activity (Wang et al. 2006). From these results one would anticipate an increase in wind speeds in the region as increased cyclone frequency should translate to more windy conditions. However, Wan et al. (2010) found evidence of significant decreases in mean near surface wind speeds over most of the Canadian Arctic and Baffin Island in all seasons of ~ 0.2 km/h/decade from homogenized anemometer records over the 1953-2006 period. This apparent discrepancy may be partly a sampling issue as the main storm tracks are located offshore.

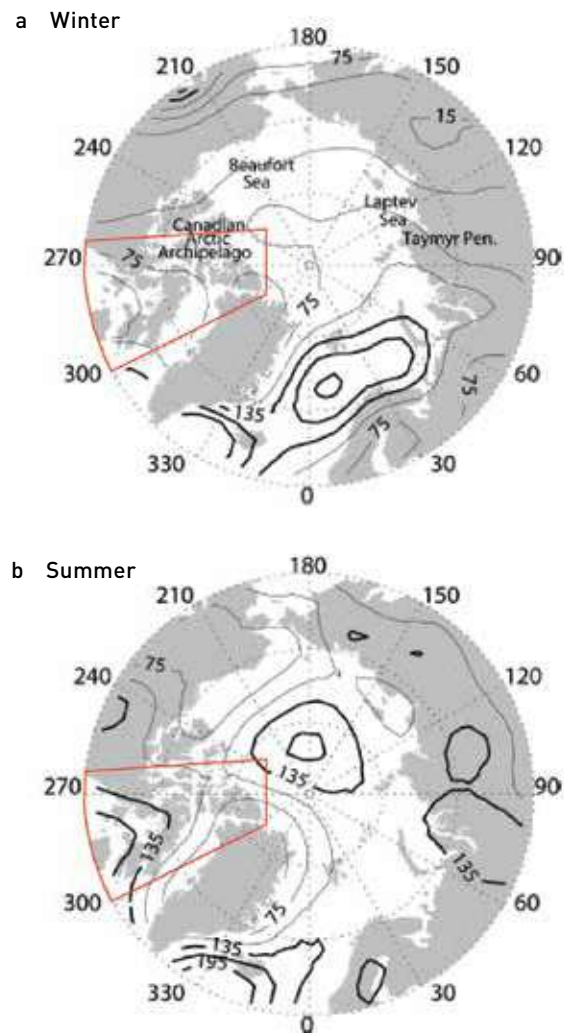


FIGURE 20. Counts of surface cyclones centers in the NCEP-1 reanalysis over equal area 250×250 km boxes for (a) winter (December, January, February (DJF)) and (b) summer (June, July, August (JJA)) totaled over the period of 1958-2005 for the region north of 60°N . The red frame box represents the approximate IRIS 2 region. Bold contours represent regions with at least 135 cyclone centres. Reproduced from Serreze and Barrett (2008).

Trends toward less sea ice and more frequent or more intense storms provide greater wave generating potential. When oriented toward the coasts waves can significantly impact shorelines through erosion, sediment transport and coastal flooding (Lantuit et al. 2011, Melling et al. 2012). Assessing the risk of increased coastal erosion and storm surge requires detailed site specific studies due to the strong fetch-dependencies involved (see recent study by Savard et al. (2014) for Nunavik coastal communities along the west coast of Hudson Bay) as well as information on local trends in relative sea level (e.g., Shaw et al. 1998).

Relatively few studies have been carried out on coastal erosion risk in the region. The northern shores of Ellesmere and Devon islands were both identified as stable or aggrading shores (Lantuit et al. 2011). In the Iqaluit area most of the shoreline was determined to be stable with only a few local areas subject to occasional wave action (Lewis and Miller 2010). Manson and Forbes (2008) studied the erosion potential at Hall Beach with data collected over the 2003 to 2008 period and concluded that strong winds coming from the southeast are subject to unrestricted fetch and have potential to impact some local areas of the coastline.

Smith et al. (2013) evaluated the sensitivity of the Canadian coastline to sea level rise following the method of Shaw et al. (1998) which takes into account a number of variables including relief, landform, rock type, sea level tendency, surficial material, tide range and wave height. Sensitivity was classified into 5 categories ranging from very low to very high. The results (Figure 21) show that coastline sensitivity to sea level rise for the Eastern Canadian Arctic is mostly low apart from Foxe Basin and some local areas along the east coasts of Baffin, Devon and Ellesmere Islands.



FIGURE 21. Estimated sensitivity of Canada's coastline to sea level rise based on the methodology of Shaw et al. (1998). The colours correspond to a 5-category severity index (SI) ranging from very low (green) to very high (red). Source: Smith et al. (2013).

2.9 Climate change projections for 2050

2.9.1 Atmospheric terrestrial projections

The climate change projections for the region were built by dynamically downscaling output from two Global Climate Models (GCMs) with spatial resolutions ~200-400 km to a much finer 45 km resolution with the Canadian Regional Climate Model (CRCM4) run at Ouranos (de Elía and Côté 2010, Paquin 2010, Music and Caya 2007). The projected change information for the 2050 time period was obtained by taking the difference between 30-year averages for the “future climate” (2041-2070) and the “reference climate” (1971-2000) assuming the SRES A2 scenario for future greenhouse gas emissions (Nakicenovic et al. 2000). A total of eight runs of CRCM 4.2.3 were used: five runs were driven by the Canadian Global Climate Model (CGCM3) (Scinocca et al. 2008, Flato and Boer 2001) and three runs driven by the ECHAM5 global model from the Max Planck Institute (Jungclaus et al. 2006). Because of the unequal number of CRCM runs using CGCM3 as pilot versus ECHAM5 the CGCM3 model runs were weighted 0.6 when computing the mean climate change projection of the ensemble. The standard deviation (STD) of the eight

runs was weighted in the same fashion. Scenarios for the marine environment were not generated at Ouranos and the reader is directed to the report of Steiner et al. (2013) for scenarios of projected changes in the marine and ocean environments (e.g., marine winds, waves, sea ice, ocean circulation).

The amplitude and annual cycle of the regionally-averaged projected change for 2 m air temperature and total precipitation are presented in Figure 22 while the spatial pattern of the projected changes in annual mean air temperature and total precipitation are summarized in Figure 23. Results for other variables and climate indicators are presented in Appendix A and are summarized in Table 1. The largest changes are projected to occur during the winter and fall seasons (~4-8 °C increase in air temperature and ~8-26% increase in precipitation). However, the spatial pattern of change is rather patchy over the region with evidence of some regional hot spots where changes are more pronounced (e.g., parts of the CAA and the Belcher Islands). A similar patchy response is seen in CORDEX CanRCM4 regional climate change projections over the region (not shown) and is linked to regional variations in the sea ice

response to warming. CanRCM4 was run at a higher resolution than CRCM4 (0.22 degrees) and was driven with CMIP5 output from the CanESM2 earth system model for the RCP4.5 and 8.5 emission scenarios (Scinocca et al. 2015). CanRCM4 RCP8.5 output gives projected increases in air temperature (3-7 °C) and precipitation (10-40%) over the region for 2050 that are similar to CRCM4.

The projected warming is associated with an earlier summer season onset (~7-15 days) and a later season end date (~5-16 days) extending the period with above-freezing temperatures by about 12 to 31 days. The snow cover season is reduced by about one month with the largest changes to the start date of snow cover. Projected increases in snowfall (15-35%) compensate for the shorter snow season with projected increases in maximum snow depths of ~5 cm over most of the region. However, snow accumulation in the fall and spring periods is projected to undergo large reductions from earlier melt and a later start to the snow season. Simulations from the higher resolution CanRCM4 model show that the largest decreases in snow cover are projected to occur in the coastal zone.

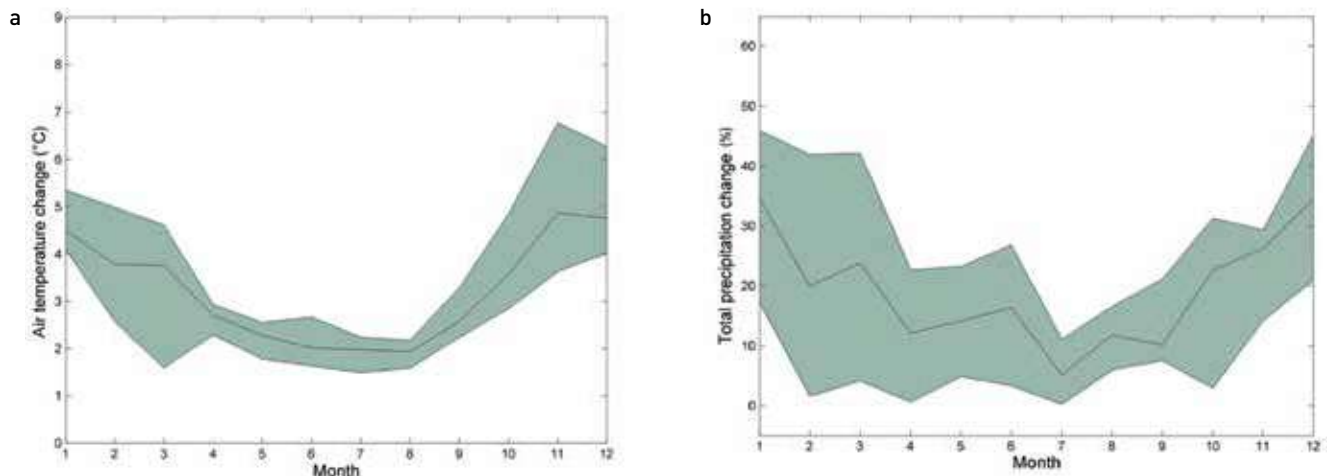


FIGURE 22. Seasonal median and range of projected changes in monthly mean air temperature (a) and total seasonal precipitation (b) from eight CRCM runs for 2050 averaged over all the grid cells of the region. The outer lines represent the range of the eight simulations.

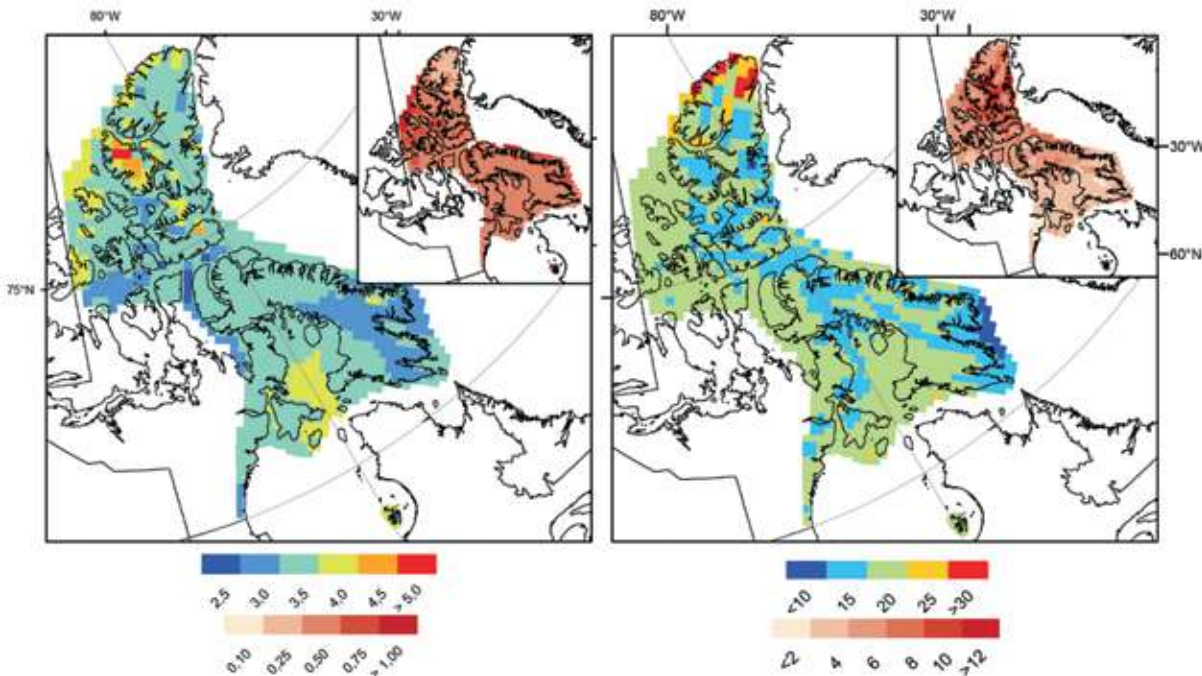


FIGURE 23. Ensemble average projected change in mean annual air temperature (left panel) (°C) and mean annual total precipitation (%) from eight CRCM runs for horizon 2050 (right panel). The inset maps show the standard deviation of the 8 runs.

2.9.2 Ice cover change projections

Climate models project a continuation of observed decreasing trends in Arctic sea-ice extent and thickness but with a large spread in the rate and timing of changes (Collins et al. 2013, Steiner et al. 2013, Semenov et al. 2015). Wang and Overland (2012) determined a model consensus for nearly ice-free Arctic summers by the 2030s using a sub-set of models that best represented the observed sea-ice regime and historical trends. Similar findings were obtained with the coupled atmosphere ocean regional climate model from the Rossby Centre (RCAO) forced by the RCP4.5 and 8.5 emission scenarios. Results showed an acceleration of decreasing sea-ice concentration through rapid ice loss events and a nearly summer ice-free Arctic Ocean by about 2040 (Paquin et al. 2013, Döscher and Koenigk 2013). Analysis of projected changes in seasonal ice concentration from 21 CMIP5 models (not shown) showed the largest decreases (20-40%) over the northern Baffin Bay area during the ice onset period (October to December).

Steiner et al. (2013) project ice thickness decreases of 10-15 cm/decade over the Baffin Bay marine area with 4-7 week reductions in the ice season by 2050.

Developing sea-ice change scenarios for coastal and inland waterways of the IRIS 2 region is complicated as most of the CMIP5 models do not resolve the CAA and the ice dynamics of the region that involves the import of MYI from the Arctic Ocean (Howell et al. 2008, 2009, 2013). Sea-ice change scenarios for the Canadian Arctic with a high resolution coupled ice-ocean model (Hu and Myers 2014) do not show completely ice-free summers in the CAA before 2100 in agreement with Sou and Flato (2009). The future response of MYI depends on factors in addition to temperature (Derksen et al. 2012) and is likely to remain a hazard for shipping for the foreseeable future. Coupled ice-ocean model simulations of the response of the Hudson Bay system to a climate-warming scenario (Joly et al. 2010) showed evidence of a number of regional “hot spots” such as the Hudson Strait-Foxe Basin region

TABLE 1. Summary of projected climate change over IRIS 2 region from eight CRCM runs for 2050 period. The range refers to the variation in the ensemble-averaged projected change across the region.

Climate variable	Projected change over region	Comments
Annual air temperature	+2 to +5 °C	No clear spatial pattern. Over land regions, change is projected to be more important over northern parts of IRIS 2 (Figure 1 Appendix C).
Seasonal air temperature	+1 to +8 °C	Changes are stronger in fall (OND) and winter (JFM). Changes over the southern part of IRIS 2 (Hudson Bay region) yield the highest values in the winter season.
Thawing degree days	0 to 350 DD	The strongest changes are projected over southern parts of the region (Belcher Islands, Kivalliq and Baffin Island). The lowest changes are projected over northern Ellesmere Island and coastal areas around Baffin Bay likely in response to the continued presence of sea ice over the summer season.
Growing degree days	0 to 210 DD	Same as Thawing DD
Summer onset date	7 to 15 days earlier	The largest changes are projected over northern parts of the region. Changes are not shown over grid points seen as land ice or semi-permanent snow in CRCM as the results are very noisy
Summer end date	5 to 16 days latter	Same as Summer onset date.
Summer duration	12 to 29 days longer	Same as Summer onset date.
Number of winter thaw (Nthaw) events	-0.6 to +1.9 events/year	The number of winter thaw events is projected to increase slightly over the IRIS 2 region with slight decreases shown over the southern part of Kivalliq and Baffin Island.
Total daily precipitation rate (rainfall + snowfall)	0 to 25%	Precipitation is projected to increase over most of the region by about 15-20% with the largest changes projected in the winter and fall.
Seasonal total precipitation rate (rainfall + snowfall)	0 to 53%	Change in total daily precipitation rate is most important during winter and fall. Changes are more pronounced in the northern part of Nunavut.
Annual total precipitation (rainfall + snowfall)	15 to 90 mm	Changes in absolute values are larger over southern regions e.g., southern Baffin shows projected changes ranging between 50 to 70 mm.
Rain-on-snow frequency (ROS days/yr)	-2.3 to 0.8 days/year	The projected changes are small and the spatial pattern noisy with only southern Baffin Island showing spatially coherent increases in ROS days.
Annual solid precipitation (snowfall)	13 to > 35 mm	Snowfall is projected to increase over the region with the largest increases over southern Baffin Island and the Belcher Islands.
Annual maximum snow depth on land and on islands	-3.1 to +7.5 cm	Maximum snow depths are projected to increase over southern Baffin Island with slight decrease in other regions.
Onset of snow season	4 to 24 days later	Snow cover onset is projected to start 4 to 18 days later over the region with the largest changes over more northern areas.
End of snow season	7 to 14 days earlier	The snow season is projected to end ~10 days earlier over most of the region.

that were particularly sensitive to warming. The ice regime in this region is more sensitive to warming due to the heat storage and water circulation characteristics of the Hudson Bay ocean system. Additional simulations from high resolution coupled ice-ocean models driven with a range of climate model output are needed to reach more robust conclusions about the projected rates of change in sea-ice cover for the region.

A variety of methods are used to generate scenarios of projected change in river and lake ice as these are typically not resolved in global climate models. Prowse et al. (2007) provided a first-order estimate of projected earlier river-ice break-up of 15-35 days over northern North America based on the average temperature sensitivity of break-up dates of 5 days/°C estimated by Magnuson et al. (2000) and projected increases of 3-7°C in spring air temperatures by the end of this century. Prowse et al. (2007) estimated a decrease in river-ice duration over most of Canada of ~20 days by 2050 based on projected changes in 0°C-crossing dates. More recent studies have applied lake ice models to estimate the response of lake ice freeze-up/break-up, ice thickness and the potential for white ice formation to changing temperature and precipitation (Dibike et al. 2011, 2012, Brown and Duguay 2011). The results from these studies project a 10-15 day earlier break-up over the IRIS 2 region and a 5-10 day later freeze-up for 2050. Ice thickness is projected to decrease by 10-30 cm with only small increases in the amount of white ice formation. These model simulations are based on an “idealized lake” of fixed depth. In reality, lake response will vary with lake morphology (size and depth) and with local factors affecting snow accumulation as shown by Brown and Duguay (2011).

2.9.3 Land ice change projections

The indications are that current trends in observed glacier and ice cap mass loss over the CAA will likely continue into the future as enhanced meltwater runoff is not sufficiently compensated by increased snowfall (Lenaerts et al. 2013). However, it should be stressed that there is considerable model variability in the sign, magnitude and timing of projected changes in snowfall and accumulated snow

mass over this region, and most climate models do not represent local moisture sources such as the NOW polynya that is an important contributor to the mass balance of the Manson and Prince of Wales Ice Caps (Boon et al. 2011). It should also be noted that Lenaerts et al. (2013) ran their mass balance model for a single modest emission scenario (RCP4.5). However, even with this modest scenario and a relatively conservative modelling scheme they conclude that it is highly unlikely that CAA glacier mass loss will reverse in the coming century, and that projected mass loss is irreversible in the foreseeable future.

Another study (Radic et al. 2013) makes global and regional projections of glacier mass changes in the 21st century. It used downscaled output from 14 different global climate models (monthly values of air temperature at 2 m and precipitation) considering two different emissions scenarios (RCP4.5 and RCP8.5) to force a glacier mass balance model. The model takes into account the changes in glacier extent that accompany reductions in glacier mass and volume, and is thus able to simulate the feedback between surface mass balance and changes in the altitudinal distribution of glacier surface area. For the period 2006-2100, this study predicts reductions in glacier volume of 10-60% in the Queen Elizabeth Islands, and 20-100% in the Baffin/Bylot region. These projections amount to a contribution to global sea level rise of between 22 and 75 mm. The glaciers of the Queen Elizabeth Islands have a relatively low sensitivity to the first 2 K of climate warming, but the sensitivity increases as warming increases beyond that point. Relative to other areas of the planet, Arctic Canada has a relatively low sensitivity of mass balance to climate warming, but this is compensated for by the relatively high magnitude of the projected temperature increases in the region.

A related study using the same global climate models forced by RCP4.5 (Bliss et al. 2014) considers the impact of these changes on glacier contributions to regional runoff. Glacier wastage contributes between 67 and 81% of glacier runoff from the Queen Elizabeth Islands throughout the 21st century, while melt of the seasonal snowpack on the glaciers accounts for a further 16-34%. However, the proportion of glaciers from which runoff is increasing

over time drops from 74.9% in the period 2003-2022 to only 1.6% in the period 2080-2099. This reflects the rapid shrinkage and eventual disappearance of relatively small glaciers located at low elevations. The fraction of surface melt that is retained within the glaciers by refreezing in snow and firn tends to decrease over time as the firn warms up under the combined forcing from atmospheric warming and the latent heat released during re-freezing.

For the Baffin/Bylot region, glacier wastage accounts for about 60% of glacier runoff throughout the 21st century, while seasonal snow melt accounts for 30-40%, and rainfall around 13%. The fraction of glaciers with increasing runoff trends is around 47% from 2003-2022, and decreases to only 5.7% by 2080-2099. Thus while the trend towards decreasing runoff volumes starts earlier in this region than it does further north, the trend itself is more gradual in this higher precipitation region.

2.9.4 Projected changes in cyclones

Analysis of projected changes in storm characteristics is challenging as the climate change signals tends to be weak (Lang and Waugh 2011) and vary significantly between climate models. Finnis et al. (2007) investigated projected changes in cyclonic activity in output from the third generation Community Climate System Model (CCSM3) for the end of the 21st Century (future 2080-2099; reference 1980-1999) run under the SRES-A1B emission scenario. The results showed a weak but significant trend toward increasing cyclonic frequency over the Arctic region for the September-May period. A more recent study by Zappa et al. (2013) used output from 37 CMIP5 GCMs for the RCP4.5 and RCP8.5 emission scenarios for the end of the century (future 2070-2099; reference 1976-2005). Results for winter (DJF) showed no changes in the number of cyclones and wind intensity in most of IRIS 2 the region with the exception of southern Baffin Island and Hudson Strait where a slight decrease is noticed. The summer (JJA) results showed increases in cyclone numbers and cyclone associated precipitation over the northern part of the region (north of Baffin and Devon Island). These results are consistent with Lambert (2004) who showed decreasing cyclone frequency

in winter time for about the same future and reference periods. Steiner et al. (2013) investigated projected changes in wind speed over the Canadian Arctic and concluded that long-term trends were close to zero.

Scenarios of changes in wind and wave conditions in the shore zone for applications such as coastal erosion and flooding (e.g., Savard et al. 2014) require detailed site-specific information that takes account of varying ocean fetch length (the horizontal distance over which wave-generating winds blow) with direction and ice conditions. The study by Savard et al. (2014) for coastal communities in Nunavik used a hydrodynamic model driven with output from regional climate model simulations for the SRES A2 emission scenario to investigate the impact of climate change on waves and storm surge. The study showed that conditions favourable to storm surges increase in a warmer climate due to a shorter ice season and an extension of the period in autumn when more intense storms affect the region. The longer open water season also contributed to an intensification of cyclones and a longer residence time of storms over Hudson Bay. The net effect of these processes resulted in a projected 15-20% increase in the number of cyclones with storm surge potential affecting communities along the east coast of Hudson Bay. This result underscores the importance of understanding and taking into account regional dynamic air-sea-ice interactions in developing future climate scenarios in coastal environments.

2.10 Summary and conclusions

Because of its geographical position, latitudinal range and topography, the Canadian Eastern Arctic experiences some of the largest climatic gradients and climate variability in the Canadian Arctic. The large areas of water in the region (Hudson Bay, Foxe Basin, Davis Strait, and Baffin Bay) also mean that the oceans and sea ice play a strong role in the climate of the region and its response to climate warming. The Canadian Eastern Arctic is currently experiencing the most rapid warming anywhere in Canada during the autumn and early winter period. According to available air temperature data sources, this rapid warming is most evident in the period since the early 1990s, and is linked to

both natural and anthropogenic factors with several anomalously warm years being primarily linked to anomalies in the AO and North Atlantic sea surface temperatures (Way and Viau 2014).

The rapid rate of warming and reductions in snow and ice cover experienced over the Eastern Canadian Arctic over a relatively short period of time echoes the findings of Derksen et al. (2012) that the pace of change over the Canadian Arctic is increasing. Analysis of temperature trends (Rapaic et al. 2015) shows that the recent warming is concentrated over the Eastern Canadian Arctic with a number of “hot spots” showing much faster rates of warming linked to the regional sea-ice regime. Recent studies have demonstrated an important positive feedback of declining sea-ice extent over the Canadian Eastern Arctic region involving the development of positive anticyclonic anomalies in the summer atmospheric circulation that promote enhanced melt. This feedback mechanism is only weakly captured in climate models and is additional evidence that current climate models are likely underestimating the rate of the climate and cryosphere response of the Arctic to global warming.

Cryospheric indicators of change over the region such as snow, ice cover and glacier mass balance show evidence of longer-term decreases that are not consistent with longer-term trends in regional air temperature. This mismatch may be potentially related to the fact that the cryosphere responds to other environmental drivers than air temperature (e.g. incoming longwave radiation). Understanding how all the pieces of the climate puzzle fit together is a challenge especially when confronted with evidence that the consistency between climate and reanalysis datasets has decreased markedly over northern Canada over the last decade (Rapaic et al. 2015). Evaluating climate models in this environment is also a challenge when the differences between observational datasets can be as large as or larger than the differences between climate models.

Climate change projections for the region indicate that current warming trends and shortening of the snow and ice seasons will continue in response to projected warming

of ~4–8°C in air temperature by 2050, with some regions likely to exhibit more rapid changes than others e.g., land areas adjacent to Foxe Basin. The climate drivers of warming and increased precipitation generate widespread changes and feedbacks in snow and ice cover, land cover (e.g. Arctic greening), terrestrial hydrology, oceanic and sea-ice dynamics that impact ecosystem services in various ways, some positive, some negative. Developing successful adaptation strategies is essential to meet these new challenges and central to this is the need to ensure that Arctic regions have access to reliable and authoritative information on observed and projected rates of change in key environmental indicators relevant to northern livelihoods.

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Appendix A

TABLE A1. Inventory of climate stations in the 2013 updates of the AHCCD datasets of Vincent et al. (2012) and Mekis and Vincent (2011) located in the IRIS 2 region with surface air temperature (SAT) and precipitation data (PCP) in the period 1950-2013. The start/end years are the first/last annual SAT and PCP values in the 1950-2013 period. The % complete is the number of non-missing annual values in the 1950-2013 period prior to gap-filling. Only the 10 PCP stations indicated in bold had sufficient data for regional averaging and trend analysis.

Station Name	Lat. (°N)	Lon. (°W)	Elevation above mean sea level (m)	SAT Start/End Year	SAT % complete 1950-2013	PCP Start/End Year	PCP % complete 1950-2013
Alert	82.50	-62.33	65	1952-2011	46.9	1951-2013	96.9
Arctic Bay	72.98	-84.62	642	1950-2005	43.8		
Broughton Island	67.53	-63.78	584	1959-2013	36.0		
Cape Dorset	64.20	-76.50	48	1950-2011	70.3	1950-2005	67.2
Cape Dyer	66.65	-61.38	393	1960-2013	43.8	1960-1992	50.0
Cape Hooper	68.47	-66.82	390	1961-2013	31.3	1959-1990	48.3
Chesterfield Inlet	63.33	-90.73	10	1950-2003	28.1	1950-2005	75.0
Clyde	70.48	-68.52	27	1950-2012	71.9	1950-1998	71.9
Coral Harbour	64.20	-83.37	64	1951-2013	89.1	1951-2012	93.8
Dewar Lakes	68.65	-71.17	527	1961-2013	31.3	1959-1992	51.6
Eureka	79.98	-85.93	10	1951-2011	46.9	1950-2013	98.4
Fox Five	67.53	-63.78	584			1961-1990	46.9
Hall Beach	68.78	-81.25	8	1959-2011	75.0	1958-2009	76.6
Iqaluit	63.75	-68.55	34	1951-2013	85.9	1950-2006	57.8
Longstaff Bluff	68.90	-75.13	161	1960-2008	29.7	1959-1990	50.0
Mackar Inlet	68.30	-85.68	395			1959-1991	51.6
Nanisivik	73.0	-84.63	642			1950-2006	57.8
Pelly Bay	68.53	-89.80	16	1961-2010	51.6		
Pond Inlet	72.70	-77.97	55	1958-2012	56.3		
Resolute	74.72	-94.98	68	1950-2013	90.6	1950-2012	98.4

TABLE A2. Air temperature climatologies for the 1981-2010 period from stations in the region with 15 years or more of complete data in the AHCCD dataset of Vincent et al. (2012). Daily gap- filled data were used to compute statistics.

Station	Annual mean SAT (°C)	Monthly mean of daily min SAT (°C)	Monthly mean of daily max SAT (°C)	Annual mean Freezing Degree-Days	Annual mean Thawing Degree-Days	Mean Thaw-onset date	Mean Freeze-onset date
Alert	-17.4	-34.3	3.6	-6538.5	207.7	Jun-16	Aug-21
Arctic Bay	-14.4	-31.6	5.7	-5551.5	337.2	Jun-13	Aug-25
Broughton	-11.0	-27.7	5.9	-4383.2	406.7	Jun-11	Sep-07
Cape Dorset	-8.4	-25.9	8.1	-3647.9	606.0	Jun-02	Sep-24
Cape Dyer	-10.7	-27.9	6.4	-4302.1	432.0	Jun-10	Sep-11
Cape Hooper	-11.3	-28.3	5.7	-4489.6	379.6	Jun-12	Sep-07
Chesterfield Inlet	-10.2	-31.4	10.2	-4529.2	828.3	May-31	Sep-28
Clyde	-12.5	-31.5	5.3	-4935.6	387.5	Jun-10	Sep-18
Coral Harbour	-10.6	-31.0	10.1	-4587.8	744.3	Jun-03	Sep-22
Dewar Lakes	-12.5	-30.3	7.0	-4941.6	424.0	Jun-13	Sep-07
Eureka	-18.7	-39.4	6.1	-7209.8	400.1	Jun-05	Aug-29
Hall Beach	-13.2	-33.7	7.0	-5233.2	464.4	Jun-10	Sep-18
Iqaluit	-8.8	-28.6	8.7	-3916.2	729.9	May-26	Sep-30
Longstaff Bluff	-12.0	-31.2	8.0	-4880.3	528.7	Jun-08	Sep-15
Pelly Bay	-13.3	-34.5	9.4	-5470.4	644.0	Jun-06	Sep-17
Pond Inlet	-14.1	-34.7	6.8	-5612.5	489.8	Jun-04	Sep-12
Resolute	-15.5	-33.6	4.6	-5896.1	269.8	Jun-12	Aug-27

TABLE A3. Linear trend in SAT indicator series over the 1950-2013 period for stations in Table 1. Trends are given per decade with statistically significant trends (0.05 level) indicated with an asterisk. The sum of freezing and thawing degree-days (FDD and TDD) represent respectively the cumulative sum of daily temperatures below 0°C and above 0°C. The 17-station regional average trend results are computed from regionally averaged station anomalies.

Station	Annual mean SAT (°C/10y)	Monthly mean of daily min SAT (°C/10y)	Monthly mean of daily max SAT (°C/10y)	FDD (sum/10y)	TDD (sum/10y)	Thaw-onset date (days/10y)	Freeze-onset date (days/10y)
Alert	0.27*	0.28	-0.01	94.3*	2.2	-0.47	0.10
Arctic Bay	0.31*	0.60*	0.38*	91.3*	22.0*	-0.62	-0.97
Broughton	0.21*	0.63*	0.06	71.5*	4.1	-0.80	-0.57
Cape Dorset	0.18	0.35	0.46*	34.4	31.7*	-0.22	0.14
Cape Dyer	0.07	0.55*	-0.05	29.6	-5.1	0.01	-1.25
Cape Hooper	0.19*	0.53*	0.04	66.6*	2.9	-0.29	0.65
Chesterfield Inlet	0.45*	0.89*	0.24*	135.0*	27.7*	-1.30*	0.38
Clyde	0.33*	0.66*	0.22*	96.2*	23.8*	-1.13*	1.89*
Coral Harbour	0.30*	0.48*	0.40*	79.6*	28.5*	-0.88	0.90*
Dewar Lakes	0.11	0.42*	0.20	32.6	6.4	0.20	-0.68
Eureka	0.29*	0.14	0.28*	91.3*	15.8*	-0.67	0.29
Hall Beach	0.12	0.15	0.21*	33.7	8.2	-0.09	0.48
Iqaluit	0.19	0.24	0.19*	54.1	16.7*	0.02	1.35*
Longstaff Bluff	0.14	0.36	0.19	43.3	8.4	-0.35	-0.03
Pelly Bay	0.13	0.11	0.51*	15.0	31.4*	-0.53	0.98*
Pond Inlet	0.23*	-0.02	0.47*	46.6	37.8*	-1.63*	0.70
Resolute	0.36*	0.48*	0.16	121.4*	9.6	-0.87	-0.43
17-stn regional average trend	0.27*	0.40*	0.28*	66.3*	16.0*	-0.55	0.23

TABLE A4. Same as Table A3 for 1984-2013.

Station	Annual mean SAT (°C/10y)	Monthly mean of daily min SAT (°C/10y)	Monthly mean of daily max SAT (°C/10y)	FDD (sum/10y)	TDD (sum/10y)	Thaw-onset date (days/10y)	Freeze-onset date (days/10y)
Alert	0.83*	0.85	0.12	287.7	17.0	-0.72	-0.61
Arctic Bay	1.07*	0.63	0.76	313.8	79.7	-1.53	7.34*
Broughton	1.16*	1.96*	0.45	379.6	42.5	-4.50*	0.17
Cape Dorset	0.74*	0.78	0.75*	204.6	67.5	-1.96	1.67
Cape Dyer	0.54*	0.88	0.21	169.4	26.9	-1.68	-0.55
Cape Hooper	1.03*	1.80*	0.15	356.2	18.1	-1.90	2.96
Chesterfield Inlet	1.11*	1.79*	0.06	367.4	37.1	-0.95	2.17
Clyde	1.03*	1.81*	0.47*	330.1	43.8	-2.01	1.50
Coral Harbour	0.95*	1.13*	0.57*	290.6	54.7	-2.06	1.69
Dewar Lakes	0.94*	1.38*	0.28	305.8	36.8	-0.23	0.61
Eureka	1.02*	1.47*	0.69*	315.9	57.3	-1.27	2.12
Hall Beach	1.02*	1.30*	0.18	355.2	15.4	0.23	0.63
Iqaluit	1.09*	1.56*	0.32	352.0	43.9	-3.17	3.49*
Longstaff Bluff	0.86*	1.22*	-0.03	302.1	12.1	0.65	0.93
Pelly Bay	1.01*	1.77*	0.18	351.4	16.8	0.43	1.28
Pond Inlet	0.90*	1.02*	0.45	282.2	47.1	-0.58	1.05
Resolute	1.03*	0.95*	0.58	325.0	53.3	-0.25	2.30
17-stn regional average trend	0.97*	1.12*	0.47*	311.1*	39.4*	-1.26	1.69

TABLE A5. Annual total precipitation climatologies for the 1981-2010 period from stations in the region with 15 years or more of complete data in the adjusted precipitation dataset of Mekis and Vincent (2011). The units are mm for rainfall and mm of water equivalent (mmWE) for snowfall.

Station	Lat. (°N)	Long. (°W)	Elev. (m)	Annual total rainfall (mm)	Annual total snowfall (mmWE)	Annual average number of Trace snowfall amounts
Alert	82.5	-62.3	65	23.1	221.3	108.8
Cape Dorset	64.2	-76.5	50	170.5	418.2	69.6
Chesterfield Inlet	63.3	-90.7	10	165.6	194.5	51.1
Clyde	70.5	-68.5	27	75.3	274.5	114.6
Coral Harbour	64.2	-83.4	64	183.6	233.9	122.7
Eureka	80.0	-85.9	10	39.5	89.5	172.4
Hall Beach	68.8	-81.2	8	111.1	211.9	129.2
Iqaluit	63.7	-68.5	34	212.1	300.8	102.9
Nanisivik	73.0	-84.6	642	87.5	297.1	73.3
Resolute	74.7	-95.0	67	75.3	179.9	172.4

TABLE A6. Linear trends in annual total precipitation over 1950-2013 and 1984-2013 for stations in Table A5 with at least 40 and 20 years of data in each respective period. Trends are given per decade with statistically significant trends (0.05 level) indicated with an asterisk. The 10-station regional average trend is computed from the regionally-averaged station anomalies. Note that Nanisivik did not have sufficient data to compute trends in either period but was included in the regional average.

Station	1950-2013 Trend		1984-2013 trend	
	Annual total rainfall (mm/10y)	Annual total snowfall (mmWE/10y)	Annual total rainfall (mm/10y)	Annual total snowfall (mmWE/10y)
Alert	-0.5	11.9*	0.1	10.2
Cape Dorset	2.8	53.8* ^a	-	-
Chesterfield Inlet	1.1	2.9	-	-
Clyde	0.8	13.7	-	-
Coral Harbour	9.6*	8.5*	15.0	7.0
Eureka	2.2	7.6*	5.6	5.2
Hall Beach	0.2	13.7*	0.0	52.0*
Iqaluit	-0.1	-13.1	-	-
Resolute	1.9	9.5*	9.0	-17.6
10-stn regional average trend	3.2*	14.2*	5.8	8.0

^a This value is probably unrealistic as there is evidence of a pronounced shift to higher snowfall amounts in the data after the station moved in 1977. There was no evidence of obvious discontinuities at Hall Beach.

TABLE A7. Snow cover climatology for stations in or adjacent to the region with at least 15 years of complete daily snow depth data in the 1981-2010 period. Data are from Brown and Braaten (1998) updated with daily snow depth data from the Environment Canada Digital Climate Archive.

Name	Lat (°N)	Long (°W)	Start date of continuous snow cover*	End date of continuous snow cover*	# days with snow cover [^]	Annual maximum snow depth (cm)	Date of annual max snow depth
Alert	82.5	-62.3	Sep-08	Jun-30	298.6	48.7	Apr-11
Arctic Bay	73.0	-84.6	Sep-13	Jun-22	282.3	39.4	Mar-28
Cape Dorset	64.2	-76.5	Oct-09	Jun-19	254.7	69.2	Apr-30
Chesterfield Inlet	63.3	-90.7	Oct-29	Jun-04	219.5	n/a	n/a
Clyde	70.5	-68.5	Sep-28	Jun-25	272.3	57.5	Apr-29
Coral Harbour	64.2	-83.4	Oct-13	Jun-16	247.8	46.8	Mar-29
Eureka	80.0	-85.9	Sep-23	Jun-09	263.3	20.3	Mar-26
Hall Beach	68.8	-81.2	Oct-07	Jun-24	261.9	51.8	Apr-20
Igloolik	69.4	-81.8	Oct-06	Jun-12	251.5	40.1	Apr-20
Iqaluit	63.7	-68.5	Oct-15	Jun-08	241.4	44.4	Mar-21
Pelly Bay	68.5	-89.8	Oct-07	Jun-13	250.7	71.3	Apr-20
Pond Inlet	72.7	-78.0	Sep-27	Jun-06	253.0	34.6	Feb-02
Rankin Inlet	62.8	-92.1	Oct-21	Jun-07	229.2	46.6	Apr-11
Resolute	74.7	-95.0	Sep-16	Jun-22	280.6	30.9	Mar-12
Taloyoak	69.6	-93.6	Oct-04	Jun-19	259.3	33.7	Apr-26
Whale Cove	62.2	-92.6	Nov-04	Jun-02	211.9	n/a	n/a

* Defined as the first (last) date in the year with 14 consecutive days of snow depths \geq 2 cm

[^] Day with \geq 2 cm snow on ground

TABLE A8. Linear trend in snow cover over 1950/51-2011/12 snow seasons for stations in or adjacent to the region with at least 36 years of data in the period. For dates, a negative (positive) trend corresponds to earlier (later) dates. The regional average trend is computed from station anomalies.

Station	Start date of continuous snow cover (days/decade)	End date of continuous snow cover (days/decade)	Annual # days with snow cover (days/decade)	Annual maximum snow depth (cm/decade)	Date of annual max snow depth (days/decade)
Alert	2.9*	0.1	-3.2*	-0.8	0.6
Clyde	4.9*	3.2	-4.2	-3.6	-0.2
Coral Harbour	3.3*	-1.5*	-4.7*	-4.5*	-6.0
Eureka	2.1	-2.3*	-3.8*	-0.1	-13.4*
Hall Beach	2.8*	-1.3	-3.9*	0.5	0.4
Iqaluit	3.1*	0.5	-1.0	-3.8	2.6
Resolute	1.0	-1.9*	-3.5*	-1.3	-18.7*
15-station regional avg trend	2.5*	-0.7	-3.3*	-1.3*	-6.0*

TABLE A9. Average ice thickness values published by the Canadian Ice Centre (1992a) for stations in the region with 20 or more years of data in the 1961-1990 averaging period. Freshwater sites are indicated with an asterisk.

Station (water body if different from station name)	Approx. coordinates Lat.(° N), Long.(° W)	Avg Max Ice Thickness (cm)	Avg date (week) of Max Ice Thickness	Avg Max On-ice Snow Depth (cm)
Alert (Parr Inlet)	82.50, -62.33	205.5	Jun 11-17	34.8
Alert (Dumbell Lake)*	82.50, -62.33	204.8	Jun 4-10	40.9
Eureka (Slidre Fiord)	79.98, -85.93	233.1	Jun 4-10	28.2
Resolute (Resolute Bay)	74.72, -94.98	194.7	Jun 11-17	49.5
Pond Inlet ^a	72.70, -77.97	161.3	May 28 – Jun 3	23.3
Clyde (Patricia Bay)	70.48, -68.52	160.6	May 21-27	33.6
Hall Beach (Foxye Basin)	68.78, -81.25	194.6	Apr 16-22	29.9
Cape Dorset (Hudson Strait)	64.20, -76.50	136.8	Apr 30 – May 6	39.6
Coral Harbour	64.20, -83.37	171.5	May 14-20	29.7
Iqaluit (Koojesee Inlet)	63.75, -68.55	163.1	May 21-27	20.6
Chesterfield Inlet (Spurrel Inlet)	63.33, -90.73	186.9	Apr 30 – May 6	12.9

^a Pond Inlet average maximum ice thickness is about 35 cm thinner than expected based on the observed relationship between maximum ice thickness, latitude, longitude and maximum snow depth for these stations. According to notes in the station history file this may be related to the measurement site being located for some period near the outflow pipe carrying waste water from the community (R. Brown).

TABLE A10. Average freeze-up/break-up values for sites in the region published by the Canadian Ice Centre (1992b) with 20 or more years of data in the 1961-1990 period. Freshwater sites are indicated with an asterisk.

Station	Average date of complete freeze over	Average period of ice safe for traffic	Average date of first deterioration of ice	Average date of water clear of ice
Alert (Parr Inlet)	Sep 07	Oct 20 – Jun 16	Jun 22	Jul 30
Alert (Dumbell Lake)*	Sep 09	Oct 22 – Jun 15	Jun 24	Infrequent clearing
Eureka (Slidre Fiord)	Dec 08	Oct 10 – May 29	Jun 12	Jul 30
Resolute (Resolute Bay)	Oct 02	Oct 03 – Jun 09	Jun 24	Aug 04
Clyde (Patricia Bay)	Nov 06	Nov 05 – Jun 04	Jun 17	Aug 05
Hall Beach (Foxye Basin)	Oct 31	Nov 02 – Jun 30	Jun 18	Jul 18
Coral Harbour	Nov 05	Nov 07 – Jun 10	Jun 19	Jul 14
Iqaluit (Koojesee Inlet)	Nov 15	Nov 18 – Jul 03	Jun 10	Jul 17



Chapter 3 Glaciers, Ice Shelves and Ice Islands

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Key messages

- Glacier and ice cap mass losses are accelerating across the Eastern Canadian Arctic, with losses over the past decade at least double that of previous decades.
- Most glacier and ice cap mass losses can be attributed to increasing summer air temperatures.
- Canadian Arctic ice shelves have decreased in area by approximately half over the past decade.
- Ice shelves and floating glacier tongues are producing large ice islands and icebergs that can provide significant hazards to offshore oil exploration and shipping companies.
- It is likely that all Arctic ice shelves will be lost by the 2040s or earlier.
- Continued losses for glaciers and ice caps are highly likely for the remainder of the 21st century, resulting in the complete disappearance of many small ice masses.
- Loss of all of these ice features will result in loss of biodiversity, and the complete extinction of globally unique ecosystems that depend on ice shelf, glacial ice and ice cap integrity.

Abstract

The Eastern Canadian Arctic contains over a third of the world's Arctic glaciers and ice caps, and the last remaining ice shelves in the Northern Hemisphere. These components of the cryosphere provide an important part of the landscape diversity of Nunavut, act as important sentinels of climate change, and provide unique habitats for life living under extreme conditions. Glaciers and ice caps have been losing significant mass in recent decades, with current melt rates at their highest for at least the past 3000 years. Recent glacier mass loss rates in the northern Canadian Arctic Archipelago (CAA) have been five times greater than the 1963-2004 average, while mass loss rates in the southern CAA were more than twice as high in 2003-2011 compared to 1963-2006. These mass losses have been linked to increasing summer air temperatures, and suggest that glaciers and ice caps in the Eastern Canadian Arctic are far out of equilibrium with current climate. On northern Ellesmere Island, the number of ice shelves has halved since 2005, with their area decreasing from >1000 km² in 2005 to ~500 km² today. These losses are expected to continue in the future, making it likely that all ice shelves will disappear in the next few decades. When ice shelves and floating glacier tongues break up they produce icebergs and ice islands, which can be significant hazards to marine navigation and offshore oil and gas exploration. Ice islands in Baffin Bay typically originate from the breakup of floating glacier tongues in northwest Greenland, while those in the interior islands of the CAA and Beaufort Sea typically originate from the breakup of ice shelves on northern Ellesmere Island.

3.1 Introduction

Glaciers and ice caps in the Eastern Canadian Arctic comprise over a third of the ~400 000 km² terrestrial ice cover in the Arctic outside of the Greenland Ice Sheet, with ~42 000 km² in the southern Canadian Arctic Archipelago (CAA) (Baffin and Bylot Islands) and ~104 000 km² in the northern CAA (Queen Elizabeth Islands, consisting of primarily Axel Heiberg, Coburg, Devon, Ellesmere, Meighen and Melville islands) (Figure 1; Sharp et al. 2014). Ice masses are primarily concentrated along coastlines adjacent to moisture sources, of which Baffin Bay is the primary source and the Arctic Ocean a secondary source (Koerner 1979). Most ice caps range in elevation from 0 to ~2000 m above sea level, and flow slowly (<15 m a⁻¹) in their interior regions where the ice is frozen to the bed (Van Wychen et al. 2014). In areas where the ice becomes confined in valleys it forms outlet glaciers which have unfrozen beds and flow towards the ocean at average speeds of ~20-200 m a⁻¹, although speeds can reach >1 km a⁻¹ for the very largest glaciers and during surges (Van Wychen et al. 2014, 2016). On average, glacier speeds are higher in the northern CAA than the southern CAA, due to the larger sizes of glaciers in the north and the tendency for more of them to reach the ocean. Where glaciers reach the ocean they are called tidewater glaciers, and they typically produce icebergs. In the Canadian Arctic, ~98% of icebergs originate from the northern CAA and ~2% from the southern CAA (Van Wychen et al. 2015).

In the coldest, northernmost parts of the Canadian Arctic, some glaciers do not produce icebergs when they reach the ocean, but instead become preserved in fiords due to the protection provided by surrounding topography and/or sea ice. Over time, this glacier ice can fill the near-surface of fiords to produce ice shelves, which can be up to ~100 m thick (Mortimer et al. 2012). Ice shelves can also be produced by the *in situ* accumulation of very old sea ice and snow (Jeffries 2002). Studies indicate that ice shelves have occupied some of the fiords of northern Ellesmere Island for the past ~4000-5500 years (England et al. 2008, Antoniades et al. 2011). These ice shelves have undergone rapid disintegration in recent years, decreasing from a

total area of ~8900 km² in 1906 (Vincent et al. 2001) to ~500 km² in 2015. As ice shelves have disintegrated they have produced ice islands, which are large tabular icebergs with a typically rolling surface topography of troughs and ridges. They can reach many tens of km² in area, and most drift for periods of years to decades in the Arctic Ocean and interior islands of the CAA, before breaking up in more southerly waters. For example, the ice island that broke away from the Ayles Ice Shelf in 2005 was roughly the size of Manhattan, and rapidly drifted westwards in the Arctic Ocean after formation, along the coast of northern Ellesmere Island (Copland et al. 2007). These immense, drifting ice features are also created from the break-up of floating glacier tongues. Ice islands located in Eastern Canadian Arctic water bodies, such as Nares Strait and Baffin Bay, most often originate from the floating glacier tongues of northwest Greenland. Ice islands found in the Western Canadian Arctic and interior islands of the northern CAA are typically derived from the break-up of the ice shelves on northern Ellesmere Island, although a few have also been produced from the breakup of floating glacier tongues in this region.

In this report we outline the characteristics and recent changes of the glaciers, ice shelves and ice islands in the Eastern Canadian Arctic. Over the past decade, satellite observations have enabled the monitoring and measurement of changes to many of these features on a regional scale for the first time, and have provided new insight into how these components of the cryosphere are changing. This builds on earlier field-based observations, which were typically more local in nature and collected on the ground or by aircraft. We finish by providing an assessment of how these features are likely to evolve in the future given current and predicted climate change.

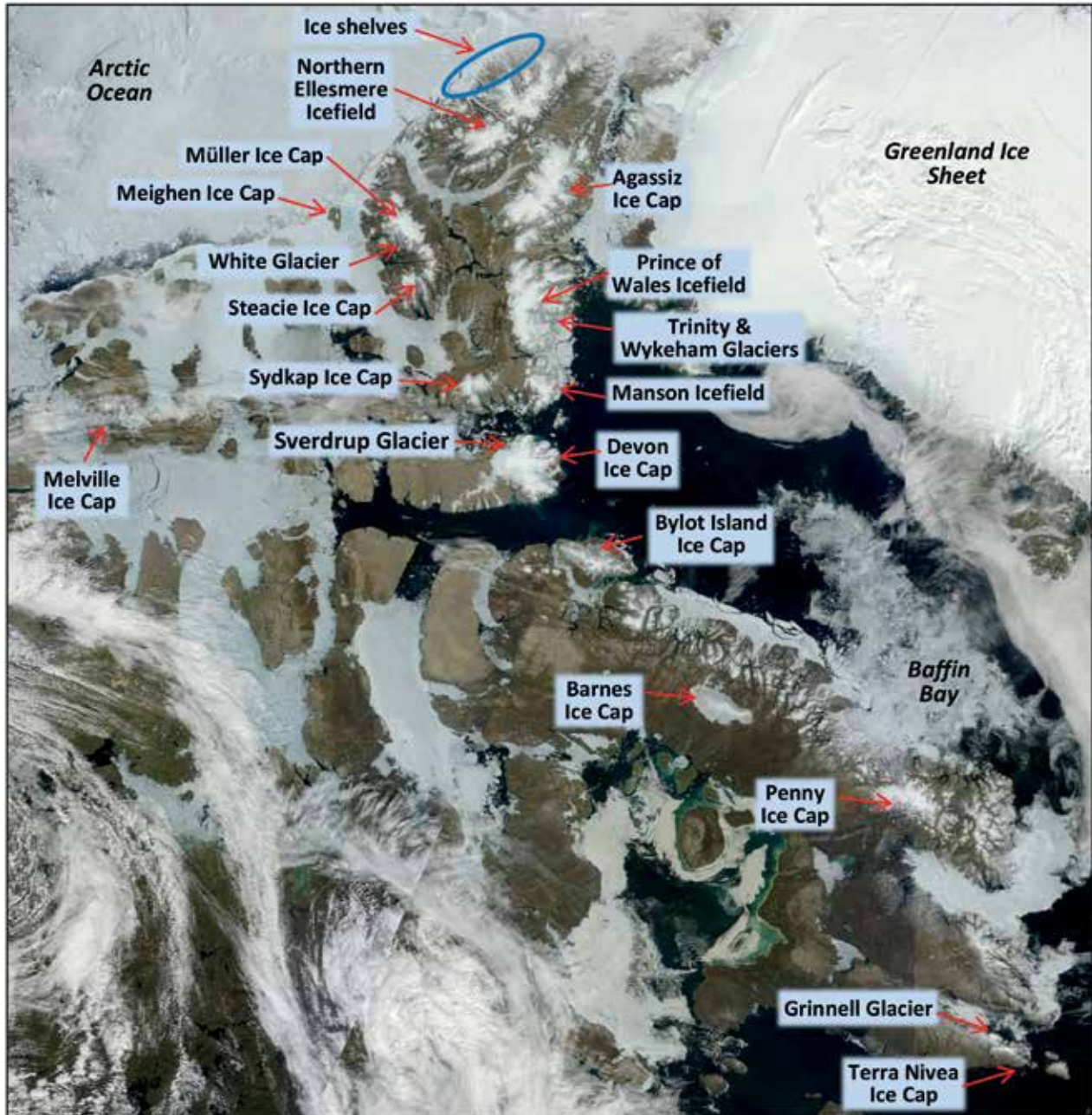


FIGURE 1. Location of the major glaciers, ice caps and icefields of the CAA. Source: MODIS Terra, July 21, 2015. The location of the ice shelves is marked by a blue oval (see Figure 5 for more detail).

3.2 Glaciers and ice caps

3.2.1 *In situ* mass balance measurements

The traditional method of determining a glacier's health involves measuring the change in height of a network of mass balance stakes drilled into the glacier surface (Box A). Annual (or more frequent) measurements of the height of these stakes in relation to the glacier surface can then provide information on accumulation and ablation patterns along the glacier length. This 'glaciological' method has been used in the Canadian Arctic since the late 1950s to early-1960s at four monitoring sites (White Glacier, Axel Heiberg Island; Meighen Ice Cap, Meighen Island; Melville Ice Cap, Melville Island; Sverdrup Glacier, Devon Ice Cap, Devon Island) (Koerner 2005, Sharp et al. 2011). This record shows that prior to the late 1980s, the ice masses of the northern CAA were largely in balance, meaning that ablation (primarily melt) was balanced by accumulation (snowfall). However, glacier mass balances became negative in the mid-1990s, and have been acutely negative for most years since 2005. For example, mass loss from 2005-2009 was nearly five times greater than the 1963-2004 average (Koerner 2005, Mair et al. 2009, Sharp et al. 2011). On the northwest sector of Devon Ice Cap, surface mass balance has been negative since 1960 (Koerner 2005), but after 2005 surface melt rates have been ~4 times greater than the long-term average (Sharp et al. 2011). Between 1960 and 2013 there has been a cumulative mass loss of almost 12 m water equivalent (w.e.) on White Glacier (Box A), >6 m w.e. on Devon Ice Cap, >8 m on Meighen ice cap and >14 m on South Melville ice cap (Figure 2; Burgess 2014). Koerner (2005) argued that this negative trend has been driven primarily by warmer summers that have increased melt and the depth of meltwater percolation, rather than by changes in winter snow accumulation.

Ice core records reveal that melt rates on CAA ice caps over the last 25 years are at their highest level in millennia. On Agassiz Ice Cap, Ellesmere Island, ice core records acquired from the summit region indicate that melt rates since the early 1990s are comparable to those last experienced ~9000 years ago when conditions were warmer

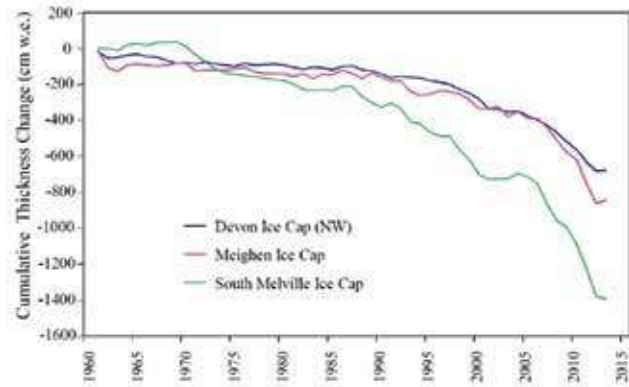


FIGURE 2. Cumulative water equivalent (w.e.) surface elevation change on Devon, Meighen and South Melville ice caps over the period 1960-2013 derived from *in situ* mass balance measurements. Adapted from Burgess [2014], © Government of Canada..

during the Holocene climatic optimum (Fisher et al. 2012). A historical climate record derived from deep and shallow ice cores on Penny Ice Cap, Baffin Island, indicates that current melting there is unprecedented in magnitude and duration for the past ~3000 years (Fisher et al. 1998, 2012). Since the mid-1990s, near-surface temperatures recorded in shallow ice cores in the accumulation area of Penny Ice Cap have increased by ~10 °C due to increased amounts of summer meltwater percolating into the ice (Zdanowicz et al. 2012). On Devon Ice Cap, significant warming between 2007 and 2012 has resulted in an increase in the amount of ice in the higher elevation regions of the ice cap, replacing the previous firn (snow more than 1 year old), and resulting in reduced vertical percolation into deeper regions and reduced water storage potential of much of the firn reservoir (Gascon et al. 2013).

BOX A. Mass balance measurements at White Glacier

White Glacier (Figure A1) is a 14 km long mountain glacier, measuring approximately 40 km² in area, located on western Axel Heiberg Island, Nunavut (Figure 1). The mass balance monitoring program at White Glacier was initiated in 1959 by Fritz Müller, founder of the McGill Arctic Research Station (Müller 1963), and today it is one of 40 official reference glaciers within the Global Terrestrial Network for Glaciers through the United Nations Framework Convention on Climate Change. These observations, submitted annually to the World Glacier Monitoring Service (www.wgms.ch), are used with others to calculate a worldwide glacier mass balance index that is regularly published in climate change assessment reports (WGMS 2008, 2015). As of 2015 the mass balance record (Figure A2) indicates that, on average, increased melt in recent years has not been offset by annual snowfall, resulting in mass loss and glacier retreat. This trend coincides with a raising of the equilibrium line altitude (ELA; the transition from regions of annual mass gain to regions of annual mass loss; Figure A1) by approximately 180 m over the past two decades (Thomson et al. 2017). The mean ELA over the period 2004-2014 was 1228 m above sea level (a.s.l.).

White Glacier's rich history of previous research provides valuable baseline data that enables us to observe in detail how Arctic glaciers are responding to climate change. Field studies are carried out in the spring (April and May) when we can access the glacier by snowmobile from our base at the nearby McGill Arctic Research Station. Our fieldwork involves measuring snow accumulation and ice melt along a transect of 40 mass balance stakes installed up the glacier centerline (Figure A1), spanning elevations from 110 to 1520 m a.s.l.. Being situated in a polar desert, annual snow depths rarely exceed 1.5 m at upper elevations (1500 m a.s.l.), and we make density measurements of the snowpack to calculate its water equivalence (Cogley et al. 1996). Summer ice melt near the terminus typically ranges between 2-3 m, but may exceed 5 m in high-melt summers (e.g., 2012). Recent results from a mapping campaign in 2014 indicate that glacier ice in the terminus region (lower 5 km) has thinned by 20 m on average over the past 55 years, with maximum losses exceeding 50 m (Thomson and Copland 2016).

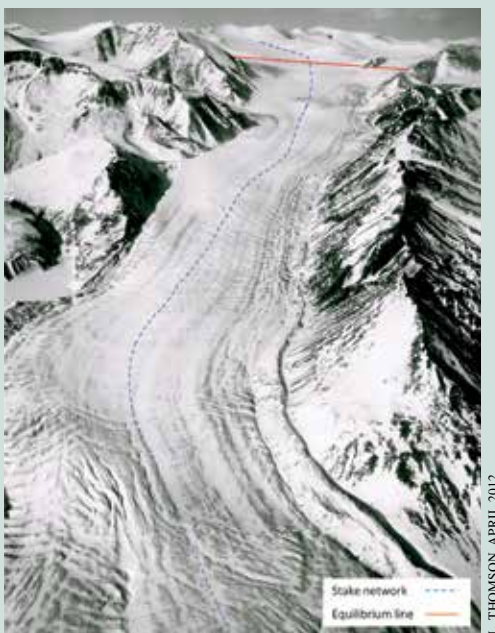


FIGURE A1. View northwards up the White Glacier terminus showing approximate location of the mass balance stake network and contemporary equilibrium line.

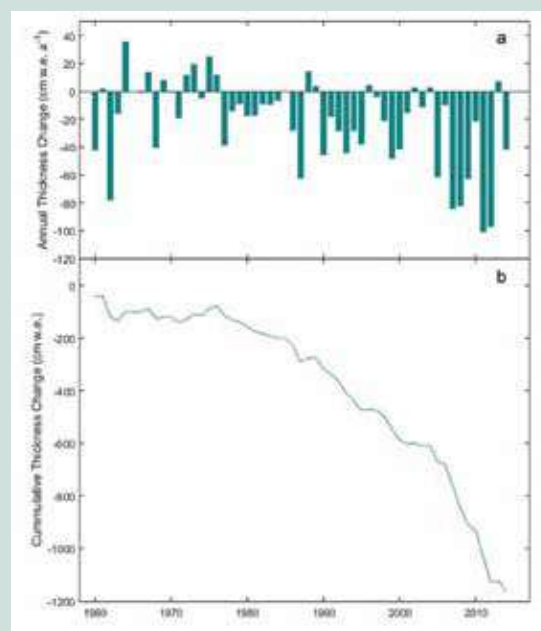


FIGURE A2. Water equivalent (w.e.) surface elevation change on White Glacier for the period 1960-2014 derived from *in situ* mass balance measurements: (a) Annual measurements; (b) Cumulative changes.

3.2.2 Airborne and satellite mass balance measurements

As an alternative to the 'glaciological' method of measuring glacier mass balance, recent studies have used airborne and satellite data to measure mass balance using the 'geodetic' method. This method relies on repeated measurements of the surface height of glaciers and ice caps, and can provide information on regional changes in mass balance that are not available from local *in situ* measurements. Some of the earliest kinds of these records are provided through repeated laser altimetry measurements made by the National Aeronautics and Space Administration (NASA), which started in 1995 over many CAA ice caps and have continued at approximately 5 year intervals to the present day. Based on thickness changes derived from repeat airborne surveys in 1995 and 2000, Abdalati et al. (2004) reported that most ice caps in the CAA were thinning at lower elevations (<1600 m), but showing thickening or little change at higher elevations. For ice caps in the northern CAA thinning was generally $<0.5 \text{ m a}^{-1}$, but on Barnes and Penny ice caps in the southern CAA, thinning was $>1 \text{ m a}^{-1}$ at lower elevations. On Penny Ice Cap, more recent measurements (2007–2011) indicate thinning of $3\text{--}4 \text{ m a}^{-1}$ near the ice cap margin, amongst the highest rates anywhere in the Canadian Arctic (Zdanowicz et al. 2012).

Gardner et al. (2012) updated the earlier measurements of glacier changes in the southern CAA by using a combination of repeat airborne and satellite altimetry measurements, satellite gravimetry measurements and digital elevation models derived from stereo air photos and satellite imagery. These measurements indicate that total mass loss from the glaciers of Baffin and Bylot Islands more than doubled from $11.1 \pm 3.4 \text{ Gt a}^{-1}$ for the period 1963–2006 to $23.8 \pm 6.1 \text{ Gt a}^{-1}$ for the period 2003–2011. These changes were primarily attributed to increases in summer temperature, with little change in precipitation over this period. Between 2003 and 2011 the glaciers of Baffin and Bylot islands contributed $\sim 16\%$ ($0.07 \pm 0.02 \text{ mm a}^{-1}$) of the total contribution to sea level rise from glaciers and ice caps outside of Greenland and Antarctica (Gardner et al. 2012). This aligns with observations from passive

satellite microwave records that the average melt season on Barnes Ice Cap lengthened by $\sim 33\%$ between 1979–1987 and 2002–2010, and nearly doubled on Penny Ice Cap between 1979 and 2010 (Dupont et al. 2012).

For the CAA as a whole, Gardner et al. (2011) used repeat satellite gravimetry, satellite laser altimetry and modelling to show that mass loss rates almost tripled from $31 \pm 8 \text{ Gt a}^{-1}$ in 2004–2006 to $92 \pm 7 \text{ Gt a}^{-1}$ in 2007–2009. Losses were extensive across both the northern and southern CAA (Figure 3). Similar to the findings of Gardner et al. (2012), these losses were attributed primarily to warmer summer air temperatures in the lower troposphere, with mass loss rates highly sensitive to relatively small temperature changes, at a rate of $64 \pm 14 \text{ Gt a}^{-1}$ per 1°C increase in temperature. These overall losses made the CAA the largest contributor to sea level rise outside of the Greenland and Antarctic ice sheets for the period 2007–2009. More recently, Harig and Simons (2016) used satellite gravimetry data to demonstrate that ice mass losses have accelerated across the CAA since 2003, with the exception of a positive mass anomaly in summer 2013. While the majority of losses has been in the form of surface melt and runoff, Van Wychen et al. (2014) determined that iceberg discharge from the CAA amounted to $2.6 \pm 0.8 \text{ Gt a}^{-1}$ in 2012, equating to 7.5% of pan-Arctic iceberg discharge and $\sim 3.1\%$ of the average total glacial runoff in the QEI from 2007–2009.

For glaciers and ice caps, Sharp et al. (2014) calculated area changes using aerial photographs and satellite imagery from ~ 1960 to ~ 2000 . Over this period, total ice-covered area in the northern CAA reduced from $107\,071 \text{ km}^2$ to $104\,186 \text{ km}^2$. The greatest area losses occurred on the ice caps on Devon Island and southern Ellesmere Island, with reductions of 4.0% and 5.9%, respectively. The northern Ellesmere Island ice cap also lost significant area, shrinking by 3.4% over this period. Using a similar technique, Thomson et al. (2011) determined that the ice coverage on Axel Heiberg Island reduced by a total of less than 1% between 1958–59 and 1999–2000. However, this hides the fact that losses were particularly pronounced on small glaciers and ice caps, with retreat of $\sim 50\text{--}80\%$ for independent ice masses less

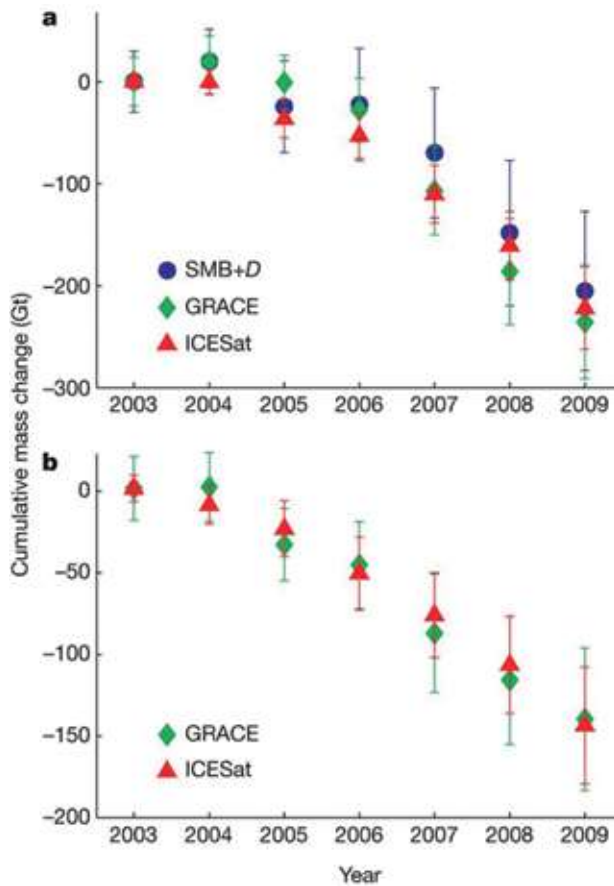


FIGURE 3. Cumulative change in glacier mass between fall 2003 and fall 2009 for the: (a) northern CAA and (b) southern CAA, derived from modelling of surface mass balance and ice dynamics (SMB+D), satellite gravimetry (GRACE) and satellite altimetry (ICESat). Note the difference in scale between the two parts. Reprinted by permission from Macmillan Publishers Ltd: Nature (Gardner et al. 2011), © 2011.

than 25 km² in size, and the complete disappearance of 90% of ice masses smaller than 0.2 km².

In the southern CAA, other studies have also shown that small ice caps and glaciers are particularly vulnerable to losses; e.g., Paul and Svoboda (2009) found total area losses of 12.5% between ~1920 and 2000 for a total of 264 glaciers located on the Cumberland Peninsula, southeast Baffin Island. These losses showed a strong dependence on glacier size, with glaciers 0.1–0.5 km² in size losing an

average of 45.6% of their area over this period, compared to mean losses of 6.4% for glaciers >50 km² in size. A recent comparison of digital elevation models derived from historical aerial photography and high resolution satellite imagery shows that there have also been dramatic reductions in the volume and area of the Grinnell and Terra Nivea ice caps on far southern Baffin Island since the 1950s (Papasodoro et al. 2015). On Terra Nivea the ice cap-wide mass balance increased from -0.30 ± 0.19 m w.e. a⁻¹ over the period 1958/59–2007 to -1.77 ± 0.36 m w.e. a⁻¹ over the period 2007–2014. Similarly, Way (2015) found that Terra Nivea Ice Cap has lost 22% of its area since the late 1950s, while Grinnell Ice Cap has lost a total of 18%. These rapid reductions in area have been linked to increasing summer air temperatures, and suggest that these ice masses are far out of equilibrium with current climate.

3.2.3 Glacier dynamics

An important question, given the widespread and increasing recent mass losses from glaciers and ice caps across the CAA, is whether glacier motion is changing in response. To address this, Van Wychen et al. (2016) matched pairs of Radarsat and Landsat satellite imagery to determine the velocity structure of the ice masses of Axel Heiberg and Ellesmere Islands for the period 1999–2015. Out of 117 sampled glaciers the vast majority did not show significant velocity changes, but six had fluctuating velocities (both speed-up and slow-down), eight slowed progressively and two accelerated throughout the observation period. To investigate the causes of these velocity variations, Van Wychen et al. (2016) combined the observed glacier dynamics with a record of terminus positions and an inventory of optical satellite imagery used to identify glacier surface features that would indicate surge activity (e.g., looped surface moraines, extensive fresh crevassing). Glacier surging refers to a period of rapid glacier advance (over months to years) that can occur after a long period of near-stagnation (of decades to centuries), typically driven by the movement of excess ice mass from the top to bottom of a glacier as part of a glacier's internal dynamics (Meier and Post 1969). Pulse glaciers refer to ice masses that share many of the

characteristics of surging, such as significant velocity variability, but where the variations do not appear to encompass the entire glacier length (Van Wychen et al. 2016). Using this classification scheme, all of the glaciers that displayed velocity variability or a progressive slow-down could be explained by surge or pulse mechanisms. For these glaciers it appears that internal mechanisms, rather than external forcing (e.g., climatic or ocean warming), are responsible for the majority of observed dynamic changes.

The major exceptions to this behaviour are the two glaciers that underwent consistent acceleration, the Trinity and Wykeham glaciers of southeastern Prince of Wales Icefield, whose changes appear to be driven by external forcing (Figure 4). Over the period 1999–2015 the surface velocity of Wykeham Glacier nearly doubled (increasing from

$\sim 200 \text{ m a}^{-1}$ to $\sim 400 \text{ m a}^{-1}$ in the lowermost terminus region), while the surface velocity of Trinity Glacier nearly tripled (increasing from $\sim 400 \text{ m a}^{-1}$ to $\sim 1200 \text{ m a}^{-1}$ in the lowermost terminus region). From 1959 to 2015, the terminus of Trinity Glacier retreated by $\sim 6 \text{ km}$ while Wykeham Glacier retreated by $\sim 2 \text{ km}$. However, roughly half of the observed retreat for both glaciers has occurred since ~ 2001 , coincident with the onset of faster motion (Van Wychen et al., 2016) and increases in summer air temperatures (Sharp et al. 2011). This pattern of terminus retreat coincident with acceleration is at odds with the expected behaviour of surge-type and pulse-type glaciers and suggests that a unique climatic and/or oceanic mechanism is driving the recent speed-up of these two glaciers. A comparison of glacier surface elevations in 2008 and 2014 indicates $\sim 2\text{--}5 \text{ m a}^{-1}$ of surface lowering in the lowermost 10 km of both

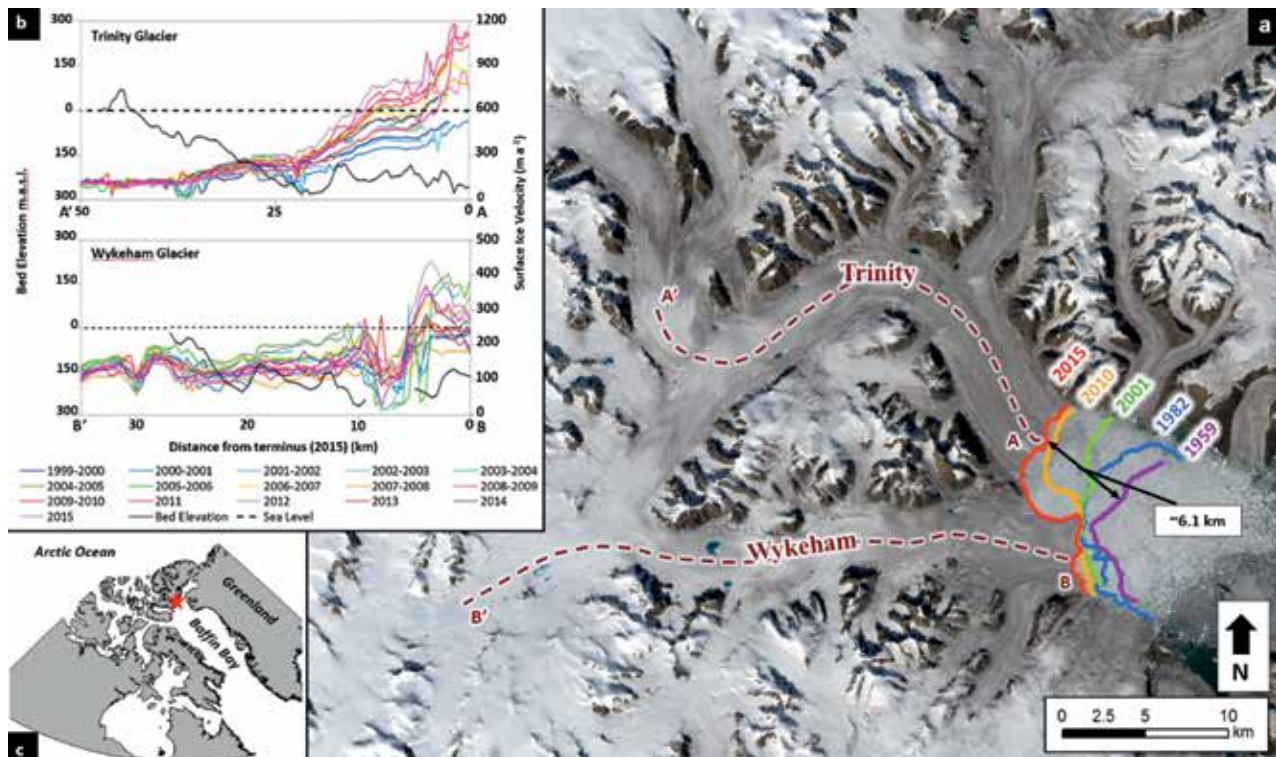


FIGURE 4. (a) Frontal retreat (1959–2015) of Trinity and Wykeham Glaciers (background: Landsat 8, July 29, 2015); (b) 1999–2015 centreline surface velocities of Trinity and Wykeham glaciers, extracted along the red dashed lines shown in (a); (c) location of Trinity and Wykeham Glaciers (marked by red star; also see Figure 1).

glaciers, approximately double that expected from surface melting (Mair et al. 2009, Marshall et al. 2007). This implies that at least half of the observed thinning is driven by glacier acceleration. This pattern of unstable terminus acceleration, thinning and prolonged retreat has previously been reported in Greenland (e.g., Helheim Glacier; Howat et al., 2005), but not previously identified in the Canadian Arctic. Trinity and Wykeham glaciers accounted for ~22% of total CAA iceberg discharge to the ocean in 2000, but ~62% in 2015 (Van Wychen et al. 2016), indicating that changes in the dynamics of just a few glaciers can change iceberg production patterns for the entire Canadian Arctic. Given that these glaciers are grounded below sea level for ~30-45 km upglacier from their current calving fronts, they are particularly prone to further retreat and break-up before re-stabilization can occur.

3.3 Ice shelves

3.3.1 Ice shelf area changes

There are currently three remaining major ice shelves on the northern coast of Ellesmere Island: the Petersen, Milne and Ward Hunt (Figure 5). These ice shelves are remnants of the Ellesmere Ice Shelf (unofficial name) that once fringed the entire northern coast of Ellesmere Island, and was first described by Lt. Aldrich of the British Arctic Expedition of 1875-76 (Nares 1878). Later observations by Peary (1907) of a 'broad glacial fringe' along the north-western coast of Ellesmere Island were used by Vincent et al. (2001) to estimate an ice shelf extent of 8900 km² and length of 500 km in 1906. In the studies of England et al. (2008) and Antoniadou et al. (2011), radiocarbon dating of driftwood collected in fiords behind ice shelves was used to infer when the north coast of Ellesmere Island was last ice-free. Based on samples collected inland of Ward Hunt Ice Shelf and five adjacent fiords, it is likely that the Ellesmere Ice Shelf began to form ~4000-5500 years ago.

Over the period 1906-1982, ~90% of the Ellesmere Ice Shelf was lost in a series of large calving events, particularly prior to the 1950s (Koenig et al. 1952). These events released many large ice islands into the Arctic Ocean and

left behind six remnant ice shelves located in fiords and bays along the coastline. From the 1950s to the end of the 20th century there were several calving and break-up (fracture development) events that further fragmented these ice shelves (Hattersley-Smith 1963, Jeffries and Serson 1983, Jeffries 1986a). During the 1960s the Ward Hunt Ice Shelf lost 50% of its area (596 km² from 1961-1962) (Hattersley-Smith 1963), and the Ayles Ice Shelf calved 15 km² (from 1962-1966; Jeffries 1986a). Between 1980 and 1983, the Ward Hunt Ice Shelf lost ~80 km² in two calving events (Jeffries and Serson 1983). From then until 2005, the ice shelves remained generally stable.

Starting in 2005, a renewed period of ice shelf losses has occurred. From 2005 to 2012, >50% of their total 2005 area of ~1043 km² was lost, with many ice islands drifting in the Beaufort Gyre as a consequence (Mueller et al. 2013). This period of ice shelf break-up began with the complete loss of the Ayles Ice Shelf (87 km²) and an ~8 km² loss from the Petersen Ice Shelf in summer 2005 (Copland et al. 2007, White et al. 2015a). In 2008, 42 km² of the Ward Hunt Ice Shelf calved away, along with 60% (122 km²) of the Serson Ice Shelf, a ~9 km² loss from the Petersen Ice Shelf, and the complete loss of the Markham Ice Shelf (50 km²; Mueller et al. 2008, White et al. 2015a). The year 2011 was also marked by substantial calving events, including a 39 km² loss from the Ward Hunt Ice Shelf as it broke into two, 5.5 km² loss from the Petersen Ice Shelf and a 32 km² loss

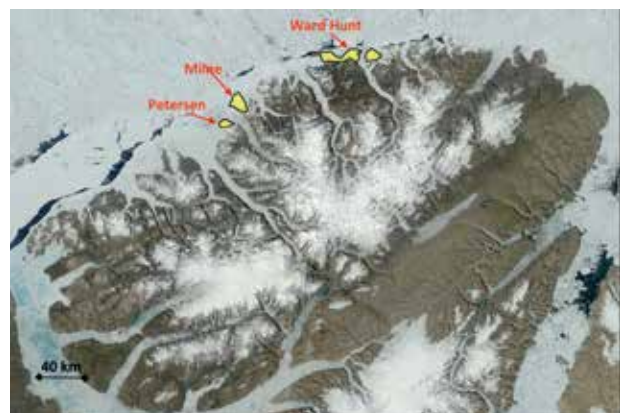


FIGURE 5. Summer 2015 location of ice shelves on northern Ellesmere Island. Base image: MODIS, July 12, 2015.

from the Serson Ice Shelf (White et al. 2015a). An additional 5.5 km² loss from the Petersen Ice Shelf occurred in summer 2012. Many of these ice shelf losses have occurred in conjunction with the loss of adjacent multi-year landfast sea ice, such as 690 km² of ~70 year old sea ice which broke out from the head of Yelverton Bay in August 2005 shortly before losses of parts of the Petersen Ice Shelf (Pope et al. 2012). Many ice shelf losses have also resulted in the loss of adjacent freshwater epishelf lakes that were once dammed behind them (Box B; White et al. 2015b).

3.3.2 Recent changes in ice shelf thickness

Recent ice shelf thickness measurements are limited to the Petersen and Milne ice shelves. In May 2011 measurements conducted with a 250 MHz ground penetrating radar (GPR) system on the Petersen Ice Shelf revealed a mean thickness

of 29 m, with a standard deviation of 24 m and maximum thickness of ~106 m for a tributary glacier (White et al. 2015a). GPR measurements on the Milne Ice Shelf in April 2008 and May 2009 revealed a mean thickness of 55 m, with a standard deviation of 22 m and a maximum of 94 m (Mortimer et al. 2012). Both of these ice shelves contain thicker ice where tributary glaciers provide input, and are thinner near their inland margins.

A comparison of the 2008/2009 ice thickness measurements on the Milne Ice Shelf with airborne measurements collected in 1981 (Prager 1983; Narod et al. 1988) provides the only direct quantification of ice shelf thickness change for the Canadian Arctic (Mortimer et al. 2012). These measurements indicate that the ice shelf reduced in volume by 13% over this period, with an average thinning of 8.1 ± 2.8 m, equivalent to -0.26 ± 0.09 m w.e. a⁻¹ (Figure 6).

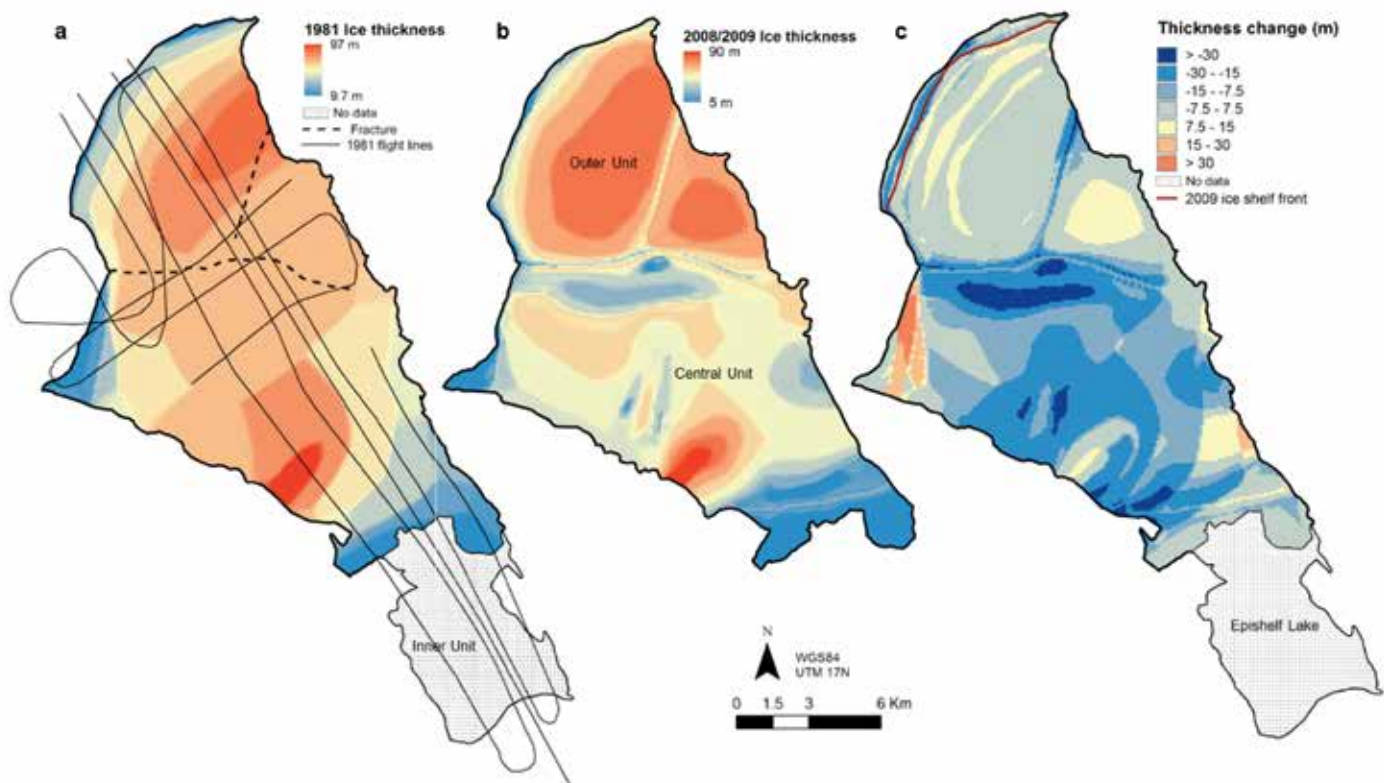


FIGURE 6. Thickness maps of the Milne Ice Shelf showing: (a) 1981 thicknesses interpolated from a contour map produced by Prager (1983), with superimposed flight lines; (b) interpolated thicknesses derived from 2008/2009 ground penetrating radar measurements; (c) changes in the thickness of the Milne Ice Shelf between 1981 and 2009. Source: Mortimer et al. (2012).

BOX B. Epishelf lakes

Ice shelves at the northern coast of Ellesmere Island are attached to the coast along the sides of fiords and embayments. However, there can also be areas at the rear of ice shelves where they are not attached to the land, which allows for the formation of a freshwater layer in the fiord that floats on the relatively high density sea water below. These are referred to as epishelf lakes and they can exert considerable influence on the ice shelves that dam them (Figure B1).

Epishelf lakes are supplied with meltwater that flows from the surrounding land in the brief summer period. This freshwater collects in the upper water column with minimal mixing with the ocean below, creating a sharp step-like change in salinity (Figure B2) at a depth that is equal to the minimum draft of the ice shelf. If more meltwater flows into the fiord, it is forced out under the ice shelf. If this water is cold enough, it can then freeze on the underside of the ice shelf (Jeffries et al. 1988). In the past, this process has increased the thickness of the ice shelf, which in turn can deepen the epishelf lake (Jeffries 2002).

In the current climate regime, with ice shelves thinning and with warmer meltwater inputs, epishelf lakes are reducing in size. For example, between 1999 and 2002 an epishelf lake in Disraeli Fiord drained through a fissure in the Ward Hunt Ice Shelf (Mueller et al. 2003). This was the largest epishelf lake (6.1 km³ in 1967) in the Northern Hemisphere and the first time that the drainage of an epishelf lake had been documented (Figure B2). Since that time, the reduction in depth of Ellesmere Island's epishelf lakes has been examined by water column profiling and the reduction in area of epishelf lakes has been inferred using RADARSAT satellite imagery (Veillette et al. 2008, White et al. 2015b). In 2011, ArcticNet researchers installed a mooring in the last large epishelf lake found in Milne Fiord to monitor the changes in this unique environment.

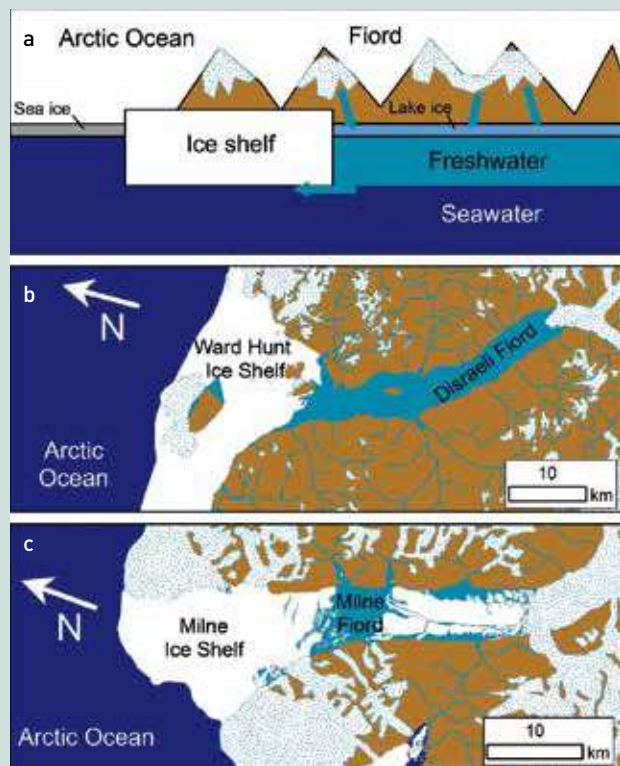
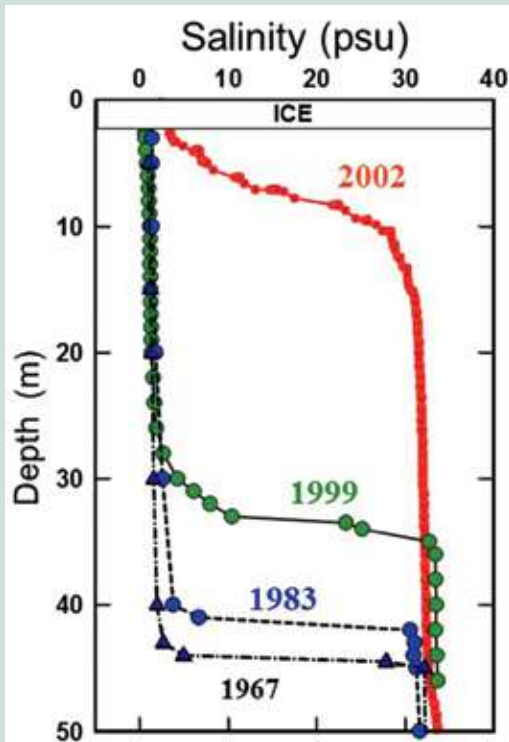


FIGURE B1. (a) Cross sectional diagram of an epishelf lake showing the freshwater layer (light blue) that is impounded behind the ice shelf. Since the freshwater is less dense than the seawater, it rests above the ocean (dark blue), persisting in a layer between the coast and the ice shelf. The lake is covered by perennial freshwater ice that prevents mixing by the wind. More meltwater (light blue arrows) from snow and glaciers (stipple) is added to the lake in the summer, which pushes freshwater out under the ice shelf. (b) Map of the epishelf lake that persisted in Disraeli Fiord behind the Ward Hunt Ice Shelf until 2002. (c) Map of the epishelf lake in Milne Fiord as of spring 2015.



Epishelf lakes are also fascinating ecosystems that are highly structured. It is possible for organisms that live in fresh or brackish water to co-exist just above marine organisms in the same water column. Green algae dominate in the fresh upper water column, whereas marine diatoms are more commonly found in deeper waters (Veillette et al. 2011). Similar distributions can be found with copepods (tiny crustaceans), bacteria and viruses where certain types of these organisms are found either in the fresh or marine environments (Van Hove et al. 2001, Veillette et al. 2011). Since these stratified ecosystems are structured by the ice shelves that dam them, they are vulnerable to ice shelf break-up, and are likely to disappear completely from Nunavut over the next few decades.

FIGURE B2. Salinity profiles showing the loss of the freshwater epishelf lake in Disraeli Fiord. Over the years, researchers lowered instruments into the water column to measure salinity. In 1999 and before, the salinity was near zero in the upper water column, indicating freshwater, before transitioning rapidly to sea water below. In 2002, the profile shows a dramatic loss of most of the freshwater epishelf lake (due to flow through a crack in the Ward Hunt Ice Shelf) and replacement by high salinity sea water from below.

3.3.3 Recent changes in ice shelf inputs and mass balance

For some of the ice shelves along northern Ellesmere Island, glaciers have provided an important source of mass input (Jeffries 1986b). Of the three remaining ice shelves today, only the Milne and Petersen show evidence of glacier input, with the Ward Hunt Ice Shelf primarily formed from the *in situ* accumulation of sea ice and snow. For the Milne Ice Shelf, it is clear that there has been a marked reduction in the importance of glacier input over the past ~50 years, with aerial photographs indicating that five tributary glaciers terminated on the ice shelf in 1959 (Mortimer et al. 2012). Three of these glaciers extended between 1.5 and 4.5 km into the ice shelf interior, but by 2011 the glacier input was limited to a single glacier contributing an estimated 0.048 m w.e. a^{-1} to the ice shelf. This accounts for

<20% of the average thinning of 0.26 m w.e. a^{-1} measured between 1981 and 2008/9, indicating that the ice shelf is far out of balance with current climate conditions (Mortimer et al. 2012).

The Petersen Ice Shelf currently receives mass from two tributary glaciers along its remaining landfast margin. An additional tributary flowed into the southern margin of the ice shelf in 1959, but this became detached by 2007, therefore eliminating it as a source of mass to the ice shelf (Figure 7; White 2012). Based on velocity measurements made between 2011 and 2012, the remaining two glaciers contribute 1.19-5.65 Mt a^{-1} to the ice shelf (White et al. 2015a). This mass input is far exceeded by the current surface ablation on the Petersen Ice Shelf of 28.45 Mt a^{-1} , helping to explain why the ice shelf has weakened to the point of disintegration.

The longest mass balance record available for a Canadian ice shelf is for the Ward Hunt Ice Shelf and adjacent Ward Hunt Ice Rise (region of the ice shelf resting on the sea bed). Braun et al. (2004) compiled a continuous record of annual surface mass balance for these locations from 1954 to 2003 (Figure 8), which show that winter snow

accumulation remained relatively constant over time, but that summer ablation was much more variable. Positive balance years have been infrequent (only 1963–1965 and 1972–1973), and negative balance years dominate the record with total mass losses of 1.68 m w.e. ($0.04 \text{ m w.e. a}^{-1}$) for Ward Hunt Ice Rise and 3.1 m w.e. ($0.07 \text{ m w.e. a}^{-1}$) for Ward Hunt

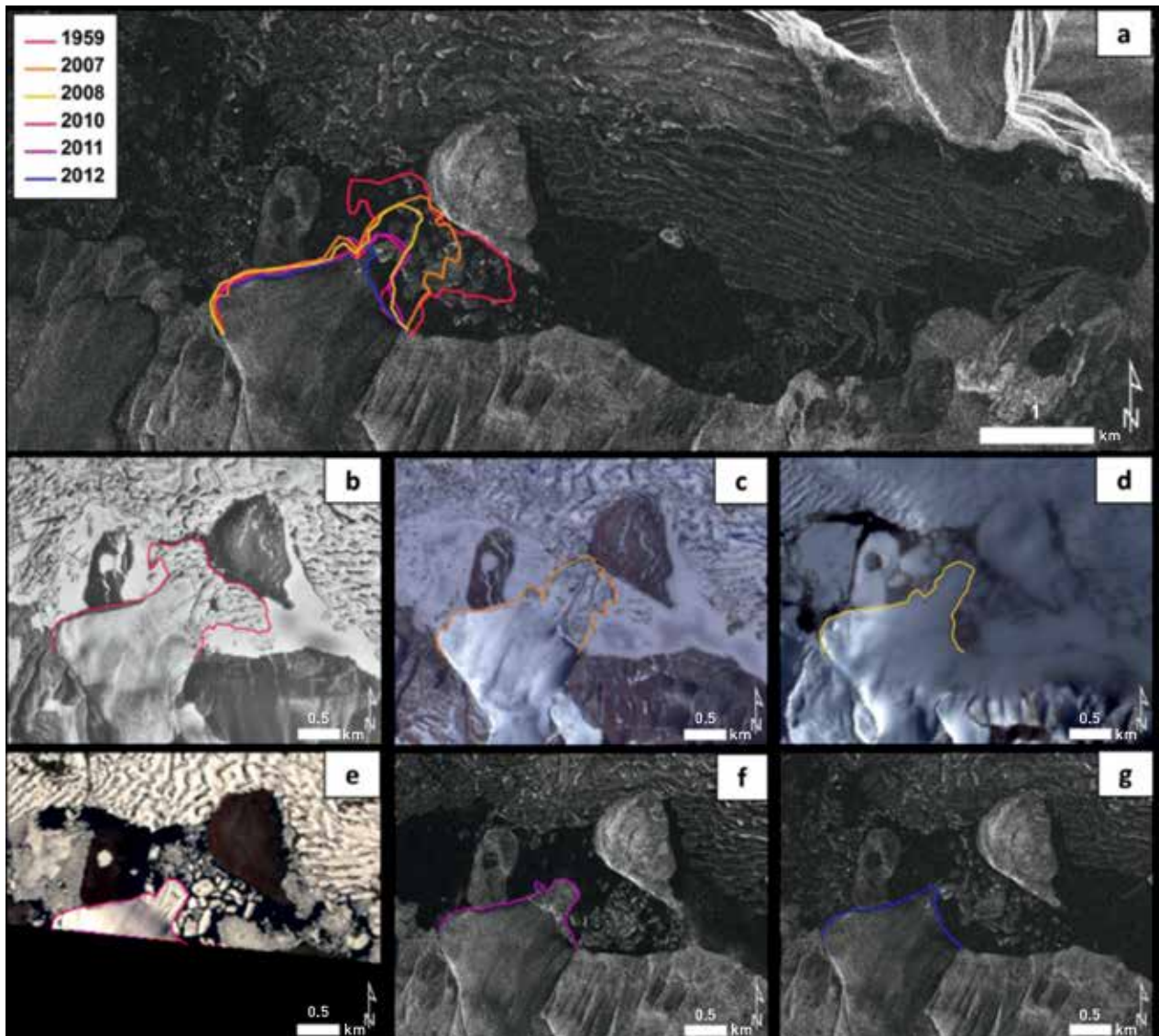


FIGURE 7. Aerial photography and satellite imagery highlighting changes in the tributary glacier flowing from the southern coast into Petersen Bay and the dispersement of icebergs. (a) Radarsat-2, February 3, 2012; (b) Aerial photography, August 13, 1959; (c) ASTER, July 7, 2007; (d) ASTER, August 22, 2008; (e) ASTER, July 19, 2010; (f) Radarsat-2, July 19, 2011; (g) Radarsat-2, February 3, 2012. Source: White (2012).

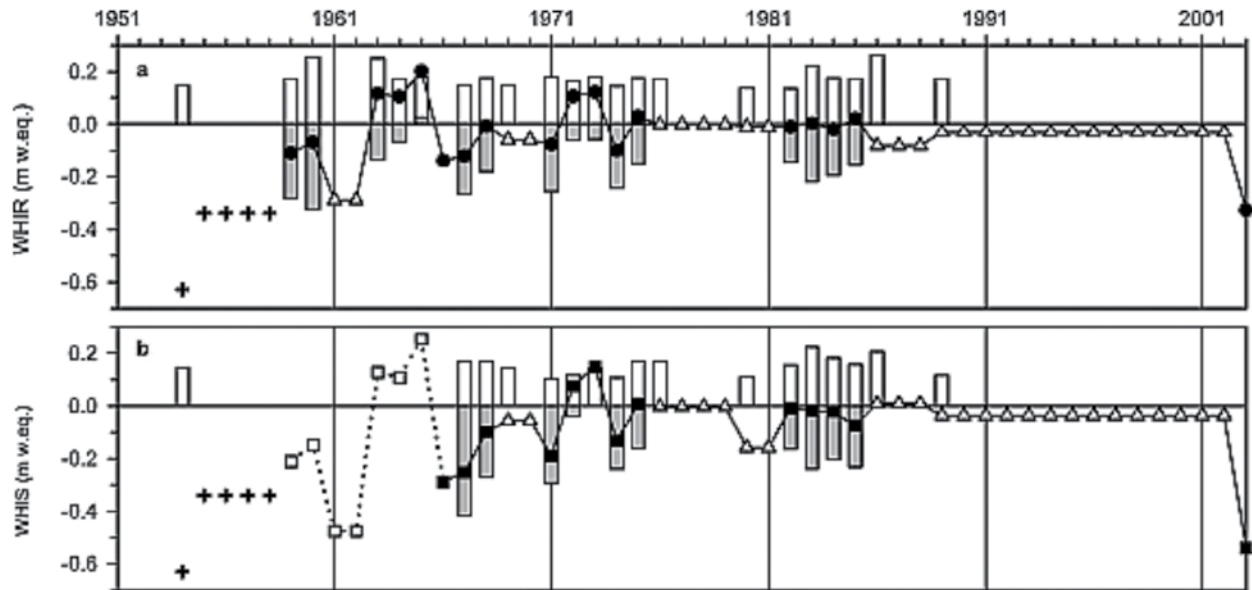


FIGURE 8. Surface mass balance for: (a) Ward Hunt Ice Rise and (b) Ward Hunt Ice Shelf from 1954 to 2003 for: winter (open bar), summer (shaded bar), and annual balances (solid square). Plus symbols represent multiyear balance estimates based on limited measurements, open triangles represent annual values calculated as averages of multiyear balances, and open square/dots are annual balances calculated using a linear regression. Modified from Braun et al. (2004).

Ice Shelf. This contrast in surface mass balance has been associated with the ridge/trough topography of the ice shelf, where meltwater collected in troughs enhances ablation (Braun et al. 2004). According to ablation measurements, 2003 was the most negative year, when 50% of the mass loss from 1989–2002 occurred (0.54 m w.e. for Ward Hunt Ice Shelf, and 0.33 m w.e. for Ward Hunt Ice Rise).

The mass balance measurements presented by Braun et al. (2004) are limited to the surface and therefore do not account for mass fluctuations at the base of the ice shelf. However, the thickness change measurements presented by Mortimer et al. (2012) provide a means to determine the state of the basal ice. Mortimer et al. (2012) applied the rate of surface mass loss for the Ward Hunt Ice Shelf to the Milne Ice Shelf and combined this rate with the total thinning determined for the 1989–2003 period. Based on this calculation, thinning due to basal melt would account for ~73% (0.19 m w.e. a^{-1}) of mass loss, suggesting that it can be a dominant loss mechanism.

3.4 Ice islands

Ice islands have been described as the “most massive ice features known in the Arctic Ocean” (Jeffries et al. 1987), with the largest observed in the CAA covering an area of ~1,000 km² (Jeffries 1992, Koenig et al. 1952). These large, tabular icebergs were first observed in the late 1940s (Fletcher 1950) and were originally used for military and scientific purposes as aircraft landing and research platforms (Althoff 2007, Jeffries 1992, Mueller et al. 2013). These ice features have become subjects of interest recently due to the link between climate change and calving events of ice shelves and floating glacial tongues (Copland et al. 2007, Derksen et al. 2012). Shipping and offshore exploration companies are also concerned due to the risk of a collision between an ice island and a vessel or infrastructure (McGonigal et al. 2011, Peterson 2011). This risk is illustrated in Figure 9, which shows ice island drift trajectories overlapping regions of shipping and natural resource extraction activity.

Ice islands drifting in the CAA typically originate from one of two locations: northwest Greenland's floating glacial tongues or the ice shelves of northern Ellesmere Island (Higgins 1989, Jeffries 2002). Ice islands from Greenland generally drift south through Eastern Canadian Arctic waters, at times reaching the Labrador Sea or the Grand Banks of Newfoundland (Newell 1993). Ice islands of Ellesmere Island origin commonly drift clockwise in the Beaufort Gyre toward the Beaufort and Chukchi seas, though some have been observed within the channels of the CAA (Jeffries et al. 1987, Van Wychen and Copland 2017), or drifting east into Nares Strait (Nutt 1966) (Figure 9).

Both of these source regions have experienced multiple, substantial calving events since the start of the 21st century (Mueller et al. 2013, Peterson 2011). The Petermann Glacier of northwest Greenland calved large ice islands in 2001 (71 km²; Johannessen et al. 2011), 2008 (31 km²; Johannessen et al. 2011), 2010 (253 km²; Falkner et al. 2011) and 2012 (32 km², NASA 2012). Johannessen et al.

(2011) note the absence of sea ice in the fiord prior to the 2010 calving, a condition also observed in MODIS satellite imagery which captured the 2012 event (NASA 2012). This situation likely promotes calving by removing the floating glacial tongue's protection from ocean and wind-induced waves (Falkner et al. 2011). Rignot and Steffen (2008) suggest that enhanced channel erosion on the subsurface of the Petermann Glacier's floating tongue caused by warming ocean waters is another probable contributor. It cannot be conclusively stated that these events are linked to climate warming, although Falkner et al. (2011) propose that global atmospheric pressure and temperature changes have an impact on both of the aforementioned calving precursors. Copland et al. (2007) also argue that these conditions, namely increasing atmospheric temperatures and the absence of protective sea ice, led to the weakening and eventual calving of the Ayles Ice Shelf in August 2005. This event created a 66 km² ice island and 21 km² of smaller fragments.

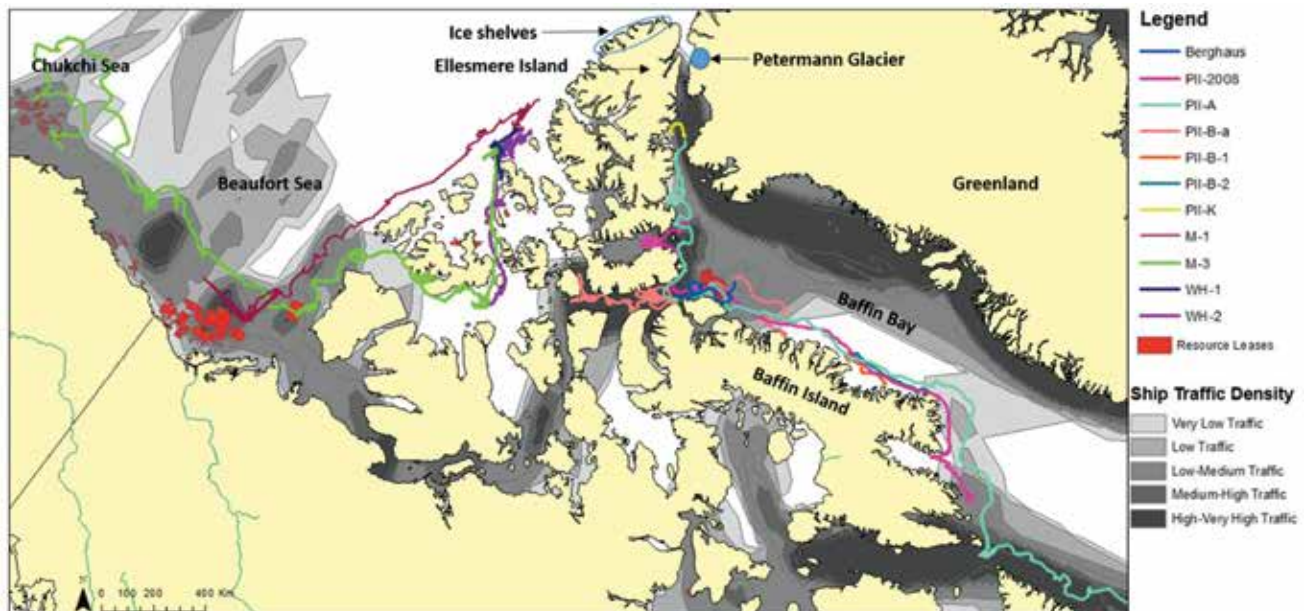


FIGURE 9. Overlap between ice island drift trajectories, historic U.S. and Canadian oil and gas exploration lease blocks and ship traffic density. Legend abbreviations are: PIL = Petermann Ice Island, M = Markham, WH = Ward Hunt. Shapefiles of oil and gas leases are courtesy of the U.S. Bureau of Ocean Energy Management (BOEM 2013) and Aboriginal Affairs and Northern Development Canada (AANDC 2013). Shipping density contours represent a snapshot of marine traffic for August 2013 (exactEarth 2013). Major sources of ice hazards annotated.

The drift and deterioration of five ice islands from the Petermann Glacier calvings were monitored between 2010 and 2015 by GPS tracking beacons and RADARSAT-1 and 2 satellite images (Crawford 2013, Crawford et al. 2015, Halliday et al. 2012, Hamilton et al. 2013, Wagner et al. 2014). These ice islands followed the common drift pattern through Nares Strait and into the cyclonic current of Baffin Bay (Newell 1993, Tang et al. 2004). Some fragments, such as Petermann Ice Island (PII)-B-a of the 2010 Petermann Glacier calving event, diverted into Lancaster Sound due to the intrusion of strong ocean currents at the north entrance of the sound (Hamilton et al. 2013, Peterson et al. 2009, Tang et al. 2004) (Figure 9).

The time it takes for an ice island to drift through the Eastern Canadian Arctic can vary considerably due to these diversions and/or grounding events. This is illustrated by comparing the 8 month and 3 year transit times of PII-A and PII-B-a, respectively, from the Petermann Glacier to the Labrador Sea (Crocker et al. 2013). The latter ice island's transit was delayed due to the aforementioned diversion and becoming grounded 130 km northeast of Clyde River, Nunavut, for a 12 month period (Crawford 2013, L. Desjardins pers. comm.). Offshore oil and gas operators will need to consider that ice islands have frequently grounded on Baffin Island's continental shelf (Crawford 2013, L. Desjardins and S. Tremblay-Therrien, pers. comm.) if natural resource extraction is to be conducted in the Eastern Canadian Arctic since sub-seafloor infrastructure will be at risk from ice island scouring (King et al. 2003).

Ice islands in the Eastern Canadian Arctic have drafts (distance between the waterline and ice bottom) ranging from approximately 60 to 140 m, as determined from GPR, multibeam sonar and autonomous underwater vehicle surveys (Crawford 2013, Forrest et al. 2012, Hamilton et al. 2013, Wendleder et al. 2015). An ice island's draft determines its possible grounding locations and, in combination with its sail, provides a dominant control on the ice feature's drift. The deterioration of this vertical dimension is relatively more important for ice islands than icebergs due to the former's extensive horizontal surfaces (Ballicater 2012).

Surface melt and micro-meteorological data indicate that the ice surface can melt at an average rate of 3.3 cm d⁻¹ in August in Lancaster Sound (Crawford et al. 2015), while average basal and surface deterioration rates of 5.0 cm d⁻¹ and 2.4 cm d⁻¹ were observed further south in the Labrador Sea (Halliday et al. 2012).

Ice islands also deteriorate through calving processes such as the 'footloose mechanism', which is induced by buoyancy stresses generated by an ice ram (an underwater protrusion at the ice island's edge) (Wagner et al. 2014). These deterioration processes result in ice island fragments, as well as 'bergy-bits' and 'growlers', which are 5-15 m and <5 m in length, respectively. These are relatively small ice features yet they are still capable of damaging vessels or infrastructure and are particularly dangerous due to the difficulty of detecting them remotely (Crocker et al. 2004, Saper 2011). Interestingly, Stern et al. (2015) observed that the temperature and salinity stratification of the water column adjacent to a large (~41 km²) grounded ice island in Baffin Bay was altered by wind-induced up- and down-welling, or Ekman transport. This process may lead to enhanced deterioration of ice island sidewalls (when grounded) to the left of the predominant wind direction, and possibly even contribute to fracture mechanisms such as the footloose mechanism.

Ice islands which have originated from the Ellesmere Island ice shelves over the past decade drifted south along the western coast of the CAA, with 'Markham-3 (M-3)' and 'Ward Hunt-2 (WH-2)' diverting into the Sverdrup Basin (Crawford 2013, McGonigal et al. 2011). M-3 drifted approximately 2200 km and was tracked as far as 161°W in the southern Beaufort Sea (Crawford 2013, Hochheim et al. 2012), reinforcing the concern of offshore exploration companies regarding these ice hazards (Mueller et al. 2013, Sackinger et al. 1991).

3.5 Summary and outlook

In summary it is clear that many parts of the cryosphere are undergoing rapid, and increasing, changes in the Eastern Canadian Arctic. All available evidence, whether from *in situ* measurements, satellite remote sensing, or modelling, indicates that glaciers and ice caps have been in a strongly negative mass balance condition since at least the start of the 21st century. Losses have accelerated over the past decade, with glacier and ice cap thinning particularly prominent at low elevations and in more southerly regions. Smaller ice masses are also experiencing high rates of mass loss, with the complete loss of some small ice bodies already recorded on Axel Heiberg Island (Thomson et al. 2011). Way (2015) predicts that if the current ice declines on Grinnell and Terra Nivea ice caps, Baffin Island, continue to AD 2100, the total ice-covered area will be reduced by >57% compared to present.

The study of Lenaerts et al. (2013) provides one of the few detailed assessments of how glaciers and ice caps across the CAA will respond to future climate warming. Using the moderate AR5 RCP4.5 warming scenario and predictions to the year 2100, Lenaerts et al. (2013) demonstrate that enhanced meltwater runoff from CAA glaciers will not be sufficiently compensated by increased snowfall. This results in sustained 21st century mass losses for glaciers across the CAA in >99% of model runs. This makes it highly likely that the recently observed mass losses of these glaciers will continue, resulting in the complete disappearance of many small glaciers and ice caps over the next century.

Both early and recent studies on the ice shelves of northern Ellesmere Island suggest that these features are unlikely to persist long into the future if current climate conditions persist (Hattersley-Smith 1955, Braun et al. 2004, Copland et al. 2007, Mortimer et al. 2012, White et al. 2015a, 2015b). This prediction is based on the inability of past ice shelves to regenerate, and gradual mass losses over the last ~100 years which have weakened ice shelves by causing thinning and fracture development. It has also been observed that increasing air temperatures and record

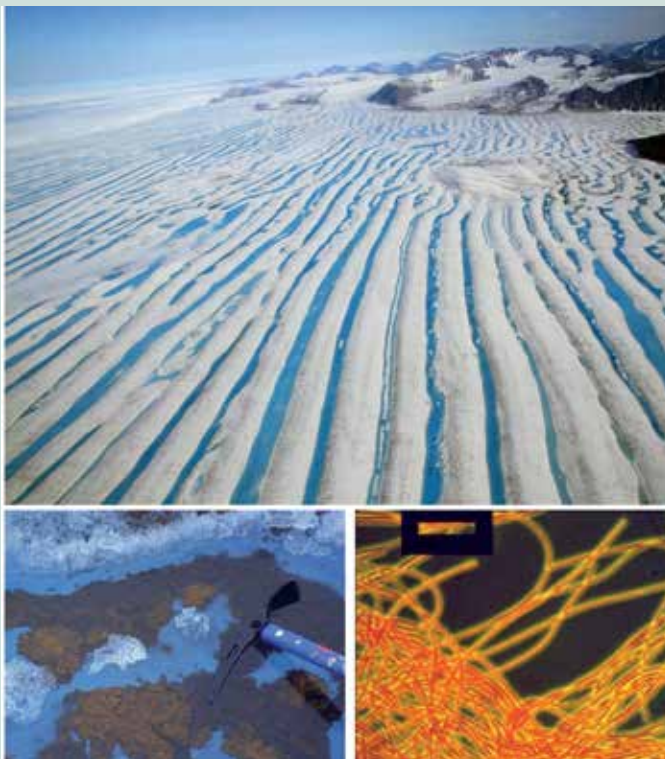
warm summers combined with the loss of multi-year land-fast sea ice, open water conditions along the northern coast of Ellesmere Island and offshore/along-shore winds are providing an environment conducive to ice shelf break-up that will eventually lead to the demise of the remaining ice shelves (Copland et al. 2007, Pope et al. 2012, White et al. 2015a). Hattersley-Smith (1955) predicted that the Ward Hunt Ice Shelf would disintegrate by 2035 if the summer conditions of 1954 continued, while White et al. (2015a) estimated that, based on the rate of surface melt and lack of glacial input, the Petersen Ice Shelf would disappear by 2041-2044. However, recent calving and open water events suggest that the complete loss of the Petersen Ice Shelf will likely occur well before this. For the Milne Ice Shelf, Mortimer et al. (2012) concluded that it is not in equilibrium with current climate as it formed under past colder conditions. Given the recent thinning of this ice mass and reduction in glacier inputs, it is likely that over the next few decades the Milne Ice Shelf will follow the pattern of breakups recently observed for all other northern Ellesmere Island ice shelves. The loss of ice shelves is also likely to lead to the loss of a unique assemblage of microbial life (Box C).

Since the Ellesmere Island ice shelves show no sign of regeneration they will eventually cease to become a source of ice islands. However, calving from floating glacier tongues on Ellesmere Island and northwest Greenland will persist for the foreseeable future, leading to continuing risks for marine shipping and offshore exploration in the Eastern Canadian Arctic.

BOX C. Life on ice

Snow fields, glaciers, ice shelves and ice islands are changing rapidly in Canada's north. However, the consequences of this are not restricted to the physical environment. These ice masses are also habitats for diverse organisms that survive, and even thrive, in the "cold biosphere", the ensemble of habitats over planet Earth that experience prolonged cold and freezing. These life forms are mostly microscopic, and they have captured the interest of microbiologists in their research on how cells cope with extreme environments and how life may have persisted and evolved during periods of glaciation on Earth (Vincent and Howard-Williams 2000). These observations have also led scientists to speculate about the potential for microbial life in icy environments elsewhere in the solar system, for example on planet Mars and certain moons of Jupiter. Biotechnologists have developed a keen interest in these microscopic 'extremophiles' because they are the potential source of unusual enzymes, antifreeze compounds and other biomolecules that could have applications in medicine, food production, bioremediation and industrial processes (e.g., Christner, 2010).

Snow was once thought of as a sterile substance, but is now known to contain many types of bacteria and a variety of more advanced, nucleus-containing cells ('microbial eukaryotes'). Studies along the northern coast of Ellesmere Island have shown that the snow contains diverse microbiota, including species likely transported in the atmosphere from the Arctic Ocean and from lakes and streams. Some of the other species were similar to those found outside Canada but from alpine regions, Antarctica, and other parts of the Arctic, indicating the global distribution of these genetically distinct cells throughout the cold biosphere (Harding et al. 2011).



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Cryoconite holes were first discovered on the Greenland Ice Sheet, and are now the focus of international attention as 'extreme ecosystems' with diverse microscopic life. These appear as small cylindrical melt holes at lower elevations on the surface of glaciers, and they are common features of the glacial environments of Nunavut. The holes form because small

FIGURE C1. Elongate melt pools on the surface of the Ward Hunt Shelf, northernmost Ellesmere Island, Nunavut, 23 July 2007 (see Figures 1 and 5). Most of this ancient ice shelf melted, fractured and disappeared over the last decade due to rapid climate warming. At some locations, brightly coloured microbial mats coat the bottom sediments of the pools (bottom left). These mats are composed of filamentous cyanobacteria (fluorescence photomicrograph, bottom right) and many associated microorganisms.

amounts of sediment (called cryoconite) heat up in the sun and melt down into the ice. Many small cryoconite holes can coalesce into larger ones, and studies on the White Glacier, Axel Heiberg Island, and on the Canada Glacier, Antarctica, have shown that they harbour microbial consortia composed of green algae, cyanobacteria, and diatoms as well as other microorganisms (Mueller et al. 2001). These cryoconite features can modify the reflective properties of ice, and thereby hasten the local melting of glacier surfaces.

The richest communities of microscopic life on ice in Nunavut have been discovered in meltwater lakes on the ice shelves along the northern coast of Ellesmere Island (Jungblut et al. 2017; Figure C1). At some locations on these ice shelves, the base of the lakes is coated with a bright orange ‘microbial mat’ composed of cyanobacterial filaments that bind together the sediments. The coloration is the result of red-orange carotenoids such as canthaxanthin that protect the cells from harsh UV radiation that penetrates to bottom of these clear waters. Genetic comparisons of these Nunavut mat communities with similar communities in Antarctica have shown that they contain hundreds of species, with an impressive genetic capacity to cope with the extreme stresses imposed in these environments (Varin et al. 2012). Climate warming in Nunavut is leading to the rapid loss of these ice-dependent habitats and the imminent extinction of these unique biological communities (Vincent et al. 2011).

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Chapter 4 Permafrost

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Key messages

- The majority of ecosystem and hydrological processes occur in the active layer (seasonally thawed layer above permafrost) including carbon fluxes, and consequently the active layer can influence the evolution of landscapes at the regional-scale.
- Ice-rich permafrost landscapes are susceptible to the effects of thermokarst development including the formation of lakes and other hydrological changes, mass movements and carbon release.
- Permafrost in the IRIS 2 region is warming. The longest record is from Canadian Force Station (CFS) Alert on Ellesmere Island and shows warming of permafrost at depth between 0.3-0.5 °C per decade since the monitoring period began in 1978.
- Climate models suggest that considerable warming will occur within the IRIS 2 region throughout this century which is expected to have a substantial effect on both permafrost distribution and thermal state.

Abstract

Permafrost is defined as earth materials that remain at or below 0 °C for two or more years. The area that is subject to seasonal thaw above permafrost is known as the active layer. Permafrost may or may not contain ground ice, however, if it does, thaw can change the landscape substantially. This includes the development of thermokarst ponds, mass movements (including active layer detachment failures and retrogressive thaw slumps), the subsidence of roads, buildings and other infrastructure that might be built in these areas, as well as the release of organic carbon which may further accelerate climate warming. Permafrost in the IRIS 2 region varies in its susceptibility to climate change. Over the last two decades, long-term observations of permafrost temperatures in the northern part of the IRIS 2 region Canadian Force Station (CFS) have shown warming trends of between 0.3-0.5 °C/decade. Climate models for these areas suggest that this area will warm with considerable effect on both permafrost distribution and temperature between now and the end of this century.

4.1 Introduction

Although the ground might not be the first thing people think about with respect to changing climates in areas of the Eastern Canadian Arctic, it is actually one of the most dynamic areas of change due to the presence of permafrost. Permafrost is defined as Earth materials that remain at or below 0 °C for two or more consecutive years (ACIA 2005). Permafrost and the layer of earth material that thaw seasonally (active layer) affect the movement of surface and subsurface moisture, causing mass movements, as well as influencing the exchange of greenhouse gasses from the subsurface to the atmosphere. Many aspects of life in the Eastern Canadian Arctic depend on the thermal state of the ground, including issues associated with infrastructure and water quality (see Chapters 14 and 15).

Permafrost is a dynamic element of the cryosphere that is currently changing in response to climate change (Bonnaventure and Lamoureux 2013). Permafrost is the only element of the cryosphere that people live on year-round; however, it is often overlooked compared to the attention that is given to other cryospheric elements such as sea ice and glaciers. The state of permafrost is particularly important with respect to transportation and natural resource infrastructure. Assessments of the current distribution, thermal state and properties of permafrost are currently needed in the Eastern Canadian Arctic in order to serve as baseline data as well as for climate adaptation and mitigation planning at both the territorial and community levels.

4.1.1 Permafrost scientific background

Permafrost is officially defined as Earth materials that remain at or below 0 °C for two or more consecutive years (ACIA 2005, French 2007). However, in areas of the Eastern Canadian Arctic, the ground has been frozen for many millennia (French 2007). Permafrost can develop in rocks, sediment or organic material and may or may not contain ice. Permafrost zones cover large parts of the Northern Hemisphere. Over 50% of Canada lies within a permafrost zone (Zhang et al. 2008), and much of the permafrost has developed over thousands of years (Davis 2001). The

primary control over both the distribution and thickness of permafrost in any area is climate with mean annual air temperature (MAAT) typically considered the primary controlling variable. Other climatic and environmental elements including snow cover duration and thickness, vegetation, hydrology, and proximity to coastline are also important controls. The spatial distribution of permafrost is essentially continuous throughout the IRIS 2 region (Figure 1).

Permafrost landform variability in the region is largely due to differential distribution of ground ice content (ice developed *in situ* below ground by a range of processes). Ground ice is present in sediments that are frost susceptible (e.g., fine grained material) (French 2007). The development of ground ice provides structure to frozen sediments in permafrost regions, but melting of this ice results in instability, disturbing both the sediment and any infrastructure built upon it. The percentages of ground ice in sediments of the region range from near zero to about 15% (Figure 1). With climate expected to change in a variety of ways within the Eastern Canadian Arctic (see Chapter 2), it is reasonable to assume that permafrost may also be responding. This chapter looks at changing permafrost within the context of the IRIS 2 region, as well as highlighting the current state of knowledge.

4.2 Permafrost areas of investigation and current research

4.2.1 Impacts of climate warming on permafrost

The impacts of a warming climate over time produces vertical temperature profile changes in the permafrost and a greater depth of summer thaw, with a thicker active layer. Both an increase in mean annual temperature and a change in precipitation regime leading to a thicker snow cover can result in more heat absorption at ground level in the summer and less heat escape in winter. In Alaska, an increase of 0.3 °C to 4 °C was observed in sediment 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), Nunavut (Smith et al. 2010, 2005) Alaska (Osterkamp and Romanovsky

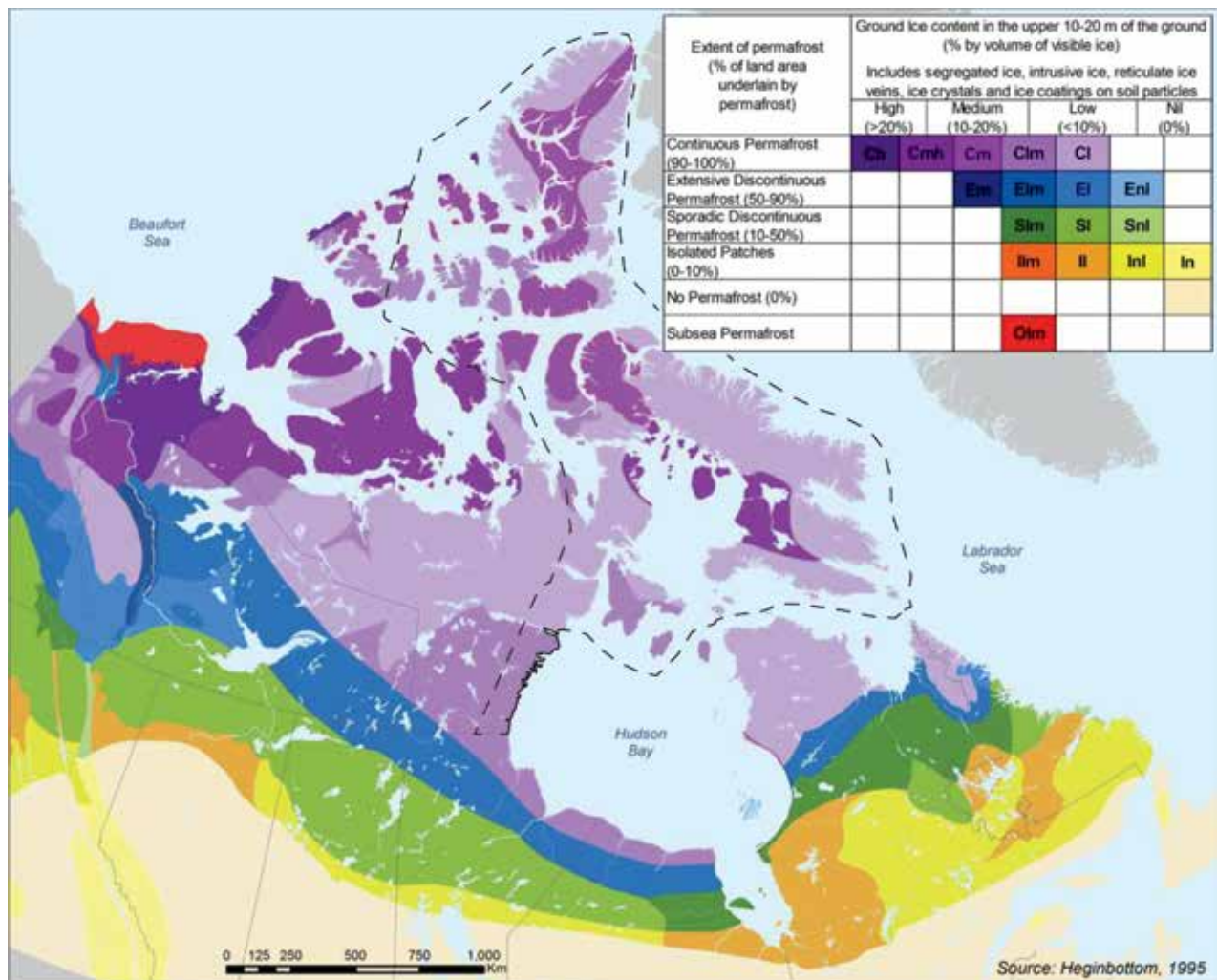


FIGURE 1. Context of permafrost and ground ice conditions in the Canadian Arctic; the dashed line represents the IRIS 2 region. Adapted from Heginbottom et al. (1995). C denotes continuous permafrost (>90% coverage in the landscape), E for extensive discontinuous (50-90%), S for sporadic discontinuous (10-50%), i for Isolated patches of permafrost (0-10%), O for subsea permafrost. The second letter denotes ground ice content (h for high, m for moderate, l for low).

1999, Osterkamp 2003) and the Canadian Eastern Subarctic (Smith et al. 2010a). In the Canadian Eastern Subarctic, a general rise of 2 °C in ground temperatures took place from 1993 to 2005 (Allard et al. 2007).

4.2.2 Active layer recent changes and system evolution

The active layer refers to the layer of ground in areas underlain by permafrost that is subject to annual freezing and thawing.

Fundamentally, this layer exists at the idealized freezing/melting point of water in nature (0 °C). Understanding the active layer is critical because the vast majority of the ecosystem and hydrological processes in permafrost terrain occur within this zone, including carbon fluxes, and as a consequence it is directly related to the landscape evolution of an area.

The controls on the thickness of the active layer can generally be seen as a combination of macro- and micro-scale variables, which work in tandem. In the broadest sense,

active layer thicknesses can be correlated with many of the same influences that control surface climate, including: vegetation cover, latitude, elevation, solar insolation patterns, albedo, proximity to glaciers and to warm maritime ocean currents (Bockheim and Hall 2002). Within the IRIS 2 region, active layers are generally thin as a result of long cold winters with limited snow cover and short summers.

Precise measurements and evolution of the active layer are difficult to obtain without direct field observation. Active layer monitoring essentially involves recording measurements during one or more thaw seasons in order to establish the spatial pattern and thickness of thaw, and to determine multi-year trends in the active layer system. The two primary ways in which this is accomplished involve a physical measurement using a metallic probe or by recording the maximum thaw depth using electronic temperature loggers or visual observation devices. A general distinction between the two approaches is that one is physical (identifying the location of frozen Earth material) while the other is thermal measuring temperature (the location of the 0 °C isotherm).

Physical probing using a metallic rod is an effective way of determining the depth to the frost table. This method is initially used in the field as a rough estimate of thaw depth as there are many variables involved in getting an accurate and comparable year-to-year reading. Probing is the primary method used with the Circumpolar Active Layer Monitoring (CALM) program, an active layer depth measurement protocol developed by Brown et al. (2000). The CALM protocol was created to address the question of how near-surface permafrost and the active layer are responding to climate change. Under the CALM protocol, grids are set up with a series of nodes where year-to-year active layer depths can be measured. CALM grids vary in size, with the majority either 100 x 100 m or 1000 x 1000 m in area. The sampling scheme used in CALM protocol employs a combination of linear and random sampling, which is used in the grid setup. Within each area selected for the study, 100 grid boxes are demarcated and the corners marked off using metallic rods, painted rocks or wooden stakes. Within each box, one random site is chosen and marked off as the location of thaw depth measurement using probing. Within

the IRIS 2 region there are 4 CALM sites: Eureka, Tanquary Fiord, Lake Hazen and Alexandria Fiord. Data collected at these sites from the mid 1990s onward (<https://www.gwu.edu/~calm/data/north.html>) show active layer depths ranging from 26 to 60 cm in late summer.

As climate is a first-order control on both permafrost and the active layer, it is logical to infer that changes to both will occur as air temperatures increase. However, an important question is: what is the link between increasing air temperatures and thickening of the active layer? The results of thickening active layers show similar effects to those of permafrost degradation, as essentially, they both involve the thaw of ground ice. During times of increased summer air temperature and increased thawing indices, active layer thicknesses increase as a direct consequence (Zhang et al. 1997). This idea is conceptualized in Figure 2 where the relationship between air temperature and active layer thickness is illustrated. This finding is also indicated in the recently compiled Snow, Water, Ice and Permafrost in the Arctic report (AMAP 2011) in which CALM grid data show thickening active layers that are linked to summer air temperatures and show substantial interannual variability.

4.2.3 Ground ice types and occurrence in permafrost

4.2.3.1 What is ground ice?

Ground ice is a term referring to any type of ice found in the frozen ground. Some types include pore ice (ice in the space between soil grains, sometimes invisible to the naked eye), segregated ice (from millimetre thin lenses to metre thick massive bodies of ice), ice-wedge ice (vein ice), and buried ice (French and Shur 2010). Although ground ice may annually freeze and thaw in the active layer, it may also persist and evolve through time. Depending on the type of sediment, moisture conditions and permafrost conditions (e.g., temperature, active layer depth), various ice structures and characteristics can be observed in the frozen ground; for example, fine grained sediments (silt clay) are typically prone to develop thicker ice-lenses than in sandy or gravelly sediments (French and Shur 2010, Stephani et al. 2014).

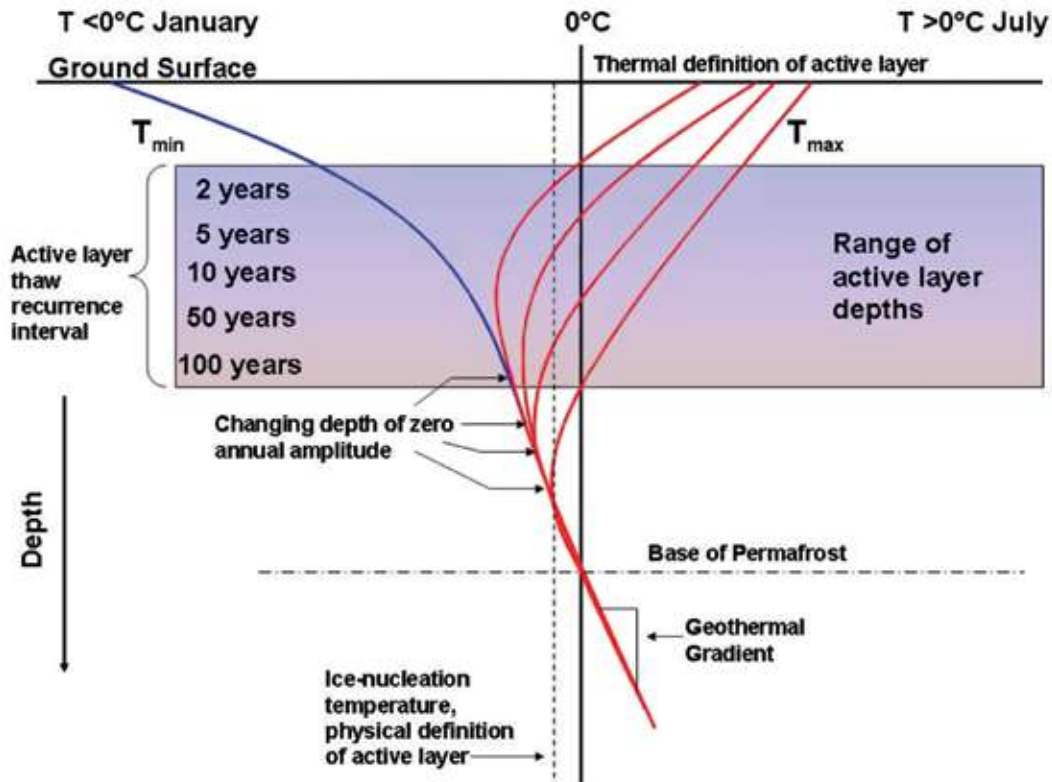


FIGURE 2. Conceptual temperature envelope showing scenarios of increased summer air temperatures and the relation to thickening active layers and depth of zero annual amplitude (the point at which there is no discernible change in temperature). The figure also suggests a recurrence interval for these scenarios, which relates to the probability of occurrence. From Bonneventure and Lamoureau (2013).

4.2.3.2 Formation process

Ground ice may either develop *in situ*, as a consequence of the past and present climate and permafrost conditions, or be buried, such as glacier ice being covered by a slope collapse and preserved after general deglaciation (French 2007). One obvious example of *in situ* ground ice formation is the genesis of an ice wedge (Figure 3). Thermal contraction of the ground during a cold spell (a significant and rapid drop in air temperature) can force the ground to crack open. These cracks usually extend through the active-layer and into permafrost (1-3 m being common). At the end of winter when snow melts, runoff water may infiltrate the still open crack, freezing as a vein of ice. A recurrence of



FIGURE 3. This exposed syngenetic ice wedge grew in peaty-silt accumulating near the front of the Qalikturvik glacier on Bylot Island, Nunavut. Shovel for scale.



FIGURE 4. Buried glacier ice found just below the active-layer on Bylot Island, NU. An increase in active layer thickness after a very warm summer caused the ice to melt, creating a small (~ 1000 m²) slope disturbance, exposing the buried ice.

this process at the same emplacement over the years will enable the formation of an ice wedge. Multiple wedges are frequently organized in networks of ice wedge polygons.

Dynamic slope processes occurring in glacial valleys can bury glacier margins; as the glacier retreats, the buried ice will be preserved in permafrost long after deglaciation (Figure 4). Consequently, buried ice is typically found along valley walls and within moraines, making former glacier margins. Buried ice can occur metres below the surface, or in other circumstances just below the active layer, where it may trigger surface disturbance as the ground thaws and the ice melts. (Coulombe et al. 2015).

4.2.3.3 Ground ice distribution

Modelled ground ice volumes for the Northern Hemisphere vary between 5.6 and 36.6 x 10³km³ depending on the assumptions used (Zhang et al. 1999). Pore and segregated



FIGURE 5. Very ice-rich permafrost core from the transient layer in coarse gravelly sediments on Ward Hunt Island, on the northern coast of Ellesmere Island. Sediments are suspended in ice, forming a suspended cryostructure.

ice overall account for between 67 and 75% of the total volume (French 2007).

Although buried ice can be found at various depths in the ground, *in situ* segregation ice or pore ice is usually distributed (or located) according to permafrost conditions developed over time. For example, at the base of the active layer, an ice-rich transient layer acts as a buffer between the permafrost and the active layer (Figure 5; Shur et al. 2005). The transient layer can stay frozen for decades between warm spells, a period during which it becomes very ice-rich. A transient layer occurs in almost all locations where liquid water is available during the melt season, and forms in most types of sediments.

Below the transient layer, ice content varies, depending on the history of the permafrost. In sites where no new sediments have accumulated after permafrost development (epigenetic permafrost), ice content usually diminishes at depth, with only scattered ice lenses present. In sites where mass movement, organic growth, fluvial deposition or aolian (wind) effects add layers of sediments on the ground as permafrost continues to form, the transient layer can slowly migrate upward as active layer depths remain similar through time. This process of syngenetic

permafrost aggradation typically creates very ice-rich sediment (Guodong 1983). Ice wedges can reach depths of more than 10 m as they continue their growth while the sediment gradually accumulates.

Factors of ice formation such as moisture availability, sediment characteristics (grain size, porosity) and landscape history are influenced by the site location. For example, plateaus may be dominated by erosional processes, and slopes are influenced by gravitational displacement and transport processes. Valley floors are likely to be characterized by inputs of water and sediments (from slope processes, and alluvial and aeolian deposition). Valley floors adjacent to coastlines are more likely to have accumulated fine-grained sediments during deglaciation and subsequent marine transgression. These factors influence the fluxes of water and sediment in each location, impacting the process of ground ice formation.

Valley floor permafrost can evolve into syngenetic permafrost, as wind-blown sediments mixed with peat growth can contribute to sediment accumulation at rates of 1 mm y^{-1} (Fortier et al. 2006). Higher rates of accumulation occur where alluvial fans and talus cones form from sediment over time, generally with higher volumetric water content capacity compared to coarse grained sediments. This aggradation of sediments and water enables the permafrost table to rise to near its equilibrium level at the surface and creates ideal conditions for the formation of ice-rich permafrost. Such processes can also occur on slopes, where slow mass movement can create local ice-rich conditions (Verpaelst et al. 2017).

Plateaus are likely to receive less input of fine sediments than do valley floors. Water will drain downstream, limiting the amount of water available to form segregational ground ice on the plateau. A plateau characterized by epigenetic permafrost is generally stable due to limited input in deposits. However, plateaus may further be eroded due to slope processes (collapses, thaw slumps), that degrade the permafrost.

4.2.4 Thermal state of permafrost, boreholes and data across the region

A key indicator of current and changing permafrost conditions is the permafrost temperature or thermal state. Information on the thermal state of permafrost is usually obtained through measurements of ground temperature in instrumented boreholes several meters deep. Knowledge on the thermal state of permafrost in Nunavut increased largely due to efforts made during the International Polar Year (IPY) to enhance the permafrost monitoring network (e.g., Smith et al. 2010 a, b). Prior to IPY, information on the permafrost temperature was largely based on historical data compiled by Smith and Burgess (2000), and only a limited number of sites had continuous data records for several years, such as CFS Alert and Iqaluit.

In 2008, boreholes, up to 15 m deep, were instrumented in six communities in the Baffin region in collaboration with the Nunavut government (Ednie and Smith 2010, 2011). In 2009, additional sites were established in the Kivalliq region. Boreholes, 10 m deep, were also established at Eureka in 2009 by Geological Survey of Canada (GSC) and the University of Ottawa. These boreholes addressed a gap in the Eastern Canadian Arctic between the monitoring sites operated by Université Laval in northern Quebec and the High Arctic site at CFS Alert maintained by the GSC. Two boreholes (7 m deep) were also instrumented in 2012 in the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island by Queen's University, providing new information on permafrost temperatures in the western Queen Elizabeth Islands.

Although, there are still a limited number of permafrost monitoring sites in Nunavut, ground temperatures are now available for a latitudinal transect in the Eastern Canadian Arctic, providing improved regional information on the thermal state of permafrost (Smith et al. 2010a). Additional information on permafrost conditions can be obtained from geotechnical investigations conducted to support engineering design at mineral resource development sites such as the proposed Mary River mine sites (e.g., Roujanski et al. 2010). Recent ground temperature data from active

permafrost monitoring sites and other sources have been compiled (Smith et al. 2013) providing a significant update of the historical database of Smith and Burgess (2000). A map was also produced (Figure 6) that provides information on the permafrost thermal state for the IRIS 2 and adjacent regions. Generally, cold permafrost conditions exist throughout the IRIS 2 region with mean annual ground temperatures below -5°C . Warmer permafrost, however,

can be found near lakes and rivers, and taliks (unfrozen ground) exist beneath large water bodies. Permafrost is greater than 100 m (thick), and commonly several hundred meters thick, except in emergent coastal areas where the land surface has been exposed to cold arctic air temperatures for a shorter period of time (Smith and Burgess 2002, Smith et al. 2001). Permafrost temperature shows a general latitudinal trend (Figure 7) with temperatures

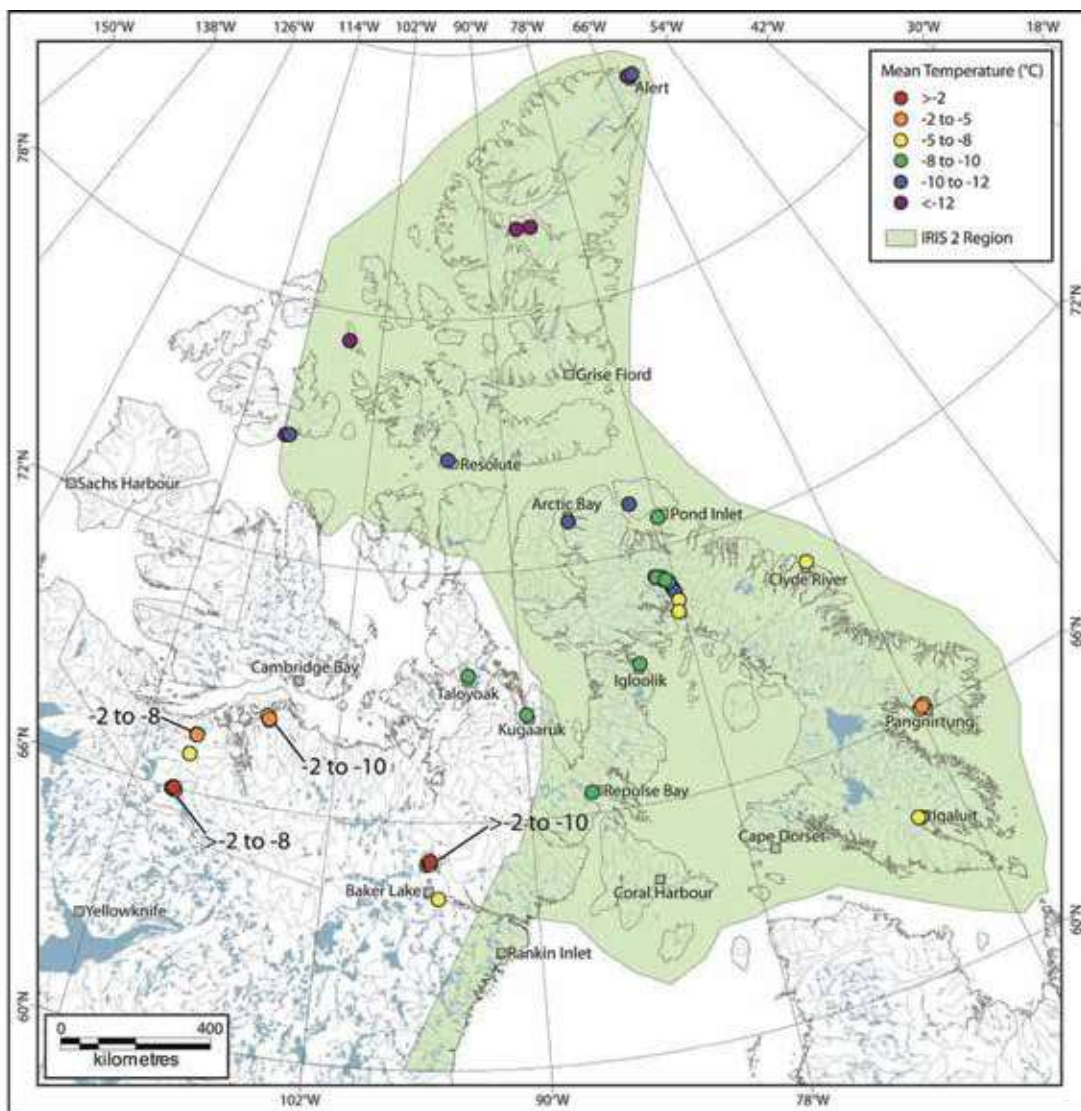


FIGURE 6. Permafrost temperatures in the IRIS 2 and adjacent regions (derived from Smith et al. (2013)). Temperatures represent mean annual ground temperature at the depth of zero annual amplitude (or closest measurement depth to it). Data presented for the IRIS 2 region were generally collected since 2008.

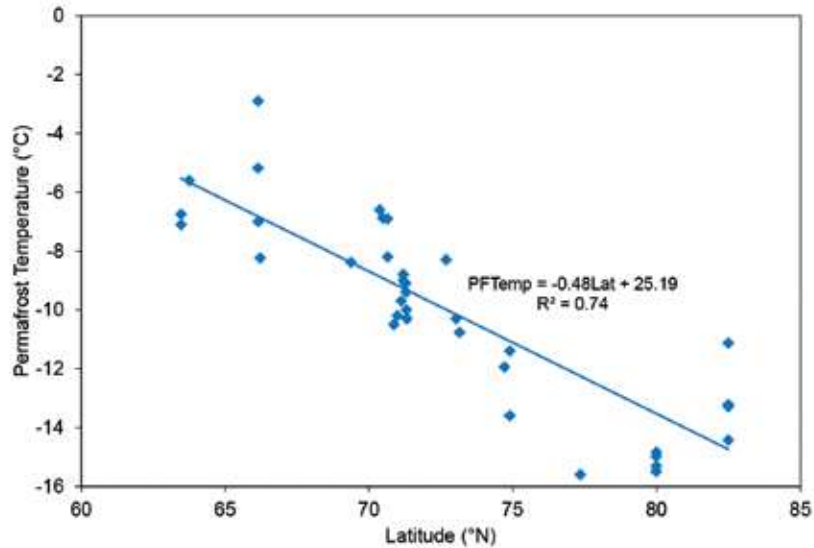


FIGURE 7. Relation between permafrost temperature and latitude for the IRIS 2 region. Permafrost temperature is based on mean annual ground temperature at the depth of zero annual amplitude (or the measurement depth closest to it). Data are derived from Smith et al. (2013).

of about -5 to -6 °C in the southern portion of the IRIS 2 region, decreasing to -15 °C on Ellesmere Island. On Baffin Island ground temperatures are generally between -5 °C and -10 °C depending on surface and material conditions (Ednie and Smith 2010, 2011).

Although the network of permafrost monitoring sites is sparse in the region, data are available to characterize permafrost at a regional scale. Increased availability of data collected during geotechnical investigations associated with potential resource development projects or other community construction activities will further improve the characterization of permafrost thermal state in the region.

4.2.5 Recent Changes in Permafrost Thermal State

Limited long-term records are available to characterize recent changes in permafrost thermal state in the IRIS 2 region. The longest record exists at CFS Alert where permafrost temperatures have been monitored since 1978. Ground temperatures in the upper 25 m have generally increased since the 1980s at rates of about 0.05 °C and 0.03 °C

per year for 15 and 24 m depth respectively (Table 1, Figure 8). The rate of temperature increase is greater for the latter part of the record with temperatures increasing since 2000 by 0.07 °C to 0.1 °C per year at 24 m and 0.14 °C per year at a depth of 15 m (Smith et al. 2010a, Romanovsky et al. 2013), consistent with regional increases in air temperature. In the polar desert of the High Arctic, ground temperatures are highly responsive to changes in air temperature due to the lack of a surface buffer layer and the ice-poor substrate (Throop et al. 2012). Snow cover is an important influence on the relationship between air and ground temperatures and a greater response in ground temperature is found for sites at Alert that have minimal snow cover compared to those having more snow (Smith et al. 2012). Winter warming was found to be largely responsible for the recent increase in permafrost temperature, and the effect is enhanced at sites with little snow cover (Smith et al. 2012).

Analysis of the shallow ground temperature record for Iqaluit between 1989 and 2004 also indicates that recent warming has occurred (Throop et al. 2010). Although cooling occurred until the early 1990s, the temperatures at 5 m depth increased by 0.2 °C per year between 1993 and 2004.

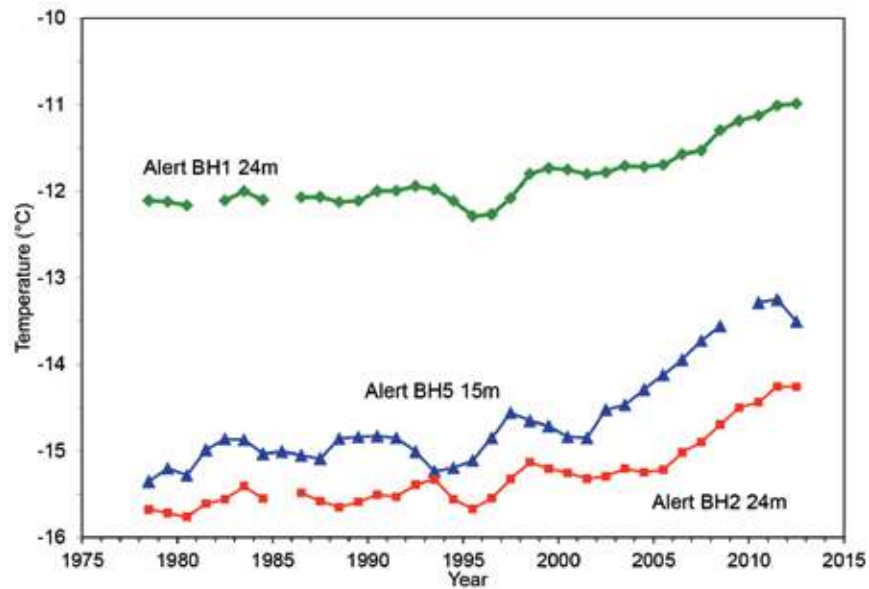


FIGURE 8. Permafrost temperature (annual mean) records for CFS Alert for depths of 15 and 24 m. BH1 is located near the coast and has greater snow cover than the other two sites. Updated from Smith et al. (2012) and Romanovsky et al. (2013).

TABLE 1. Change in permafrost temperature over time for selected sites. (Updated or derived from Romanovsky et al. (2013), Smith et al. (2012), Throop et al. (2012)).

Site and measurement depth	Time period	Rate of temperature change (°C per year)
Alert BH1 (24 m)	1978-2013	+0.03
	2000-2013	+0.07
Alert BH2 (24 m)	1978-2013	+0.03
	2000-2013	+0.1
Alert BH5 (15 m)	1978-2013	+0.05
	2000-2013	+0.14
Resolute (15 m)	2008-2012	+0.33
Eureka (10 m)	2009-2012	+0.29
Arctic Bay (15 m)	2008-2013	+0.18
Pond Inlet (15 m)	2008-2013	+0.15
Igloodik (15 m)	2008-2011	+0.07
Repulse Bay (15 m)	2009-2013	+0.25
Iqaluit (5 m)	1993-2004	+0.2

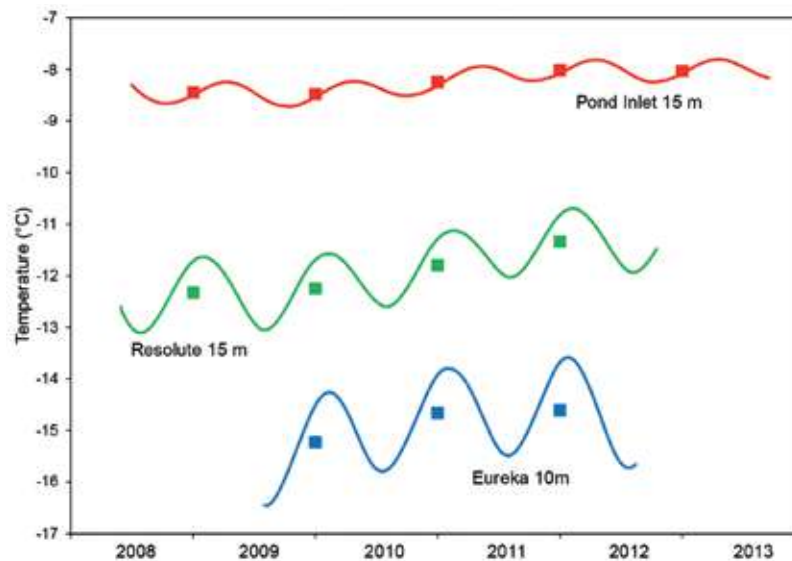


FIGURE 9. Time series of daily permafrost temperatures at 10-15 m depth for selected sites in the Baffin region. Annual mean ground temperatures are also shown (squares). From Ednie and Smith (2015).

Data records for other sites in the Baffin region are only 4 to 5 years long, too short to characterize long-term trends. However, these short records show some warming at depths of 10 to 15 m, following a similar pattern to the most recent records for Alert (Figure 9, Table 1), consistent with increases in air temperature between 2008 and 2010. These measurements are at depths above the zero-annual amplitude (> 20 m for most of these sites) and can reflect short term variations in surface temperature.

Although long-term records are limited, the information available indicates that there is ongoing general warming of permafrost in the Eastern Canadian Arctic. These changes are consistent with increases in air temperature and are similar to the changes in permafrost changes observed in northern Quebec and other locations across the High Arctic (Smith et al. 2010a,b, Allard et al. 2012).

4.2.6 Hazards: slope failures, retrogressive thaw slumps

The Eastern Canadian Arctic landscape is underlain by a wide variety of permafrost materials. Ice-rich permafrost is present in the region and particularly susceptible

to thaw and water drainage, which result in a wide range of landscape degradation and disturbance features. These permafrost landscape changes are of particular practical interest to northern communities, land management agencies, and other organizations due to the risk of damage to buildings and other infrastructure, and related risks to environmental quality (e.g., water quality).

Ice-rich permafrost is widespread in the western and central regions of Kitikmeot and the High Arctic. Degradation of this permafrost occurs when summer active layer depths are greater than normal and the ice in the upper permafrost is subject to melt. Deeper thaw can occur due to warmer summer conditions in a given year, or can be induced by alteration of the surface by removal of vegetation or compaction by heavy equipment. The water released can drain away and result in land subsidence. However, the most common and substantial impact is the formation of thermokarst (subsidence by ground ice melt), usually in the formation of irregular surface depressions where ice loss has occurred (Figure 10). In many instances, these depressions fill with water and can become thermokarst ponds (or lakes). These ponds will further warm the soil and permafrost and normally the ponds can grow in size by further ice loss and



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FIGURE 10. Examples of thermokarst from Melville Island, Nunavut. (a) Early thermokarst with irregular ground ice melt; (b) initial thermokarst pond formation; (c) an aerial view of thermokarst ponds.



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FIGURE 11. A thermo-erosional niche that developed on Bylot Island, Nunavut. These features can cause drainage of ponds or lakes, and expand rapidly through a combination of ice thaw and sediment erosion.

by bank erosion (Figure 10). In some cases, bank erosion may result in catastrophic drainage. Hence, thermokarst systems can change substantially over years to decades.

In other cases, ground ice thaw can result in localized erosion of the sediment surface and cause thermo-erosional niching. These features are characterized by narrow, often deep gullies either in former ice wedges or on slopes (Figure 11). They can expand rapidly with further melt and erosion, and are often associated with the drainage of thermokarst ponds and lakes (Godin and Fortier 2012).

Permafrost thaw can also result in larger disturbances that affect slopes. Active layer detachments (ALD) are a form of shallow sediment movement that occurs on relatively gentle slopes, when ice-rich permafrost melts and reduces the strength of the soil, resulting in a slide of material downslope over the frozen surface (Figure 12) (Lewkowicz 2007). These disturbances are associated with warm

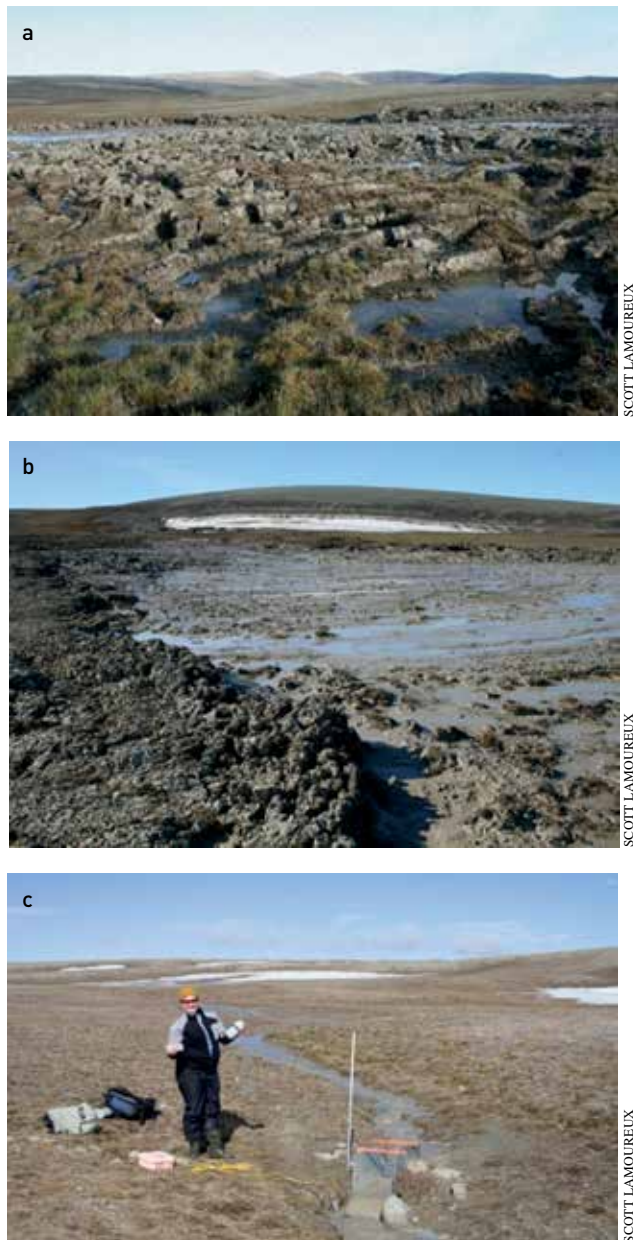


FIGURE 12. Active layer detachments (ALD) on Melville Island, Nunavut. (a) Fractured sediment and vegetation in a newly formed ALD; (b) the exposed scar zone where vegetation has been removed, resulting in a highly erodible surface; (c) downstream changes in water quality from an ALD are evident as high suspended sediment loads in streams.

summers and often follow major rainfall events, and can develop over a few hours or days. Many ALD are small, and the movement of sediment downslope is limited, but large examples can occur with dimensions >500 m in length (Lamoureux and Lafrenière 2009) (Figure 12). In addition to the immediate disturbance caused by the ALD, these features impact sediment erosion and water quality (Figure 12), and the effect of these environmental effects can last for many years (Lamoureux et al. 2014). The effect of ALD varies considerably, depending on the size, location, and water drainage through the disturbance. In many cases, the ALD results in the formation of a new stream channel on a slope where previously none existed. Recovery of vegetation and the formation of stable channels in the ALD reduce the effects of sediment erosion, but other water quality effects may last longer periods of time (Lamoureux et al. 2014).

The second major type of disturbance related to permafrost degradation is referred to as a retrogressive thaw slump (RTS). These features are characterized by the exposure of ground ice that rapidly melts, causing failure of the sediment overburden that is removed by runoff. RTS usually have a distinct head scarp composed of exposed ice and sediment, and a relatively flat floor composed of highly liquid mud (Figure 13). Unlike ALD, RTS are typically long-lived features that may be active for years to decades,



FIGURE 13. A retrogressive thaw slump (RTS) on northern Melville Island, near Drake Point. Note the exposed ground ice below the person and the flows of mud from the floor.

and can grow to large dimensions as a result. These features develop where thick ground ice is present near the surface, and can be initiated by exposure of the ice by stream bank or coastal erosion (Lantuit and Pollard 2008, Kokelj et al. 2013), an active layer detachment or other surface disturbances. The large size and persistence of these features makes them particularly important hazards and the downstream water quality effects are marked (Kokelj et al. 2013). This is seen in the form of increased sediment content in the water which has a substantial effect on aquatic life including fish.

The impact and risk associated with permafrost degradation and disturbance features requires careful assessment of terrain prior to construction of infrastructure, both to minimize the risk to the project and to reduce the risk of an environmental impact arising from permafrost changes (Lamoureux et al. 2015). Terrain analysis and mapping can provide insights where ground ice is present and may represent a risk in communities. Drilling to determine permafrost properties is also an important approach (LeBlanc et al. 2011). Methods to identify disturbances with remote

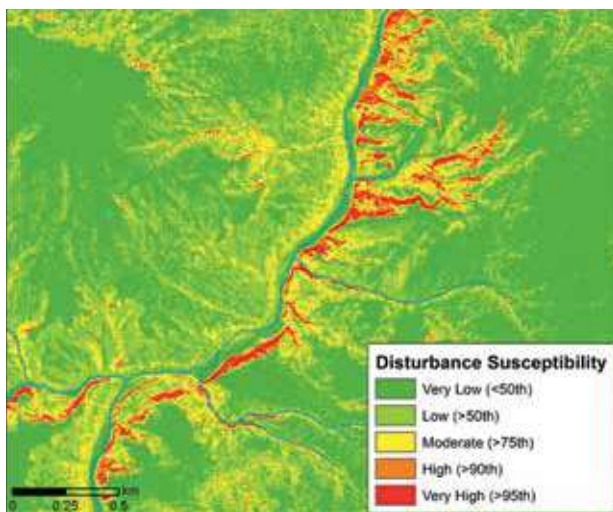


FIGURE 14. An example of a permafrost disturbance susceptibility map from near Drake Point, Melville Island, Nunavut. The map is produced by combining field mapping of disturbances with landscape modelling. The locations most susceptible to disturbance are indicated in orange and red (courtesy A. Rudy, Queen's University).

sensing (Rudy et al. 2013, Brooker et al. 2014) provide a means to efficiently determine the extent of landscape disturbance, and land disturbance susceptibility modelling approaches provide an improved understanding of the locations on the landscape that are most likely to be effected by degradation and disturbance (Figure 14) (Rudy et al. 2016). These methods can also help to improve our understanding of the environmental effects of permafrost degradation on surface waters (Bowden et al. 2008, Lewis et al. 2012, Lafrenière and Lamoureux 2013, Lamoureux et al. 2014).

4.2.7 Ecosystem and greenhouse gas impacts

Permafrost stores more carbon than does the atmosphere (Hugelius et al. 2014). Warming of the Arctic is associated with many impacts on the landscape, including permafrost thawing and erosion, which can lead to the release of organic carbon as carbon dioxide (CO₂) and methane (CH₄) greenhouse gases (GHG). Aquatic permafrost ecosystems can act as biogeochemical hotspots, and represent substantial sources of GHG. The age, source(s), and emission rates of carbon released can be strongly influenced by local ground conditions, which in turn affect the biogeochemical dynamics of ponds and lakes.

Located in centre the of Eastern Canadian Arctic, Bylot Island includes numerous periglacial aquatic landscapes (Figure 15). Several glacial valleys of the island represent highly dynamic biogeosystems rich in permafrost ground ice, peat, and aquatic environments. Studies here have been aimed at characterizing the influence of geomorphology and permafrost degradation on aquatic biogeochemistry. All aquatic systems are located within a ~ 3 m-thick permafrost terrace composed of alternating organic (peat) and mineral (aeolian silt) layers, that started to accumulate at the bottom of the valley ~ 3700 years ago (Fortier and Allard 2004).

Results and field observations indicate a relation between pond/lake morphology, processes of permafrost degradation, and the age of carbon processed – ultimately released as GHG – in these aquatic systems (Bouchard et al. 2015). The age and GHG concentration of gas bubbles



FIGURE 15. Location of the study site in the continuous permafrost zone of the Eastern Canadian Arctic (a), north of Baffin Island (b), within one of the several glacier valleys of Bylot Island, Nunavut (c). The studied valley contains numerous aquatic systems of different sizes (d). Source of the permafrost map (a): Brown et al. (1998). Satellite photo (c): Terra-MODIS, 22 July 2012. Photograph (d): I. Laurion.

show different trends in the various types of water bodies (Figure 16). Small and shallow polygonal and ice-wedge ponds produce modern CH_4 and modern to young (< 500 years BP) CO_2 , whereas larger and deeper lakes release older GHG, up to ~ 3500 BP for CH_4 , close to the maximum age of the permafrost terrace. There seems to be a gradient in CH_4 age and concentration within lakes, with younger and less concentrated CH_4 from the lake edge, and older and more concentrated CH_4 from the center (deeper and older bottom sediments). This suggests that the CH_4 age and concentration in bubbles are controlled by the geomorphology and development of the lake. Considering all ponds and lakes as a whole, CH_4 is generally one or two orders of magnitude more concentrated than CO_2 in emitted bubbles. These results are representative of summer conditions only but show that this type of activity is associated with permafrost degradation in the region.

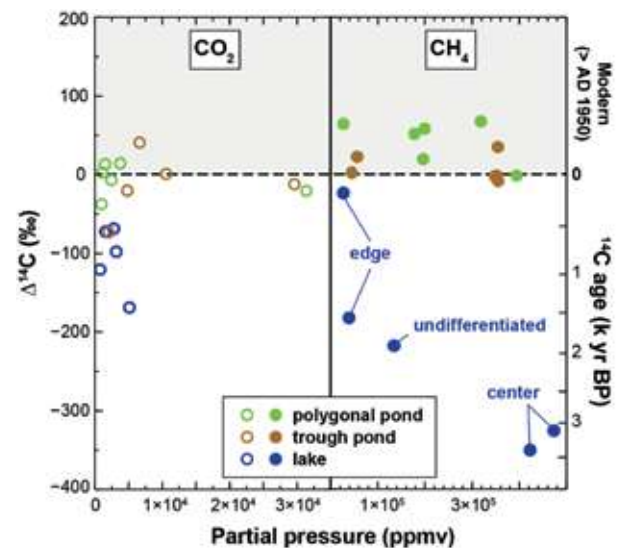


FIGURE 16. Concentration and age of bubbling GHG collected from ponds and lakes on Bylot Island, Nunavut. Gas concentration (x-axis) is expressed as partial pressure (in ppmv, parts per million volumetric) of CO_2 (open circles) and CH_4 (full circles). Radiocarbon age is expressed as the normalized radiocarbon activity ($\Delta^{14}\text{C}$, in ppt; left y-axis) corrected for isotopic fractionation and decay that took place between sampling and measurement dates, and in thousands of years before present (k yr. BP; right y-axis).

Dissolved GHG saturation levels in the water column of these aquatic systems show very different trends across the various water bodies (Figure 17). Polygonal ponds are generally CO₂ sinks, and CH₄ sources. Larger lakes are near equilibrium with the atmosphere (small sources), and ice-wedge ponds are supersaturated in both gases, especially when their margins are actively eroding.

The observed differences are related to morphology and limnology. The polygonal ponds have flat and shallow bottoms covered by abundant cyanobacterial mats, resulting in active photosynthesis and CO₂ consumption. Waters in deeper lakes are generally well-mixed by wind, thus equilibrating their GHG concentrations with the atmosphere. Ice-wedge ponds are strongly stratified and have oxygen-depleted bottom waters, which can lead to a high production of dissolved CO₂ and CH₄ especially when shores are eroding and transferring organic carbon to the water. The highest saturation values were measured in an ice-wedge pond with actively eroding shores (Figure 14). These results are representative of summer conditions only, and more

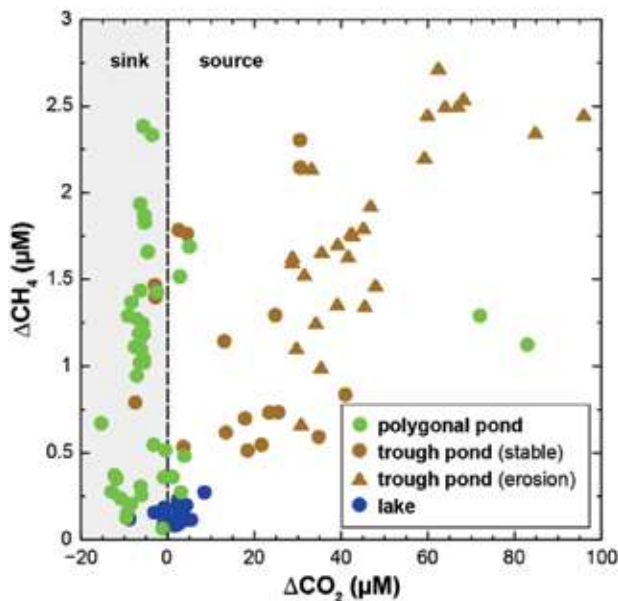


FIGURE 17. Saturation levels of dissolved GHG in pond and lake water. Values are expressed as the departure from saturation (in μM) for CO₂ (x-axis) and CH₄ (y-axis). Values < 0 indicate a sink, whereas values > 0 indicate a source.

measurements will be needed to provide a complete understanding of processes involved. Such findings nevertheless underscore the strong impact of local geomorphology and permafrost degradation processes on aquatic system biogeochemistry.

4.2.8 Permafrost and climate models

Global climate models (GCMs) from the climate model intercomparison project (CMIP3/CMIP5) show general agreement that permafrost degradation will occur in northern Canada throughout the next century (Arzhanov et al. 2012, Koven et al. 2013, Slater and Lawrence 2013). However, model projections of the magnitude of permafrost degradation and the spatial distribution of expected changes vary considerably due to inter-model differences in projected warming and surface parameterization (Koven et al. 2013). For example, considering a moderate global warming scenario (Representative Concentration Pathway, RCP 4.5), the suite of CMIP5 climate models project a reduction in near-surface permafrost across the Northern Hemisphere ranging from 15% to 87% by 2100 AD (Slater and Lawrence 2013).

In the IRIS 2 region, CMIP5 models project limited to no changes in permafrost area. The only regions projected to lose permafrost are the southernmost margins of Baffin Island such as the Meta Incognita Peninsula (Slater and Lawrence 2013). However, under a substantially more aggressive global warming scenario (RCP 8.5), GCMs project widespread permafrost thaw in the Eastern Canadian Arctic by 2100, with many models showing large reductions in permafrost area across most of south-central Baffin Island (Slater and Lawrence 2013).

There are numerous challenges for modelling permafrost changes using GCMs, particularly in regions with complex topography such as the Eastern Canadian Arctic (Burn and Nelson 2006). In particular, many GCMs cannot accurately model the contemporary distribution of permafrost at the national scale using either direct or indirect metrics (Lawrence and Slater 2005, Koven et al. 2013). Furthermore, models that underestimate current permafrost

distribution and overestimate active layer depths project the greatest changes in overall permafrost distribution. The Eastern Canadian Arctic GCMs, including those with more complex land-surface parameterizations (e.g., BCC-CSM1-1, GISS-ER-R), are unable to replicate the presence of contemporary permafrost along the southern margins of Baffin Island, while others have produced unrealistically thick active layers (Koven et al. 2013). The wide range (15-87%) of projected permafrost losses at the hemispheric-scale further highlights the large uncertainties present in the various climate model runs. Inter-model variability in permafrost thaw estimates primarily reflects the disagreement over the magnitude of expected high latitude warming and the difficulties in modelling subsurface-surface-atmosphere coupling (Koven et al. 2013, Slater and Lawrence 2013). There is also evidence that differences in model projections of permafrost change are linked to difficulties in simulating the thermal relationships between winter snowcover and ground surface temperatures, leading to unrealistic air-ground thermal offsets in some regions (Koven et al. 2013). Complex topography adds additional uncertainty to permafrost projections with the lowest spatial resolution (~1.0-2.5°) climate models unlikely to capture fine-scale topographic variability and associated permafrost processes (e.g., Gruber 2012) (Figure 18).

Although the most recent generation of GCMs represent a substantial improvement over earlier models (e.g., Lawrence and Slater 2005), the above-mentioned challenges highlight the necessity for improvements in modeling subsurface-surface-atmosphere coupling and future climate scenarios (Rinke et al. 2012). A potential step towards the integration of permafrost processes and climate modelling is the development of high resolution regional permafrost distribution models which can be perturbed by climate data derived from GCM runs (Riseborough et al. 2008). Several recent studies have noted promising results by perturbing regional empirical statistical or transient permafrost models with GCM projections (e.g., Bonnaventure and Lewkowicz 2013, Zhang et al. 2013, Zhang et al. 2008). Using the transient Northern Ecosystem Soil Temperature model (NEST, Zhang 2003) perturbed with CMIP3 climate model scenarios, Zhang et al. (2008) projected changes in

regional permafrost and active layer thickness across all of northern Canada. In total, permafrost area was projected to decline by 16-20% by the 2090s, with active layer thickness increasing typically by 41-104%. In the Eastern Canadian Arctic, Zhang et al (2008) found no change in the total area of permafrost but projected increases in active layer depths of ~50 cm across much of the region with regional increases of up to ~1.0 m in south-central Baffin Island. The further application of numerical or analytical permafrost modelling perturbed with higher resolution Arctic regional climate model output (e.g., Rinke et al. 2012) may therefore be a useful means of assessing the future development of geocryological hazards in the region.

4.3 Conclusions

As permafrost is the only element of the cryosphere that people live on year-round, assessments of permafrost attributes both current and future are critical in the region. Currently there are many active research programs investigating a wide range of topics from the thermal evolution of permafrost, to the emergence and change of terrestrial and aquatic features within the terrain. As climate is the primary driver of both permafrost distribution and attributes we have a firm understanding that this has and will continue to change. These changes will continue to reshape the landscape, changing the ecosystem with both local and global consequences. Some of these changes will be obvious impacting the lives of northerners in subtle ways whereas others will have profound and long-lasting impacts. The aim of this chapter has been to serve as a baseline of the current state of permafrost knowledge in the IRIS 2 region, outlining research within the region itself while highlighting some of the expected changes.

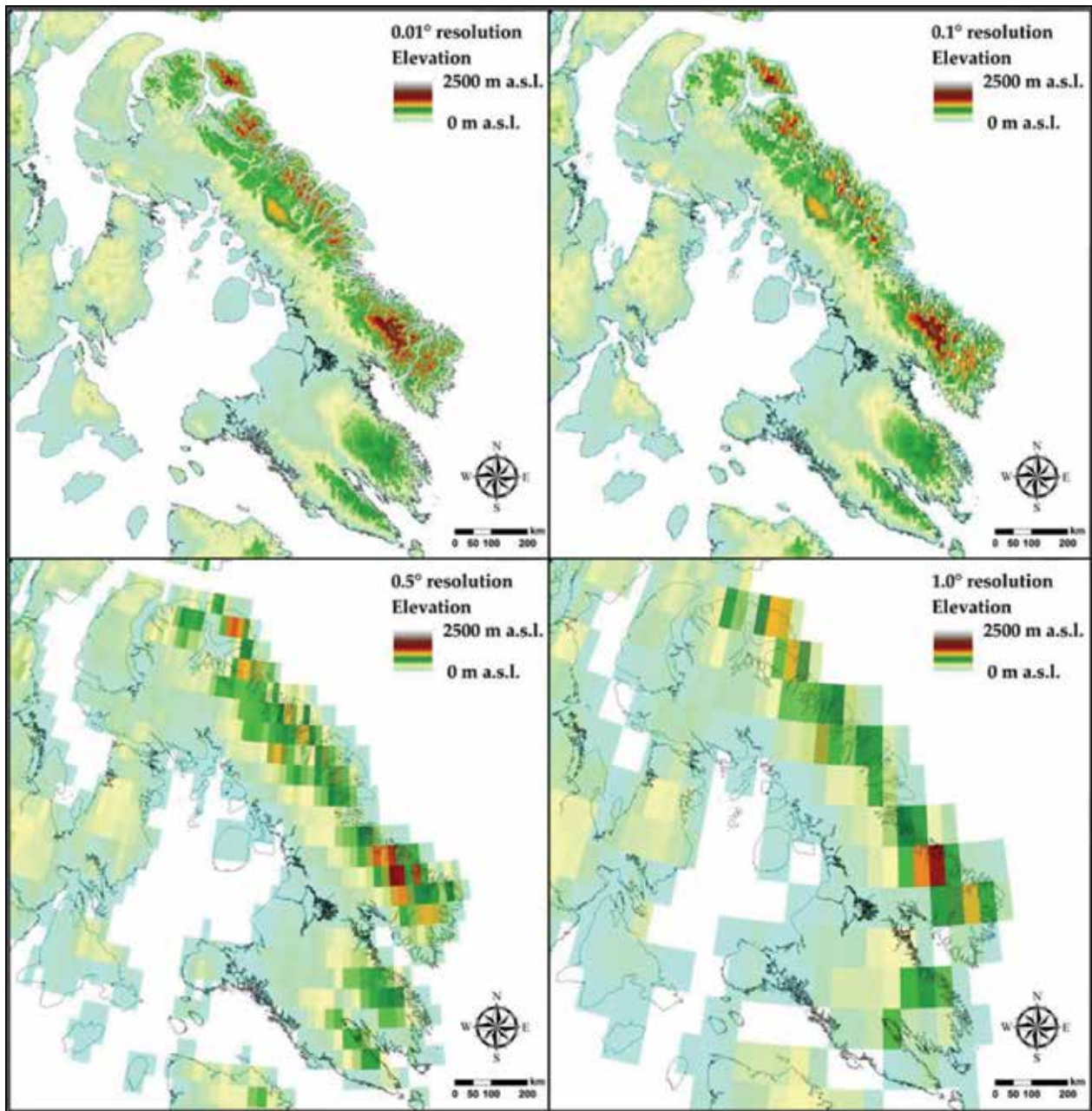


FIGURE 18. GTOPO30 digital elevation model (USGS) covering Baffin Island resampled to four different resolutions (0.01°, 0.1°, 0.5°, 1.0°).

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Chapter 5 Marine Ecosystem Productivity

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Key messages

- The location of the Eastern Canadian Arctic with respect to ocean currents and remote oceanic processes strongly limits marine biological productivity in the area.
- The potential and realized yield of commercial fisheries in eastern Baffin Bay is limited by a combination of environmental, social and economical factors.
- In the future, marine productivity seems unlikely to increase with rising temperature, acidity and freshwater loading.

Abstract

The marine ecosystem of the Eastern Canadian Arctic is shaped by a combination of remote and regional processes that affect freshwater loading, nutrient supply and ratios, acidification, and ice dynamics. Remote drivers include the inflow of waters from the Pacific Ocean and rivers, as well as their transformations in transit toward eastern Baffin Bay. These waters are relatively fresh, acidic and nutrient-poor with respect to the Atlantic waters entering the Bay through the West Greenland Current. Changes in the physical/chemical properties and sea-ice conditions of these waters and their relative proportions condition the productivity of harvestable resources. In the East, where waters are strongly stratified and highly acidic, this productivity is presently low compared to western Baffin Bay. In the future, warming and the melting of glaciers/icebergs and sea ice are likely to further increase vertical stratification and oppose the increase in productivity that should occur under reduced-ice conditions, where more light is available to phytoplankton. Current hotspots of marine productivity and harvestable resources (e.g., northern shrimp, Greenland halibut) are found where regional oceanographic processes (e.g., mixing and upwelling) facilitate the upward renewal of nutrients under ice-free conditions. The productivity and location of these hotspots will possibly shift in response to the changing climate. While marine productivity in the Eastern Canadian Arctic is very low when compared to productive areas of the World's Oceans, commercial landings are also limited by a combination of socio-economic factors.

5.1 Introduction

The rapid and profound transformation of the physical Arctic environment can impact marine ecosystems and the services they provide in at least two major ways in the Eastern Canadian Arctic. Firstly, it directly challenges marine animals whose survival depends on cold temperatures or sea ice for foraging, refuge or reproduction. Impending declines in these populations as well as invasions by temperate species are likely to reshape biodiversity and ecological interactions (e.g., predation, competition) in marine food webs (blue arrows in Figure 1). The second impact works indirectly by changing the amount of food available to consumers. It starts at the base of the food chain, where perturbations of

the physical and chemical environment readily affect the unicellular photosynthetic plants that synthesize the new organic matter on which the ecosystem depends (green arrows in Figure 1). The amount of organic matter thus produced constrains the amount of food that can be harvested from the sea. The overall response of marine ecosystems to climate change integrates these so-called “top-down” and “bottom-up” effects. Through their activity, primary producers, zooplankton and the smallest microbes (e.g., bacteria, archaea) also exert a feedback on the environment by affecting the ocean’s ability to store or release climate-active gases (e.g., carbon dioxide, CO₂; methane, CH₄; dimethylsulfide, DMS), thereby modulating the global rate of warming.

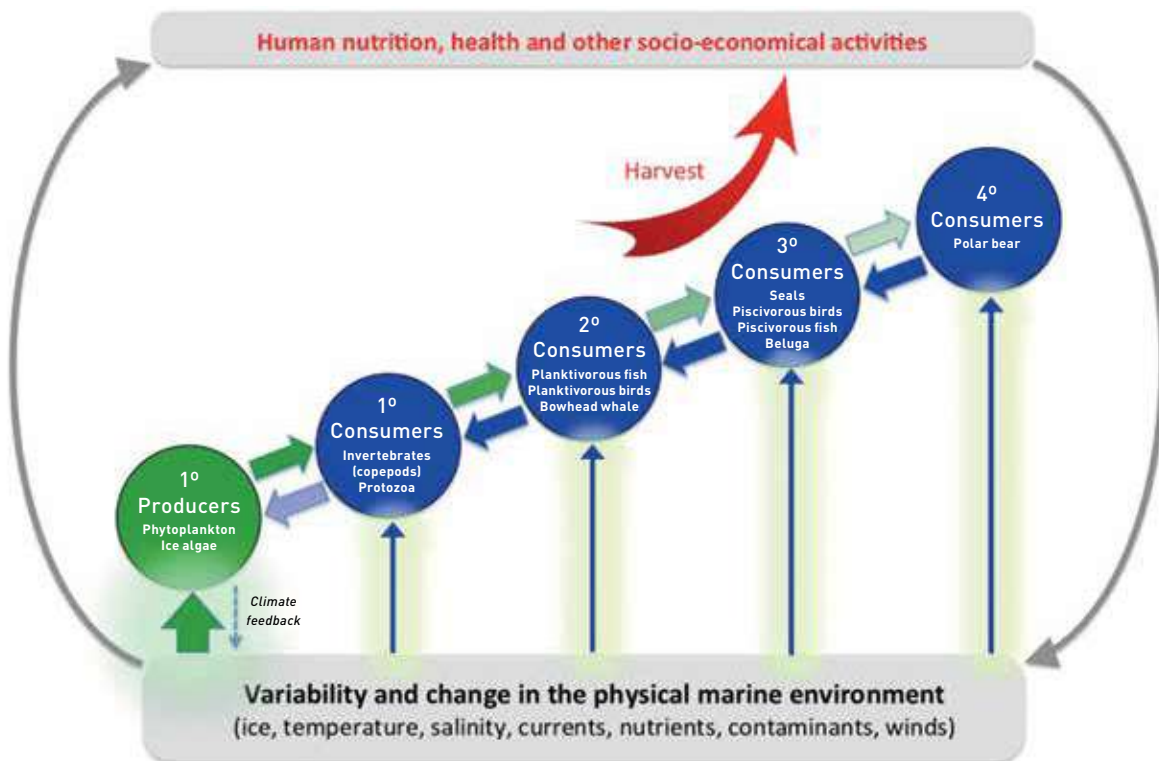


FIGURE 1. Conceptual framework showing the diverse effects of environmental change on the marine food web and the services it provides to society in the Eastern Canadian Arctic. Alterations in the behavior, fitness, abundance or productivity of any animal in the food web can result directly from fluctuations or changes in the physical environment (vertical blue arrows). These alterations cascade to other levels of the food web through changes in predation or competition pressures (oblique blue arrows). In parallel, changes in the primary production of plant food by different types of phytoplankton and ice algae (vertical green arrow) set the quantity and quality of food available for consumers and harvestable resources up the food web (oblique green arrows) and also feedback on climate through the production or release of climate-active gases by the microbial community. These ecological shifts combine with societal responses (e.g., changing use of ice and ocean, economic development) to further affect the physical environment and so on.

The small, photosynthetic algae that grow in the brine channels of sea ice and in surface seawaters are like miniature factories that harvest light and incorporate CO_2 and essential nutrients into organic matter, which is then exploited by primary consumers such as protozoa (protozooplankton) or copepods (metazooplankton) and passed on to larger consumers. By contrast with the terrestrial environment, marine plants, animal carcasses and organic debris are not tethered and so will episodically sink tens, hundreds or thousands of metres beneath the sunlit layer depending on how deep the ocean is. A portion of this sinking biomass is decomposed (or re-mineralized) by bacteria and archaea, which liberates elemental constituents in the water under the form of dissolved nutrients. The rest reaches the deep ocean or the seafloor, where it can feed benthic animals (e.g., sea stars, mussels and their consumers) or be stored in the sediment. In practice, this gravitational settling moves vital nutrients away from the ocean surface. The vertical movement of zooplankton and fish that feed at the surface and perform daily and/or seasonal migrations to deep waters also transports significant amounts of carbon and organic matter to depth (Benoit et al. 2010, Darnis and Fortier 2012). So the ocean has a problem: nutrients are needed at the surface where photosynthetic plants can use them, but gravity and migrations trap nutrients in the deep. By modulating the efficiency of this “nutrient trap”, environmental change at global and regional scales affects the quantity of algae produced in surface waters (e.g., Li et al. 2009, Primeau et al., 2013). This quantity conditions the productivity of the food web that depends on it and also impacts the biodiversity (i.e., number) of organisms living in the water column and on the sea floor (Witman et al. 2008, Vallina et al. 2014).

Once organic matter is decomposed in deep waters or at the seafloor, a minute fraction of the re-mineralized nutrients released will make it back to the upper layers through a slow, physical process known as diffusion. The only means of re-injecting large amounts of nutrients toward the surface is by moving deep water upward, which occurs through wind-driven or topographically-steered (i.e. when a current hits a vertical obstacle or becomes laterally constricted) mixing or upwelling. Productive marine areas and lucrative commercial fisheries are located where these

physical processes are most active and support the production of large, nutritious phytoplankton species such as diatoms. Indeed, different indices of marine food web productivity, ranging from zooplankton biomass to fish landings, are strongly correlated with primary production at regional (Ware and Thomson 2005) and global (Nixon and Thomas 2001, Irigoien et al. 2004, Chassot et al. 2010, Conti and Scardi 2010) scales. Since these relationships hold in Nordic seas and the Atlantic sector of the Arctic Ocean (Chassot et al. 2007) (Figure 2), it is expected that any change in primary production will affect the biomass yield of organisms higher up the food chain in the Eastern Canadian Arctic as well. Such change can occur through alterations of the intensity of primary production or the type of primary producers responsible for this production. A switch from nutritious diatoms to the marine analogs of ragweed (e.g., coccolithophores or the prymnesiophyte *Phaeocystis*), has been known to alter food webs in other cold seas (e.g., Macklin et al. 2002, Merico et al. 2003). The possibility therefore exists that these organisms may become more active in the future Eastern Canadian Arctic.

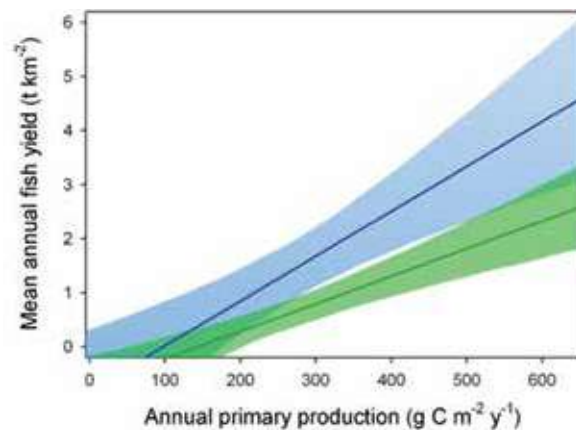


FIGURE 2. Relationship between mean fisheries yield for all (blue) and planktonic (green) fish and annual primary production in Nordic and European seas. Shaded areas represent 95% confidence intervals on the linear regressions. C represents carbon. Adapted from Chassot et al. (2007). Refer to Chapter 18, Figure 8 for values specific to central Baffin Bay and the North Water Polynya and Davis Strait.

We know that approximately 189 fish species inhabit the Canadian Arctic (Archambault et al. 2010) and we have a coarse overview of the distribution of benthic resources in the region (Jorgensen et al. 2005), but comprehensive surveys of harvestable species at the spatial and temporal scale needed to assess their potential yield and its temporal change/fluctuations are not available (Boyer Chammard-Bangratz 2013). Because primary production can be readily estimated with satellites or ships, it provides a viable alternative to infer changes in the aggregate productivity of harvestable resources using the coarse relationships shown in Figure 2. To do so, we will first review the knowledge gained through ArcticNet's expeditions and remote sensing program (Figure 3) as well as previously published work, and will then propose a future outlook.

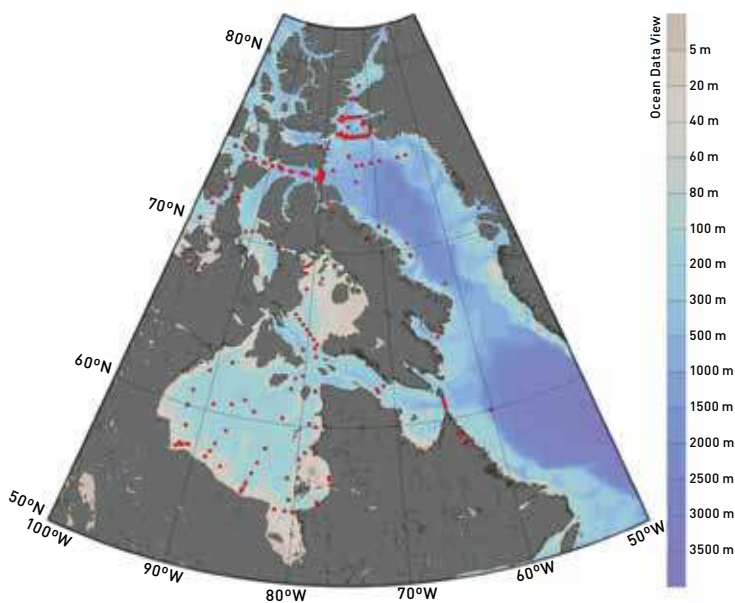


FIGURE 3. Position of the oceanographic stations sampled with the CCGS *Amundsen* during ArcticNet expeditions in the IRIS 2 region (2005–2011).

5.2 The large-scale and regional oceanographic context

In the Eastern Canadian Arctic, the marine environment is shaped by a combination of local and remote processes that

must be taken into account to understand present and future biological productivity. The oceanographic system formed by Lancaster Sound, Baffin Bay and the northern Labrador Sea is a central ecological hub where southward flows of water, sea ice and glacial ice converge along the Eastern Canadian coastline (Figure 4). The region collects waters that, for a large part, originate from the Pacific Ocean and thus spent over a decade transiting across the high Arctic (Figure 5), where their properties have been modified by ice growth and decay, precipitation, river discharge and biological activity (Azetsu-Scott et al. 2010). These waters therefore integrate a myriad of signals that reflect prior events and the cumulated impact of climate-driven processes in recent years. By modulating the fluxes and configuration of ice and water in Baffin Bay, the changing Arctic climate will affect ecosystem services regionally and far beyond in the western North Atlantic.

The situation is different along the coast of Greenland, which receives water from the so-called “West Greenland Current” that carries a mixture of relatively warm and salty Atlantic water (Figures 4, 5). Along the way, this water collects the melt water produced by the disintegration of Greenlandic glaciers. Most of this water arcs west and then south in northern Baffin Bay and the rest continues northward into Smith Sound. This regional circulation affects the physical and chemical properties of waters in the Eastern Canadian Arctic, but it also transports organisms from the North and the South (e.g., Reid et al. 2007).

5.3 Recent changes and events within or upstream of the Eastern Canadian Arctic

In the central Arctic, most of the thick multi-year sea ice has now vanished and released its freshwater into the surface ocean (Perovich et al. 2013, Timmermans et al. 2013). Increased river discharge has considerably enriched this freshwater pool in recent years (Morison et al. 2012). Depending on the dominant mode of climate forcing over the Arctic Ocean, this freshwater is either stored in or released from the Beaufort Gyre (Yamamoto-Kawai et al. 2009, Morison et al. 2012) (Figure 5). The gyre is a large rotary current that “attracts” water toward its center and

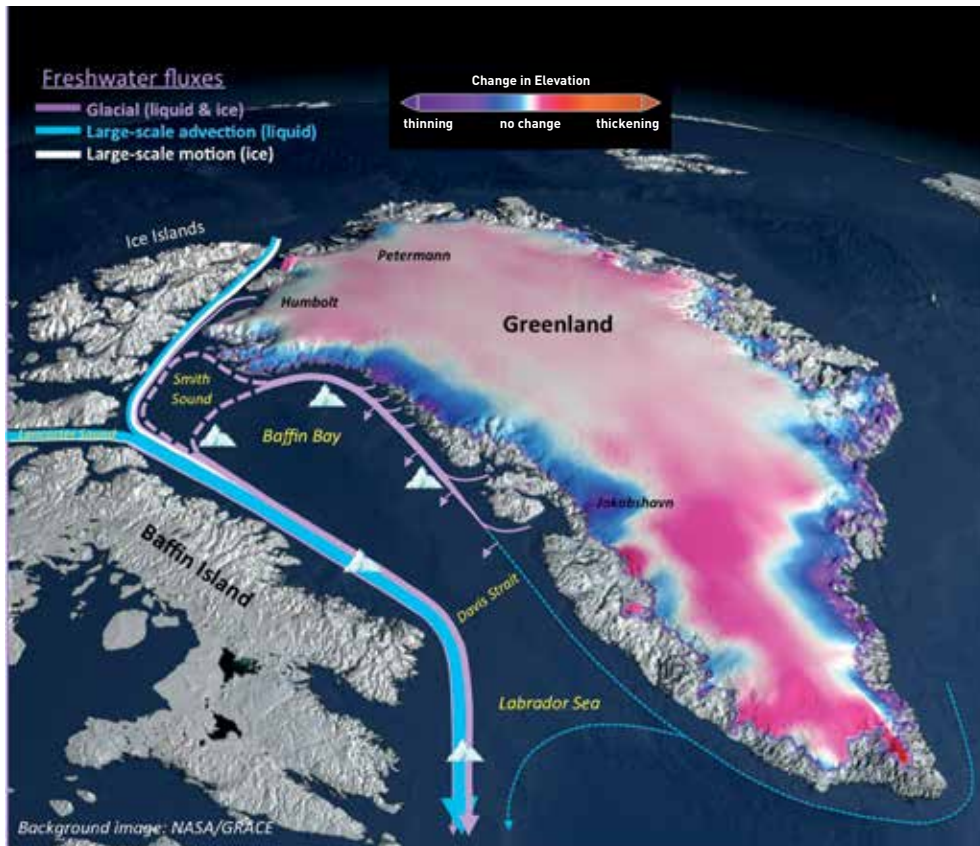


FIGURE 4. Map showing the convergence of liquid and solid freshwater from glaciers (purple lines), sea ice (white line) and freshwater from the high Arctic (blue line) into the IRIS 2 region. The Background image is from the NASA/GRACE program.

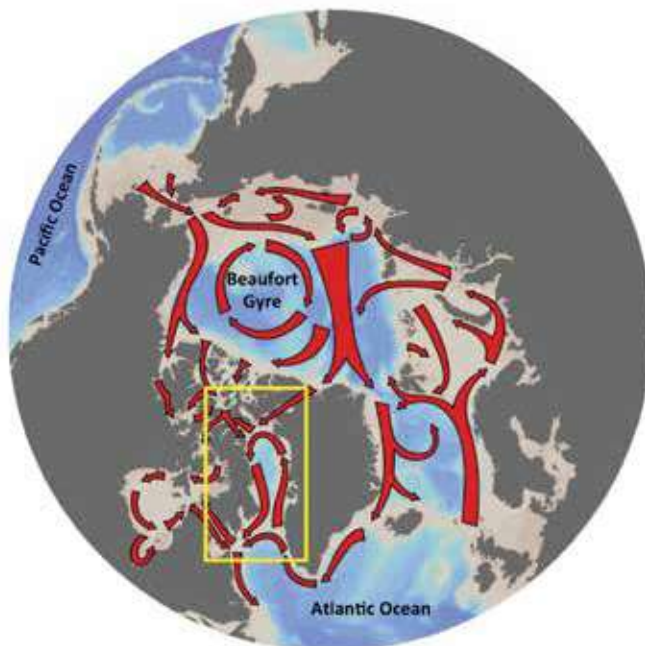


FIGURE 5. Location of the IRIS 2 region (yellow box) with respect to the large-scale oceanic circulation of water masses from the Pacific and Atlantic oceans at the surface.

acts as a water castle when it is energetic. When the gyre weakens, a portion of the low-salinity water it holds leaks into the Eastern Canadian Arctic through Lancaster Sound and Nares Strait. The properties of this water are further influenced by regional conditions and events. Accelerated runoff, melting and iceberg calving bleed Greenlandic and Canadian glaciers, leading to sea level rise and surface freshening. The remnants of secular coastal ice shelves shed colossal ice islands into the sea (England et al. 2008). All these changes impact the IRIS 2 region and are bound to affect vital ecosystem services, navigation and the access to natural resources both regionally and downstream along the Eastern Canadian seaboard.

5.4 Multiple stressors impacting the lower food web

5.4.1 Loss of sea ice

Sea ice is a platform for breeding and hunting as well as a habitat for the algal community that supplies food to the keystone copepod *Calanus glacialis* and benthic organisms during spring (Loeng et al. 2005). It also constrains the productivity of the pelagic ecosystem by blocking the light necessary for photosynthesis. Sea ice seldom melts where it grows. Between 500 and 900 km³ y⁻¹ of sea ice produced in the high Arctic are exported into Baffin Bay (Tang et al. 2004). The minimum extent of sea ice in the Arctic reached a new record low in September 2012, dropping to 47% of its mean area for the period 1979-2000 (National Snow and Ice Data Centre). This ongoing loss will dramatically alter the amount of ice exported into the Eastern Canadian Arctic. The region also forms its own seasonal sea-ice cover.

In Baffin Bay, the ice season has been contracting at the mean rate of 8 days per decade since 1979 (Markus et al. 2009) and the southern edge of winter ice retreats north by several hundred kilometres during negative phases of the North Atlantic Oscillation (Heide-Jorgensen et al. 2007). This interaction and the underlying ocean circulation are instrumental in the formation of ice arches that generate open water singularities such as leads and polynyas

(Dumont et al. 2009). The North Water Polynya in Smith Sound has been considered as a secular oasis for thriving populations of resident and migrant marine birds and mammals (Tremblay et al. 2006). The Smith Sound ice arch (ca. 78.6° N), which peculiarly characterizes the northern extremity of the polynya, results from the hydro-mechanical behavior of sea ice when winds and currents force it into the restricted passage between Ellesmere Island and Greenland. The arch itself is a failure line in the ice cover that, according to the 45-year long ice chart dataset (1968-2013) of the Canadian Ice Service, appears somewhere between October and January but becomes more easily visible from space only when downstream sea ice loosens and drifts southwards. The onset of this motion marks the opening of the polynya. A detailed analysis of the arch from ice charts reveals that before 1994, it broke up (the polynya ends) at week 31 ± 3 while after 1994 the break-up occurs at week 27 ± 3, a one-month advance (Figure 6). While the time series is not long enough to diagnose a climate-related change, the frequency of occurrence also seems to decrease over the 45-year period; the arch did not form in 1990, 1993, 1995, 2007, 2009 and 2010, i.e., 6 times over the last 23 years. Unfortunately, the dataset does not allow for a similar characterization of the timing of the arch formation. However, changes in the life cycle of the arch have direct repercussions on regional

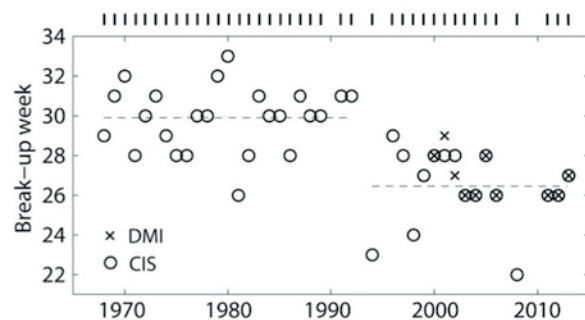


FIGURE 6. Long-term change in the week of arch break-up, assessed with ice charts from the Canadian Ice Service (CIS) and the Danmarks Meteorologisk Institut (DMI) (unpublished data). A one-week uncertainty is implied for all data points. The vertical black lines indicate years for which an arch was present for at least two consecutive weeks between January and August (CIS dataset).

ice dynamics, the availability of light for photosynthetic organisms (Bélanger et al. 2013) and the circulation of the upper ocean (Dumont et al. 2010).

5.4.2 Ice islands and icebergs

In recent years, several ice shelves have been lost from northern Ellesmere Island and numerous large fragments broke off the Petermann glacier (see Chapter 3 for more information on glaciers and ice shelves). Most glacial ice singularities drift south toward Baffin Bay and Lancaster Sound, with significant impacts on freshwater loading and the motion of sea ice and water. West Greenland glaciers shed tens of thousands of icebergs annually and those account for the majority of glacial ice transiting through Canadian waters. Most of these icebergs are eventually carried north by the West Greenland current. Then some of the largest ones continue north into Smith Sound while most drift west across northern Baffin Bay and finally south with the Baffin Land Current (Iceberg Alley), which entrains additional icebergs from other glaciers (Tang et al. 2004). A few of these icebergs can enter Lancaster Sound, where they become grounded. Changes in seasonal sea ice, such as a contraction in its seaward extent and lifespan, and ocean circulation are bound to affect the pathways and transit times of icebergs and ice islands.

Icebergs scour the seafloor sediment and disturb benthic communities (Conlan et al. 1998) that supply food to several species of fish and marine mammals. Scouring removes late-succession organisms, creates opportunities for colonizer species and releases nutrients into the water column. Full re-colonization of a benthic community can take more than 9 years following a scouring event (Conlan and Kvitek 2005). On the Baffin Island shelf, scouring can trigger the release of oil (seeps) and gas (vents), which potentially impacts marine organisms and the air-sea exchange of methane, a highly potent greenhouse gas (Levy and Ehrhardt 1981, Judd 2003). Although the ecological impacts of icebergs have not been studied in the Eastern Canadian Arctic, drifting icebergs in the Southern Ocean show elevated concentrations of chlorophyll on their walls and in their wake (Schwarz and Schodlok 2009), which is

attributed to the release of micronutrients having a positive effect on algal growth and accumulation (Smith et al. 2007, Schwarz and Schodlok 2009). The elevated productivity attracts zooplankton and marine birds in the Weddell Sea and is quantitatively significant at the regional scale (Smith et al. 2007). In the Arctic, the upward supply of macronutrients caused by the upwelling of subsurface melt water (Jenkins 1999) and the mixing effect of breaking waves on icebergs potentially stimulate primary production. These impacts have yet to be documented in the Canadian Arctic.

5.4.3 Freshening

A variety of freshwater sources dilute seawater, affecting its physical and chemical properties with direct and indirect effects on organisms and biological productivity. Figure 7 shows the relative contribution of different freshwater sources to the waters flowing south along the Eastern Canadian Arctic and those flowing north along the Greenland coast. These sources are generally divided into (1) oceanic water from the Pacific (which globally receives more precipitation than the Atlantic and is thus a source of remote freshwater), (2) the so-called “meteoric” water, which includes waters provided directly or indirectly by

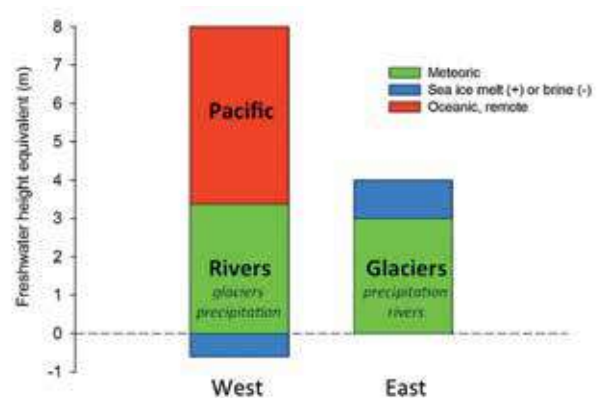


FIGURE 7. Estimates of the quantities of freshwater (in total height equivalent) and the contributions of different sources in western (Canadian side) and eastern (Greenland side) Davis Strait during September-October 2004. For each category, the dominant or sole contributing source is given in bold and possible but unresolved secondary sources are given in *italic*. Adapted from Azetsu-Scott et al. [2012].

regional precipitation (river discharge, glacier melt, precipitation) and (3) sea-ice melt water. Brine rejection during sea-ice growth increases salinity and therefore leads to an apparent decrease in liquid freshwater flux when the sites of ice formation and melt are separated. For the year 2004, Azetsu-Scott et al. (2012) estimated a total southward freshwater flux of ca. $125\,000\text{ m}^3\text{ s}^{-1}$ in western Davis Strait, composed mainly of Pacific-derived water and meteoric water of predominantly riverine provenance (e.g., the Mackenzie River) with unresolved contributions by precipitation and glacial melt (Figure 7). The flow of waters influenced by brine rejection exceeded the amount of sea-ice melt, thereby partially canceling out the combined flux of Pacific and meteoric water. In eastern Davis Strait (Greenland side), approximately $52\,000\text{ m}^3\text{ s}^{-1}$ of freshwater, produced mainly by glacial melt with a secondary contribution of sea-ice melt, flowed northward (Azetsu-Scott et al. 2012).

By lowering the salinity, freshwater produces a buoyant surface layer that augments the vertical “stratification” of the upper ocean. The relatively “light” surface layer then behaves like oil on “heavier” water. Warming contributes to make the surface layer even lighter since water density decreases with increasing temperature. The density difference acts as a physical barrier that impedes the vertical exchanges of heat, nutrients and gases between the surface and the deep ocean. These exchanges drive biological productivity, biogeochemical cycling and the oceanic circulation (or conveyor belt) that prevents the poles from getting much colder and the tropics from getting much hotter (Dickson et al. 2007). Increased stratification opposes all these crucial functions. As previously mentioned, essential nutrients must be transported from the deep ocean to the sunlit, surface layer in order to sustain photosynthesis and harvestable resources. This transport diminishes with increasing stratification.

An example of how freshwater stratification impacts Baffin Bay is provided in Figure 8, which shows a vertical section of oceanic properties from Ellesmere Island (left) to Greenland (right). Sampling was performed during the ArcticNet expedition of the CCGS *Amundsen* in early October 2007, the previous record year of minimum sea-ice

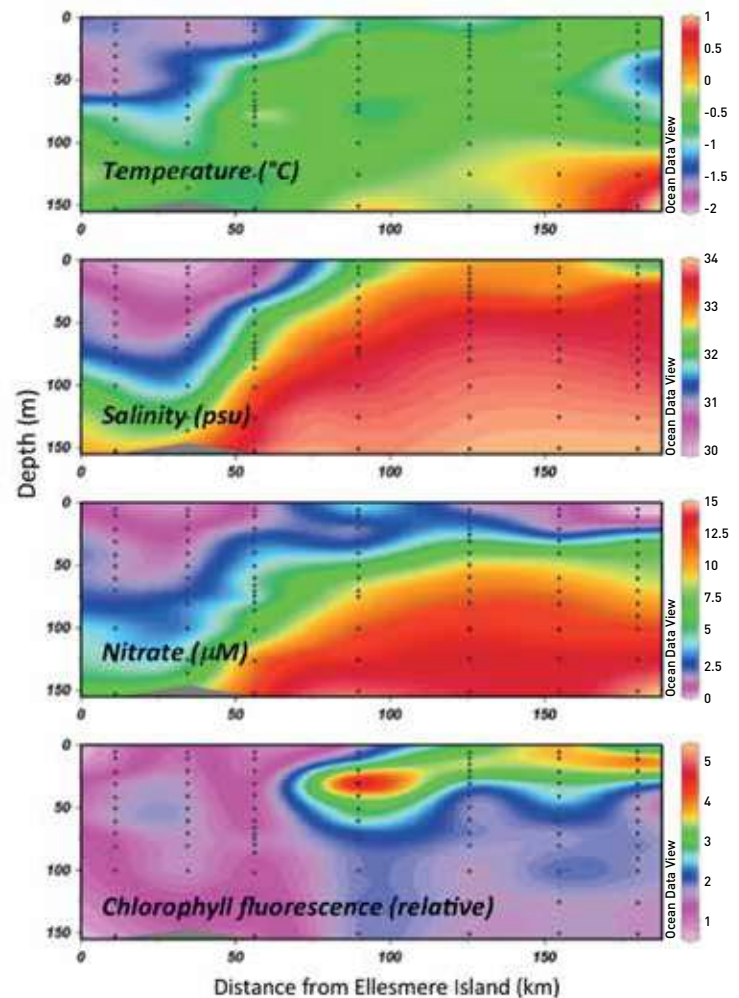


FIGURE 8. Lateral and vertical gradients of temperature, salinity, nitrate and chlorophyll fluorescence across northern Baffin Bay at 76.2°N .

extent before 2012. The cold and relatively fresh Arctic outflow is clearly visible at the surface in the west, whereas the relatively warm and saline waters from the West Greenland Current are seen in the East. The distribution of the nutrient “nitrate”, which is known to limit primary production in the Arctic Ocean (Tremblay and Gagnon 2009), matches salinity patterns. Surface concentrations of nitrate are extremely low where the stratification is strongest in the west. Note that the lowest values of chlorophyll fluorescence (and index of phytoplankton biomass) co-occur with the nitrate-poor water in the west. A sharp increase

in fluorescence occurs toward Greenland, where the waters are warmer and the sunlit upper layer coincides with relatively high concentrations of nitrate. Below this latitude, the Arctic outflow continues its transit to the south and defines the oceanographic and biological setting of coastal waters in the IRIS 2 region. This pre-conditioning severely constrains primary productivity in the region.

Upward deliveries of the nutrient nitrate are crucial to sustain photosynthesis and food webs in the Arctic Ocean (Tremblay and Gagnon 2009), but respond negatively to stratification. Inverse relationships have been observed between the strength of the stratification and primary production in Baffin Bay, Lancaster Sound and adjacent regions (Ardyna et al. 2011, Ferland et al. 2011). In addition to the intensity of primary production, the contribution of different functional groups of phytoplankton also responds to increasing stratification, which generally favours small species that do not efficiently support harvestable resources (e.g., Li et al. 2009). By contrast, diatoms are associated with productive food webs, efficient sequestration of CO₂ in the ocean via gravitational settling and low production of DMS, a climate-active gas acting as cloud nucleator and providing negative feedback on photosynthesis. Other bloom-forming algae such as *Phaeocystis* and coccolithophores typically have negative impacts on food webs, a low potential for CO₂ sequestration and are often good producers of DMS. When present in high abundance, these organisms hamper the feeding success of zooplankton and their predators higher up the food chain. *Phaeocystis* colonies can clog fishing nets and degrade the shoreline by producing large accumulations of foam (Walsh et al. 2011 and references therein).

The reasons leading to functional shifts in phytoplankton dominance are not fully understood, but coccolithophores and toxic dinoflagellates typically develop in strongly stratified, nutrient-impoverished surface waters (Sabine and Tanhua 2010). The northern limit of their boreal extent will possibly expand with warming (Walsh et al. 2011). Coccolithophores have already replaced diatoms in portions of the coastal Bering Sea, with dire consequences for food webs (Macklin et al. 2002), and in some years, colonies of *Phaeocystis pouchetii* are abundant in the Barents

Sea (e.g., Wassmann et al. 1990) and the Greenland Sea (e.g., Calbet et al. 2011). As far as we can tell, these organisms have not yet developed high biomasses in the Eastern Canadian Arctic (e.g., Tremblay et al. 2009; Ardyna et al. 2011), where the blooms investigated so far were dominated by diatoms (Lovejoy et al. 2002, Tremblay and Smith 2007). An intriguing possibility is that the very cold temperature or some nutrient deficiency that prevails in the Arctic outflow presently guards our nearshore waters against harmful algal blooms (HAB). At lower latitudes (e.g., the North Sea), the incidence of these HAB has been positively linked to population growth and the release of nutrient-rich effluents in the coastal zone (Heisler et al. 2008). It would be prudent to anticipate these effects as economic opportunities foster coastal development in the North.

5.4.4 Acidification

The increasing freshwater loading is likely to have other direct impacts on productivity, since it may affect the survival or fitness of organisms through osmotic stress and acidification. The dissolution of anthropogenic CO₂ in seawater leads to the production of carbonic acid and the release of hydrogen ions that acidify the water (and thus lower pH). This phenomenon is global, but is most acute in cold waters since the solubility of gases increases with decreasing temperature. Because CO₂ dissolves more readily in freshwater than in saline water, a decrease in salinity caused by ice melt increases the solubility of calcium carbonate, which decreases pH and exacerbates acidification. The potential consequence of this acidification for living organisms can be assessed, for example, using the saturation state of aragonite (Ω_{arg}), a form of calcium carbonate that constitutes the hard shells of pelagic pteropods, bottom dwelling mollusks and cold-water corals. When Ω_{arg} decreases, the water becomes corrosive to these organisms and spontaneous dissolution of their shells may occur (Orr et al. 2005, Fabry et al. 2008). While these effects are well demonstrated in the laboratory, their long-term impact with respect to other stressors (warming, stratification) and the flexibility that organisms have to adjust to decreasing Ω_{arg} remains to be fully assessed.

In the Eastern Canadian Arctic, Ω_{arg} is lowest in surface waters originating from the Pacific Ocean or sea-ice melt and in the deep waters affected by the decomposition of sinking organic matter (which releases CO_2) (Azetsu-Scott et al. 2010). Figure 9 shows the layers where waters are either saturated (blue area) or under-saturated with respect to aragonite (red area). The layers in red are those that potentially create severe stress to animals with aragonite shells. Across Baffin Bay and Davis Strait, the deep under-saturated central layer results largely from the decomposition of sinking debris, while another shallower horizon corresponding to the Arctic outflow is clearly visible in the West. This water is shallow enough to flow over corals along Baffin Island. Large areas of Baffin Bay are colonized by cold-water corals, especially large gorgonian coral forests (Kenchington et al. 2010). These organisms are ecologically crucial since they can act as a refuge for many species of fish and invertebrates (Edinger et al. 2007a). The skeletons of cold-water corals contain aragonite, which makes them highly vulnerable to acidification (Wisshak et al. 2012). This vulnerability as well as the

fragility of corals to fishing impact (Edinger et al. 2007b) brought the United Nations General Assembly (UNGA) to create a resolution (Resolution 61/105) to protect them. While recent experiments showed that cold-water corals may continue to produce skeletons under acidified conditions, this production occurs at a high metabolic cost that could prove detrimental to the organisms (McCulloch et al. 2012). Furthermore, there is a lack of information on how they will react to the indirect effects of acidification on the pelagic ecosystem as well as to other stressors, such as warming and scouring by icebergs.

5.5 Productivity regimes

Under ice-free and clear-sky conditions, satellites can inform us of what happens immediately at the surface since phytoplankton can be “seen” due to the green color of chlorophyll. Primary production, which is usually expressed as the amount of carbon fixed by unit of ocean surface area during a day or a year (e.g., $\text{g C m}^{-2} \text{y}^{-1}$), is then estimated using mathematical algorithms that relate chlorophyll *a* (the photosynthetic pigment present in all algal species) to solar irradiance and water temperature (also estimated from space). The results are usually color-coded on an artificial scale to make spatial differences more obvious to the eye. Other approaches require a ship and the incubation of water samples to determine how much dissolved inorganic carbon is consumed by phytoplankton.

Satellite-based estimates of primary production for the Eastern Canadian Arctic range from 5 to $100 \text{ g C m}^{-2} \text{y}^{-1}$ for the period 1998-2010 (Figure 10). The spatial patterns shown in Figure 10 are mostly driven by two remotely sensed quantities: 1) the phytoplankton biomass (i.e. chlorophyll-*a* concentration) and 2) the amount of underwater light available for photosynthesis, which strongly depends on sea ice and clouds. The satellite-based estimation ignores primary production occurring under the ice, which can be significant when the ice is thin or covered with melt ponds (Gosselin et al. 1997, Mundy et al. 2009, Arrigo et al. 2012). Very low productivity values (purple in Figure 10) characterize most of the area, indicating that productivity levels in the region are generally

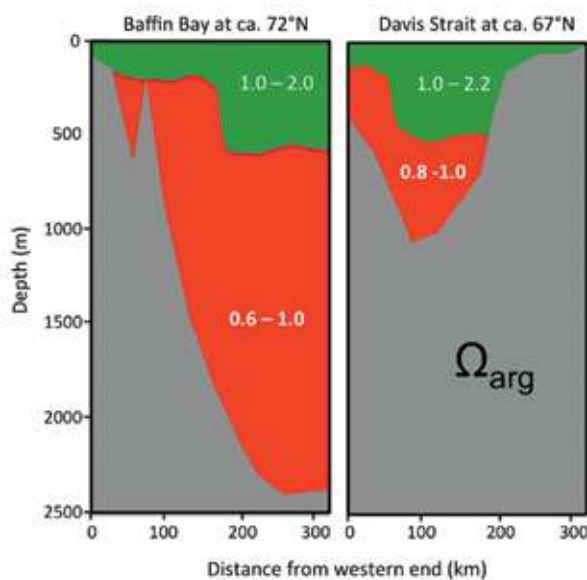


FIGURE 9. Lateral sections of the saturation state of aragonite (Ω_{arg}) in Baffin Bay and Davis Strait. Waters in the red area are undersaturated with respect to aragonite. Adapted from Azetsu-Scott et al. 2010).

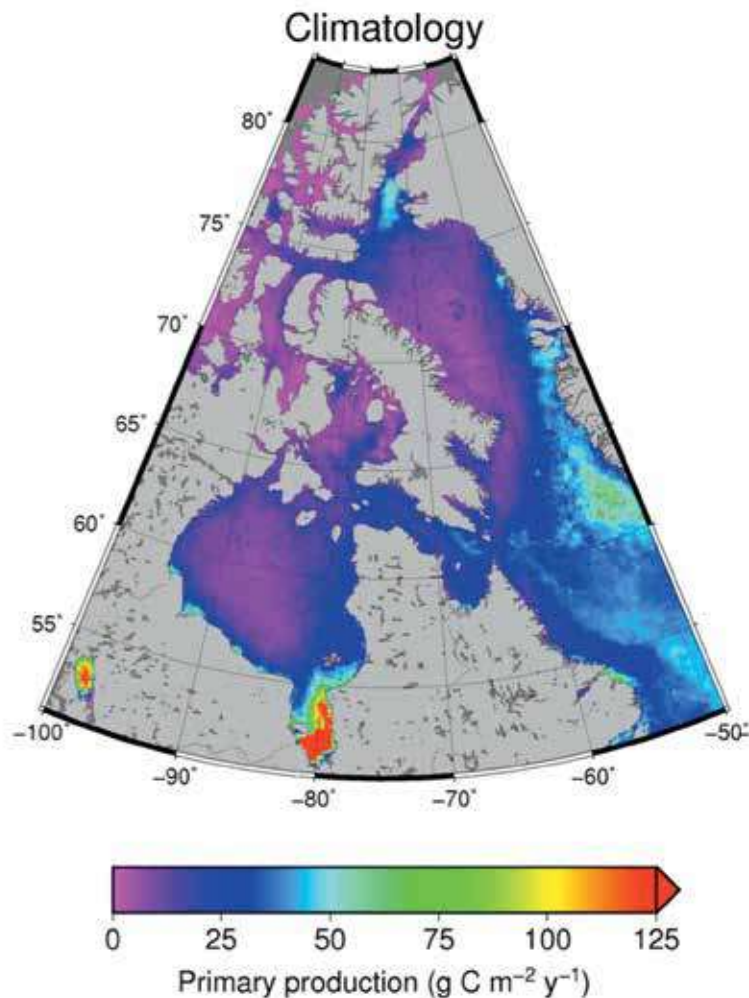


FIGURE 10. Spatial distribution of satellite-based estimates of annual primary production, averaged for the period 1998-2010. Productivity zones can be divided into very low (purple), low (dark blue), moderate (light blue – green) and high (yellow-red). Methods and algorithms are described in Bélanger et al. (2013).

close to those of a “biological desert”. Slightly higher values (dark blue) are often observed near the coasts, with the exception of Baffin Island, which exhibits low coastal productivity across its entire latitudinal swath. There is a clear contrast with the Greenland side, where productivity reaches moderate values (green). This pattern is consistent with the prevalent southward flow of strongly stratified, nutrient poor waters in the West (Figure 8). A comparison with Figure 2 is most instructive and indicates that productivity in the Eastern Canadian Arctic is generally below the level required to support even the smallest reported

fish catches for European and Nordic seas. Against this backdrop some areas stand out as being more productive, including the northern tip of Baffin Bay (North Water), and the northeast sector of Hudson Strait. Primary production at these “hotspots” is generally comparable to the higher productivity observed in the less stratified waters off Greenland. Riverine input appears to contribute to the signatures observed in James/Hudson Bay. Ice edge production and production in small polynyas also contribute to increased estimates (and location of “hot spots”).

Satellite-based estimates of primary production are corroborated by shipboard measurements of chlorophyll concentration (an index of phytoplankton biomass), which clearly show elevated phytoplankton biomass in the North Water and Lancaster Sound, but much lower values down the coast of Baffin Island (Figure 11). In general, the high values occur in less stratified, ice-free areas where the availability of nutrients is greater (Figure 12). When or where

ice cover is substantial, chlorophyll biomass typically remains low due to the negative effect of ice and snow on light penetration and photosynthesis (Ardyna et al. 2011). As the ice cover gets lower, however, photosynthesis and phytoplankton biomass only increases in specific areas where nutrients are abundant near the surface, thereby generating “hotspots” of biological activity (Figure 12). Therefore the loss of ice alone cannot be expected to bolster

Chlorophyll a biomass (mg chl a m⁻²)

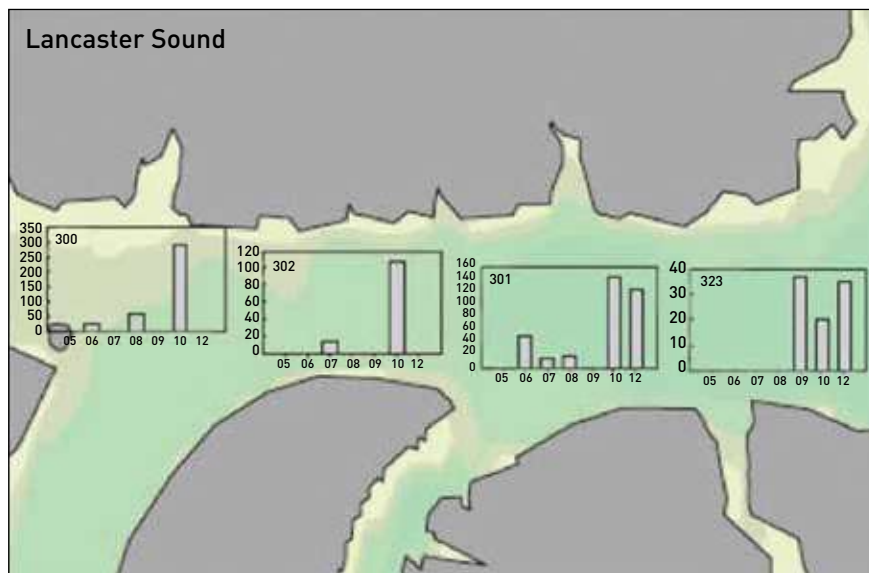
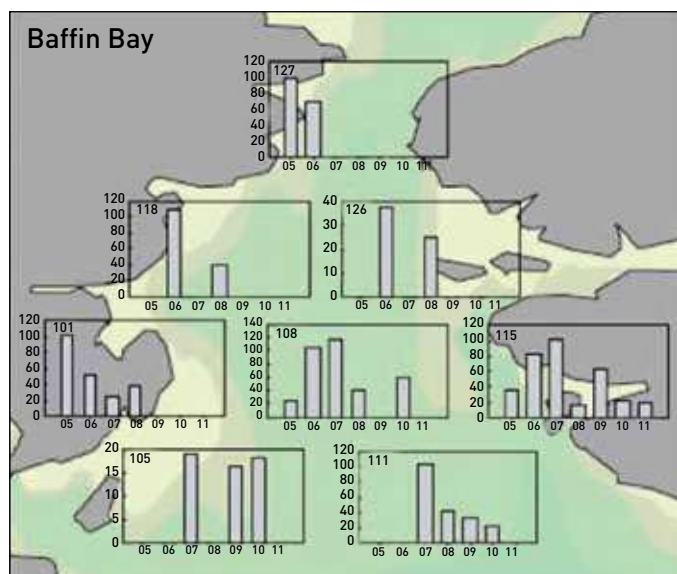
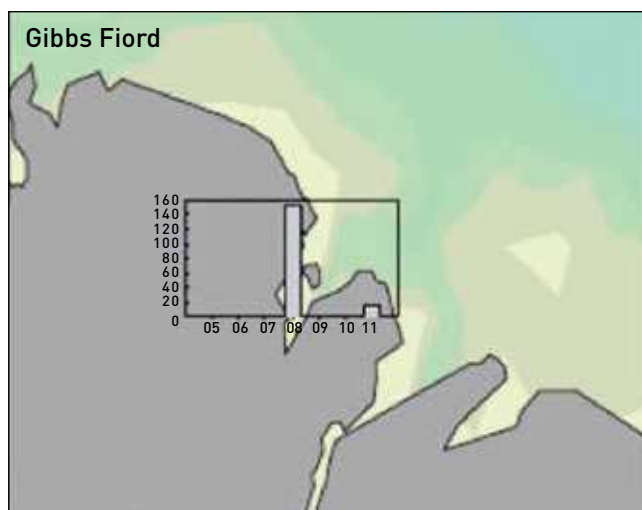


FIGURE 11. Variation of phytoplankton chlorophyll a biomass in different sectors of the Eastern Canadian Arctic between 2005 and 2011, based on direct measurements made during expeditions of the CCGS *Amundsen*.



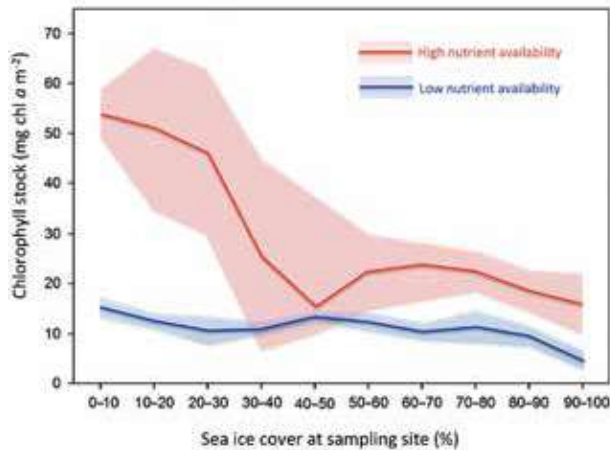


FIGURE 12. Relationships between observed chlorophyll a biomass and ice coverage at specific locations sampled by the CCGS *Amundsen* in Canadian Arctic waters where nutrient availability is high (red line and area) or low (blue line and area). The shaded areas and solid lines respectively provide the range and mean of values observed for a given class of ice concentration. Adapted from Ardyna et al. (2011).

primary production and the yield of harvestable resources that depend on it. This is consistent with pan-Arctic patterns of annual primary production, which clearly indicate that nutrient availability exerts the primary control on biological productivity in seasonally ice-free areas (Tremblay and Gagnon 2009).

Judging from Figure 2 again, even the most productive waters in the Eastern Canadian Arctic have a low potential for commercial fish yield. Greenland halibut (or turbot) and two species of northern shrimp (*Pandalus montagui* and *Pandalus borealis*) are fished commercially in western Baffin Bay, Western Labrador Sea and Hudson Strait, but those fisheries historically have a low yield relative to those on the Greenland side. By contrast with the Greenland Shelf, the Baffin Island Shelf becomes very narrow and interrupted by deep troughs north of Davis Strait, which is thought to prevent the northward spread of the northern shrimp. In this context, and because these species rely on cold temperatures ($< 6^{\circ}\text{C}$), the shrimp catch is likely to be negatively impacted by warming. This impact seems to be

most severe in areas influenced by relatively warm Atlantic water, judging from diminishing landings in the eastern Labrador Sea (Boyer Chammard-Bangratz 2013).

While the potential yield of fisheries in the Eastern Canadian Arctic can be considered low on a global scale, it has yet to reach its full potential. Several economic and social circumstances seem to contain the expansion of commercial fishing, including port facilities and tidal constraints on access, a capacity to fish offshore during summer months, the availability of processing plants and the remoteness of markets in the South (Boyer Chammard-Bangratz 2013).

5.6 Changes in the timing and magnitude of biological productivity

Satellite-based investigations report an overall increase in primary production at the pan-arctic scale (Arrigo and van Dijken 2011, Bélanger et al. 2013), with responses that vary broadly across regions. These changes can result from modifications of light availability (e.g., through a reduction of the ice cover) and/or nutrient supply affecting both the timing and intensity of production. Against a generally positive trend, we find strong indications that total annual primary production is declining in regions of prime ecological importance in the Eastern Canadian Arctic (Figure 13). The North Water (NOW), located in the northern Baffin Bay, experienced one of the most severe drops in primary production ($5 \text{ g C m}^{-2} \text{ yr}^{-1}$; Figure 13). This decline is particularly pronounced on the western side where Pacific-derived Arctic waters flow south, which is consistent with decreases in measured chlorophyll during expeditions of the CCGS *Amundsen* (Figure 11). A concomitant increase in productivity above the North Water in Kane Basin implies that the productive zone has shifted north, possibly because reduced ice cover there now allows the phytoplankton to exhaust nutrients before the southbound waters enter Smith Sound. Nutrients in western Kane Basin are known to be plentiful during early spring due to vigorous mixing in Nares Strait (see Tremblay et al. 2002). An analogous situation has developed in Lancaster Sound, where chlorophyll biomass (Figure 11) is increasing

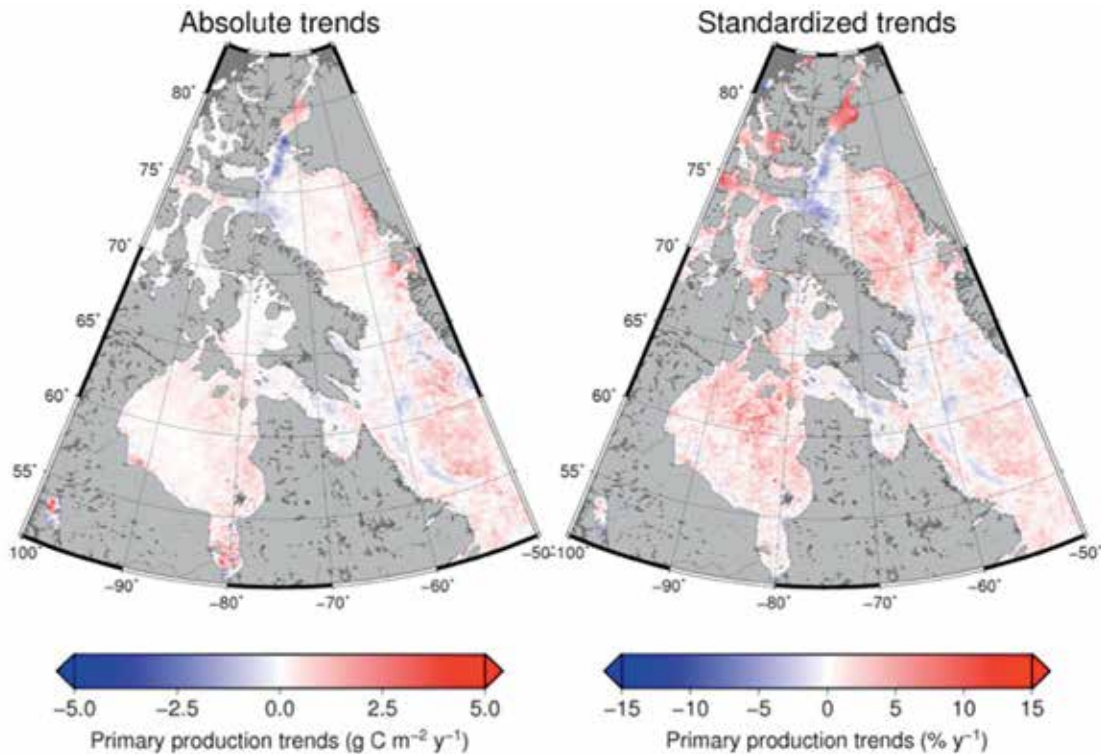


FIGURE 13. Absolute and standardized temporal trends in marine primary production in the Eastern Canadian Arctic for the period 1998-2010. Results vary from strongly declining productivity (blue) to no discernible change (white) and strongly increasing productivity (red).

in the West but remains stable at the southern entrance to Baffin Bay.

The North Water and Lancaster Sound polynyas have historically been regarded as productive areas supporting intense diatom blooms. In the North Water the bloom started in May and fuelled a rich marine ecosystem supporting polar cods, large aggregations of marine mammals and sea birds (Dunbar 1981, Stirling 1997). The transfer of phytoplankton biomass to copepods and the herbivorous food chain was highly efficient, leaving little material for export to the seafloor (Tremblay et al. 2006). Yet recent analyses of the shells of mollusks living on the sea floor at ca. 600 m suggests that a large increase in the vertical deliveries of freshly produced organic matter has occurred

during the last decade (Gaillard et al. 2017). The cause is not clear but the authors hypothesize that changing sea-ice dynamics and a lesser match between zooplankton grazing and PP resulting from an earlier phytoplankton bloom is likely. This is supported by satellite-based estimations of monthly primary production, which reveal an increasing trend for May and a decreasing trend for June and July. It is also possible that the combined horizontal transport and vertical sinking of organic matter now produced further north results in larger deliveries of food to the seafloor in Smith Sound (as opposed to south of it in former times).

At the larger scale, the continued existence of productive zones inside Lancaster Sound and north of Baffin Bay, wherever their exact position is, constitutes a “nutrient trap”

whereby phytoplankton strip surface waters of the nutrients provided by mixing in the narrow channels and shallow sills of the Canadian Archipelago and Nares Strait. Once the organic matter has sunk, the strong stratification in the Arctic outflow subsequently prevents re-mineralized nutrients from coming back to the surface. This secular context contributes to the persistently low productivity of coastal waters along Baffin Island. Absolute trends in satellite-based PP for this sector are negligible (Figure 13), although standardized trends suggest a small increase caused by a greater availability of light (Bélanger et al. 2013). Point, ship-based sampling along the latitudinal swath of eastern Baffin Bay suggests a generalized, but non-universal decrease in chlorophyll *a* biomass, including stations located in fiords and on the inner shelf (Figure 11). Meanwhile, absolute productivity levels have been rising substantially along the Greenland Coast (Figure 13), widening the contrast in productivity between the two sectors.

5.7 Outlook

Climate scenarios forecast local temperature increases of 4 to 8 °C by 2050 in the Eastern Canadian Arctic (see Chapter 2). For 2012, sea surface temperatures in Baffin Bay were up by 2 to 3 °C relative to the 1982-2006 mean for August (Timmermans et al. 2013). Total precipitation is also expected to increase by 15 to 20% by 2050 in the region (see Chapter 2). In combination, warming and freshening will increase the buoyancy of surface waters flowing south through the area. This increase will be augmented by accrued melting of Canadian glaciers and the Greenland ice sheet, which attained a record high in 2012 (Nghiem et al. 2012, see Chapter 3), as well as by remote events that affect the rising supply of low-salinity, Pacific water across Bering Strait (Woodgate et al. 2012), river discharge and precipitation in the High Arctic (Yamamoto-Kawai et al. 2009, see Chapter 6 for more information on freshwater systems). The Beaufort Gyre has been storing huge amounts of freshwater in the central Arctic (Timmermans et al. 2013), but there are indications that the gyre is now weakening and poised to release freshwater into the Canadian Arctic. These events all conspire to increase the vertical stratification and

nutrient deficiency of coastal surface waters in the Eastern Canadian Arctic.

Given the geographical location of the Eastern Canadian Arctic with respect to the large-scale oceanic circulation, it seems highly improbable at present that overall marine productivity will increase in the region. The apparent shift of elevated productivity zones toward the north (Kane Basin) or the west (inner Lancaster Sound) implies that nutrients are stripped from surface waters before flowing into the once productive zones of Smith Sound and eastern Lancaster Sound. The seasonal timing of primary production in these zones may also continue to change, with added consequences on the structure and function of marine food webs. The current fisheries yield is low and might somewhat increase if fishing effort intensified with the greater incidence of ice-free conditions (fishing vessels can spend more time offshore) and if new port facilities allowed fast turnover of the catch (Boyer-Chammard-Bangratz 2013). However, the relatively short seaward extent of Eastern Canadian Arctic shelves, their low-productivity status and susceptibility to strong acidification makes it doubtful that this ecosystem could support a local boom of harvestable resources in the foreseeable future.

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Chapter 6 Drivers, Trends and Uncertainties of Changing Freshwater Systems

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Key messages

- The limited number of survey gauges, and significant data gaps where gauges exist largely preclude any assessment of trends in river runoff in the region.
- Shifts in precipitation to evaporation ratios are leading to pronounced shrinkage of shallow ponds, and warming is leading to decreases in ice cover on lakes and changes in phytoplankton and bacterial communities, along with enhanced nutrients and/or water temperature changes.
- Hydrological modelling efforts predict higher peak flows, longer flow duration and increased suspended sediment loads over the twenty first century (due to increases in precipitation and warming fall temperatures).
- Permafrost degradation and thermo-erosion processes are likely to continue to disturb the landscape, drain ponds and ultimately transform the hydrology, biogeochemistry, and ecosystems of surface waters in the Eastern Canadian Arctic.
- Nunavut lakes are likely to experience warming rates well above the global average, but with large variations among individual lakes. This will affect ice cover duration, water mixing and aquatic ecosystem properties such as biological production, greenhouse gas fluxes, species composition and fish stocks. Paleoenvironmental proxy records indicate a range in surface water runoff changes across the region, including areas where snowmelt runoff has decreased, and other sites where snowmelt, rainfall and/or glacially derived runoff have increased over the long-term.

Abstract

Freshwater ecosystems, water quality and quantity are directly affected by climate, and indirectly via climate driven changes in permafrost and landscapes. Recent observations and trends of freshwater systems (including rivers, ponds, wetlands, and lakes) in the region are presented. The sparse number of observational records, combined with the challenges associated with field measurements of water balance parameters (e.g., end of year snow accumulation and runoff) preclude robust interpretations of trends in river flows and water budgets across the region. Satellite data has been used successfully to identify trends in lake ice conditions (later freeze-up and earlier break-up) and snow cover duration (decrease of approximately 3 weeks) across the region over approximately the last 30 years. Paleoenvironmental proxy records and paleoecological studies have been used to determine the longer-term trends in freshwater hydrology and ecology. Paleoenvironmental proxies largely indicate an intensification of runoff due to increases in snowfall, rainfall and glacial mass wasting, while paleoecological studies indicate changes in aquatic ecosystems related to increased ice off, nutrients and/or water temperatures. Active layer thickening and permafrost disturbances have significantly transformed the hydrology and ecosystems of ponds, wetlands and lakes, as well as the sediment, nutrient, metal and ion loads in rivers and downstream water bodies. Extreme ecological changes such as the loss of epishelf lakes and drying of ponds have been observed across the region. Continued and expanded monitoring of the responses of water quantity, water quality, and aquatic ecology to climate change is required to improve our understanding of how freshwater ecosystems are changing across the region.



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6.1 Introduction

Freshwater systems, including lakes, ponds, wetlands, and rivers, are the foundation of major ecosystems, and represent a key resource for communities in the Arctic. Climate change will have multiple direct, and interacting, impacts on both the volume and integrity of freshwater systems. Examples include, impacts on the physical processes that control the inputs and losses of water (such as rain, snow-fall, ground ice melt, ice cover, and evaporation), and the terrestrial conditions (such as active layer depth, thermokarst topography, slope stability) that control the movement, storage, and export of freshwater on the landscape (Figure 1).

This chapter includes a brief review of the recent observations and trends in precipitation, and active layer and permafrost conditions that are presented in Chapters 2 and 4 of this report, and discusses these changes in the context of their control on surface hydrology in the region. Understanding the characteristics of changes in precipitation, such as precipitation type and seasonality, as well as changes in ground thermal regime, are important for projecting changes in watershed hydrology and water quality. Recent observations of conditions and changes in freshwater systems in the Eastern Canadian Arctic, including changes to water volumes, water quality in rivers, wetlands, and lakes are also discussed. Changes in glaciers are not included as these are presented in Chapter 3 of this report.

Over the last 10-15 years significant integrated long term research and monitoring efforts at a number of sites across the Eastern Canadian Arctic, including the Cape Bounty Arctic Watershed Observatory (Melville Island), Ward Hunt Island, Bylot Island, Lake Hazen (Ellesmere Island), and the Apex River watershed in Iqaluit, have significantly advanced our knowledge of the direct connection between climate change and freshwater resources, biogeochemical processes, and ecosystem health. These studies have observed and documented the impact of rapidly warming temperatures on Arctic freshwater systems, during some of the warmest years on record in the region. Much of the

knowledge gained from these studies is reviewed in this chapter and/or elsewhere in this IRIS 2 report.

6.2 Climate change as driver of freshwater systems

The surface air temperatures in the Arctic between 2005-2010 were higher than for any other five-year period since measurements began in the late 1800's (AMAP 2011). As reported in Chapter 2, the warming in the Eastern Canadian Arctic was more rapid than most other Arctic regions, and is most pronounced in fall and winter, in response to later sea-ice formation. This warming began relatively recently (~1993), and is driven by both anthropogenic forcing as well as changes in the North Atlantic sea surface temperatures and the Arctic Oscillation (Chapter 2). Over the last 30 years the coldest months have warmed more than twice the rate as the warmest months (Chapter 2). The discussion below highlights the important implications of these warming temperatures on the various aspects of Arctic freshwater hydrology.

6.2.1 Timing, volume and type of precipitation

Changing climate will directly impact the type (liquid/solid), volume and timing of precipitation. As air temperatures increase, so do the rates of evaporation and the capacity for the atmosphere to hold water vapour. As a result, the likelihood of increased frequency and/or intensity of precipitation will also increase; especially if/where there is an unlimited source of moisture at the surface.

Air temperatures in the Arctic have exhibited warming in all months (Derksen et al. 2012) and increases in evaporation rates and water vapour have also been observed (Boisvert and Stroeve 2015, Serreze et al. 2012). The ocean and freshwater lakes represent important sources of water vapour to the atmosphere, hence climate driven decreases in the extent of lake and sea-ice cover feedback on (or influence) the hydrologic cycle and climate by increasing the availability of liquid water and thus evaporation rates. Increases in atmospheric vapour are expected to lead to higher rates of precipitation and possibly increased storm

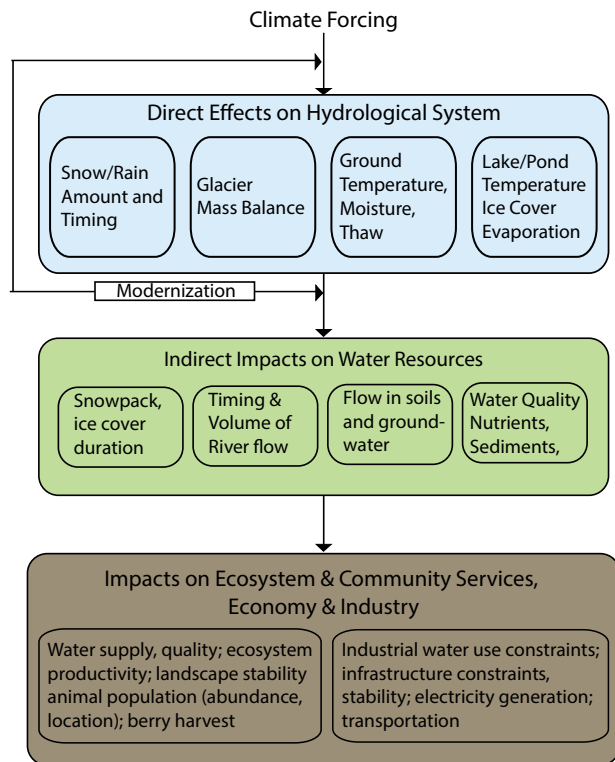


FIGURE 1. Conceptual diagram illustrating the direct and indirect impacts of climate change on hydrology, freshwater resources, and ecosystems, community services and economy.

intensities, although our ability to predict the likely spatial or seasonal distribution of the precipitation is poor (Hartmann et al. 2013).

Climate station data for the 1981-2010 indicates that roughly 65% of all precipitation in the region occurs in the summer and fall (Chapter 2, Figure 9). Although observations generally suggest there have been increases in precipitation, there is considerable uncertainty concerning these trends for the region (Chapter 2). For example, although the average of the nine climate stations in IRIS 2 exhibited significant increases in both rainfall and snowfall during the 1950-2013 period, part of this increase is attributed to abnormally low snowfall amounts prior to 1965 (Chapter 2, Figure 10). If the period prior to 1965 is omitted, significant increasing trends are observed for both rainfall (5.3% per decade) and snowfall (3.0% per decade). However, the

trends over the most recent 30-year period were not significant (Chapter 2).

The importance of these changes originate from the control that the timing and amount of precipitation have on the volume and timing of both the peak snowmelt runoff and summer rainfall volumes, which in turn have important implications for fisheries, recreational activities, water supply, and water quality (sediment, pathogens, nutrients, contaminants) (Figure 1).

6.2.2 Snow cover and snow cover duration

Seasonal snow cover exists for 7-9 months out of the year across the Arctic, and is a critical factor determining river, lake and wetland water volumes in unglaciated watersheds. Snow cover in the IRIS 2 region varies widely, from very deep (up to 500mm) in the mountainous regions of Ellesmere and Baffin Islands, to relatively thin and patchy across the large lowlands of Bathurst and Melville Islands (Chapter 2).

Snow cover duration is largely a function of latitude and altitude, but spring radiation budgets (air temperatures) that typically lead to rapid melt in May-June are also important (Chapter 2, Figure 11). Snow cover duration increases moving north-east across the IRIS 2 region, with the earliest onset and longest duration of snow cover occurring at high altitudes in the mountainous regions of Ellesmere Island, Axel Heiberg Island, and on the north-east coast of Baffin Island.

Surface observations and satellite data indicate a decrease of approximately 3 weeks in the snow cover duration since 1950, which is largely attributed to a delay in snow cover onset as a result of enhanced air temperatures in the fall (Chapter 2). Climate stations indicate an average ~20% decrease in snow depth across the region since the 1950's however, estimates of the trends in maximum annual accumulation as snow water equivalence (SWE) from satellite data show increases in SWE over the region (Chapter 2).

Snowfall accumulation has a direct impact on spring runoff volumes across the Arctic, and the timing and amount of snow depth has a significant impact on ground temperatures. Experimental snow augmentation experiments at the Cape Bounty Watershed Observatory (CBAWO) on Melville Island, demonstrate that increases in snow depth on the order of 40 cm (approximately triple the ambient snow cover), can lead to a 7-10 °C increase in mean monthly winter soil temperatures (Lafrenière et al. 2013). Similarly, very deep snow accumulation that occurs on land or in stream channels has a strong heat retention effect, with soil and channel surface temperatures up to 30 °C warmer than air temperatures mid-winter (Bonnaventure et al. 2016). However, a delay in onset of snow accumulation can substantially lower winter soil temperatures, despite considerably higher end of season snow accumulation (Lafrenière et al. 2013).

6.2.3 Ice cover duration, evaporation in rivers and lakes

Ice cover plays an important role in the thermal regime of lakes, including mixing, and rates of evaporation. As is highlighted in Chapter 2, the lack of *in situ* observations of lake and river ice in the region limits our ability to assess trends for these conditions in the region. However, a Pan Arctic assessment of *in situ* and river ice trends shows a trend towards earlier break-up dates across the Arctic (Duguay et al. 2006, Lacroix et al. 2005). Data from satellite imagery from 1985-2004 indicates that lakes within the IRIS 2 region were consistent with the Arctic-wide trend of later freeze-up (~0.8 days/year later) and earlier break-up. (1.2 days/yr earlier) (Latifovic and Pouliot 2007). Changes at Ward Hunt Lake on northern Ellesmere Island suggest that the summer perennial ice regime was relatively stable from 1953 to 2007, but experienced rapid thinning beginning in 2008, and was ice free in the warm summer of 2011 (Figure 2, Paquette et al. 2015). The increase in the time and extent of open water conditions has important implications for water balance due to changes in evaporation rates, and also lake ecology due to changes in water temperature and wind-induced mixing of the water column.

6.2.4 Ground thermal conditions, active layer thickness

The rate and depth of seasonal thaw, hence active layer thickness, exerts an important control on surface water hydrology in permafrost watersheds. As the extent of the active layer increases (i.e., as the frost table descends), the storage capacity available for water in the subsurface increases, which delays the time required for surface water runoff to respond to precipitation inputs. Hence any processes affecting the development of the active layer, also have direct impacts on soil moisture, potential evaporation, groundwater flow and storage, and surface runoff.

Ground thermal conditions which are largely a function of air temperatures, hence active layers within the region are generally thin due to the extended cold winters, and relatively short and typically cool summers (Chapter 4). At the local scale active layer thickness varies as a function of ground cover (e.g., organic vs. mineral soil), and soil moisture, with greater active layer thickness developing in mineral soils, and/or where moisture is lowest.

There are sparse records of active layer depths in the IRIS 2 region from 4 Circumpolar Active Layer Monitoring (CALM) sites including: Eureka, Tanqueray Fiord, Lake Hazen and Alexandria Fiord. These records show the active layer extending to between 41-62 cm depth between 1996 and 2001 (<https://www2.gwu.edu/~calm/>). These data are too sparse to interpret temporal and spatial trends, but the thickest active layers were found in 2000 and 2001. Given that significant increases in mean annual air temperatures have been observed across all stations in the region over the last 30 years (Chapter 2), increases in active layer thickness can be expected across this region.

Thickening of the active layer can have significant implications for surface water runoff and quality in areas of ice rich permafrost, which is particularly susceptible to subsidence and disturbances, such as active layer detachments (ALDs), retrogressive thaw slumps (RTS), and thermokarst gullies (gullies) (see also Chapter 4). Disturbances such as ALDs, RTS and thermokarst gullies are associated with warming and are abundant across the region (Godin and Fortier



FIGURE 2. The shrinking ice-cover of Ward Hunt Lake, at the far northern coast of Nunavut.

2012, Lamoureux et al. 2009, Rudy et al. 2013, Rudy et al. 2016). These studies indicate that recent warming has initiated widespread thermokarst and disturbance across the region, but it remains unclear the extent to which this represents a trend. Studies have shown these features have occurred sporadically over the region during the past 50 years, but it appears likely that the recent observations are unusual in density and frequency (Rudy et al. 2013).

6.3 Observations of change in freshwater systems

6.3.1 Changes in river flow volumes

Very little is known about recent changes in surface runoff volumes, or river flow in the Eastern Canadian Arctic (Spence and Burke 2008). Despite the presence of a number of water survey gauges in the region, the limited length of the records precludes the inference of trends from observational data. Even less is known about how Arctic river

quality (e.g., sediment loads, nutrient, dissolved ions, metals) is being affected by climate and related watershed changes.

In unglacierized watersheds, surface runoff in the region is largely a function of the difference between precipitation and evapotranspiration, plus contributions from subsurface water flows (e.g., thawing of ground ice, or permafrost ice), and any groundwater flow in areas where permafrost is absent. Because recent observations and projections for the next 100 years indicate both increases in precipitation and evaporation due to warming (Chapter 2), even estimating the direction of change of river runoff for small rivers is not straightforward. Trends for runoff from the Yukon and the Mackenzie rivers between 1957-1996 suggest that for these subarctic rivers, runoff is more dependant on precipitation inputs than losses from evapotranspiration (ACIA 2005, Table 6.12).

Glacier watersheds and non-glacier watersheds may respond differently to climate warming, as glacier ice melt in warm and relatively dry years drives increases in discharge, while non-glacial watersheds experience decreases in runoff associated with the higher rates of evaporation and diminished precipitation inputs (Lafrenière and Sharp 2003). Given the accelerating rates of glacier mass losses in the Eastern Canadian Arctic, it can be expected that glacial rivers will continue to see increases in runoff volumes in the near future. However, as glacier areas diminish these rivers will reach a tipping point where runoff volumes will eventually decrease (Pelto 1996), or trigger a reorganization of watershed boundaries and stream courses where the melting glacier is situated on a drainage divide (e.g., recent river piracy Slims River, Yukon, Shugar et al. 2017)

The Apex River in Iqaluit is one of only a few unglacierized rivers in the region with a Water Survey of Canada gauge (Spence and Burke 2008). A study investigating the relationship between climate and discharge in the Apex River, between 1973-1995, and 2006-2013 indicates that both the seasonal discharges (including only years with complete records, $n=19$) and the flow duration (the time from onset of runoff to freeze up) between 2007-2013 were higher than

the long term mean (Kjikjerkovska 2016). These observations for the Apex River are consistent with other Canadian subarctic rivers that have shown a trend toward later freeze up as a result of warmer autumn temperatures (Magnuson et al. 2000). The 11-year gap in the discharge record, as well as the absence of data pertaining to precipitation type (snow vs. rain) after 1997, significantly limited the analysis of the relationships between the climate variables (temperature, precipitation) and the seasonal components of runoff (snowmelt runoff, rainfall runoff and baseflow) in the Apex River. This study highlights how the absence of consistent long-term observations in the Eastern Canadian Arctic limits our capacity to describe, let alone predict, the response of the river flows to changing climate.

In a study that combined hydrological modelling with down-scaled climate projections in effort to predict twenty first century runoff trends for a small High Arctic river (West River at the Cape Bounty Arctic Watershed Observatory, Melville Island) Lewis and Lamoureux (2010) determined that total runoff for this river would increase, because projected increases in precipitation exceeded projected increases in evaporation. This modelling effort also predicts higher peak flows and delays in flow cessation (hence longer flow duration) in this High Arctic system over the twenty first century due to increases in precipitation (snow storage during the winter and total precipitation) and warming fall temperatures (Lewis and Lamoureux 2010; Figure 3).

A number of paleoenvironmental proxy and anecdotal observations indicate substantial changes in surface water conditions, ice cover and river discharge in recent decades. For instance, Smol and Douglas (2007) showed that a series of ponds that have been studied for 30 years have sharply reduced volumes and in some cases have dried out entirely (e.g., Figure 4). They noted that the volume reduction had clear impact on the concentration of dissolved solids and constituted a major change for aquatic communities in the ponds. This work parallels reconstructed river discharge in the northern Arctic coast that suggests snowmelt runoff in major rivers has declined substantially during the past 400 years (Lamoureux et al. 2006). By contrast, other lake sediment proxy records suggest increased runoff due to

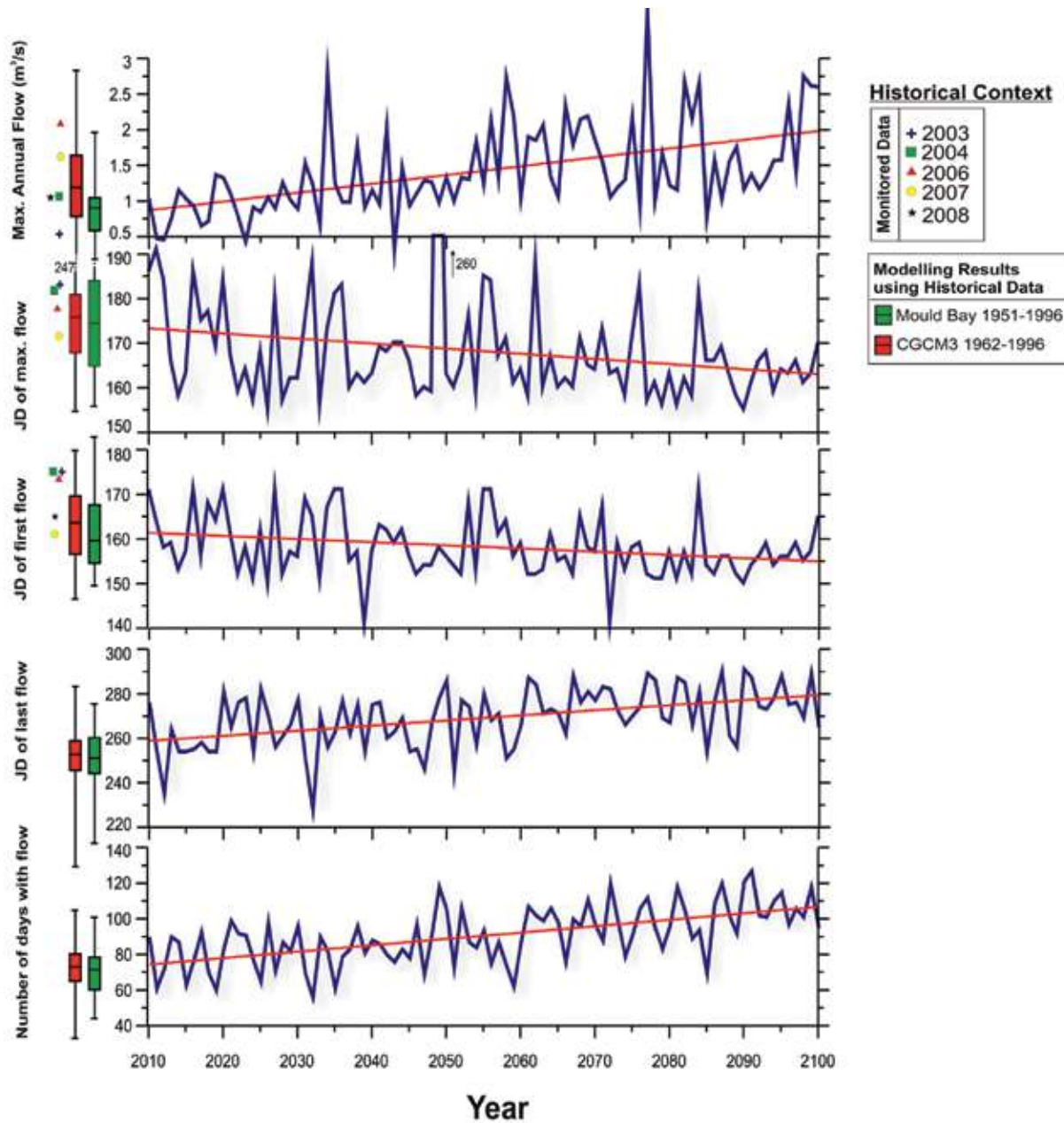
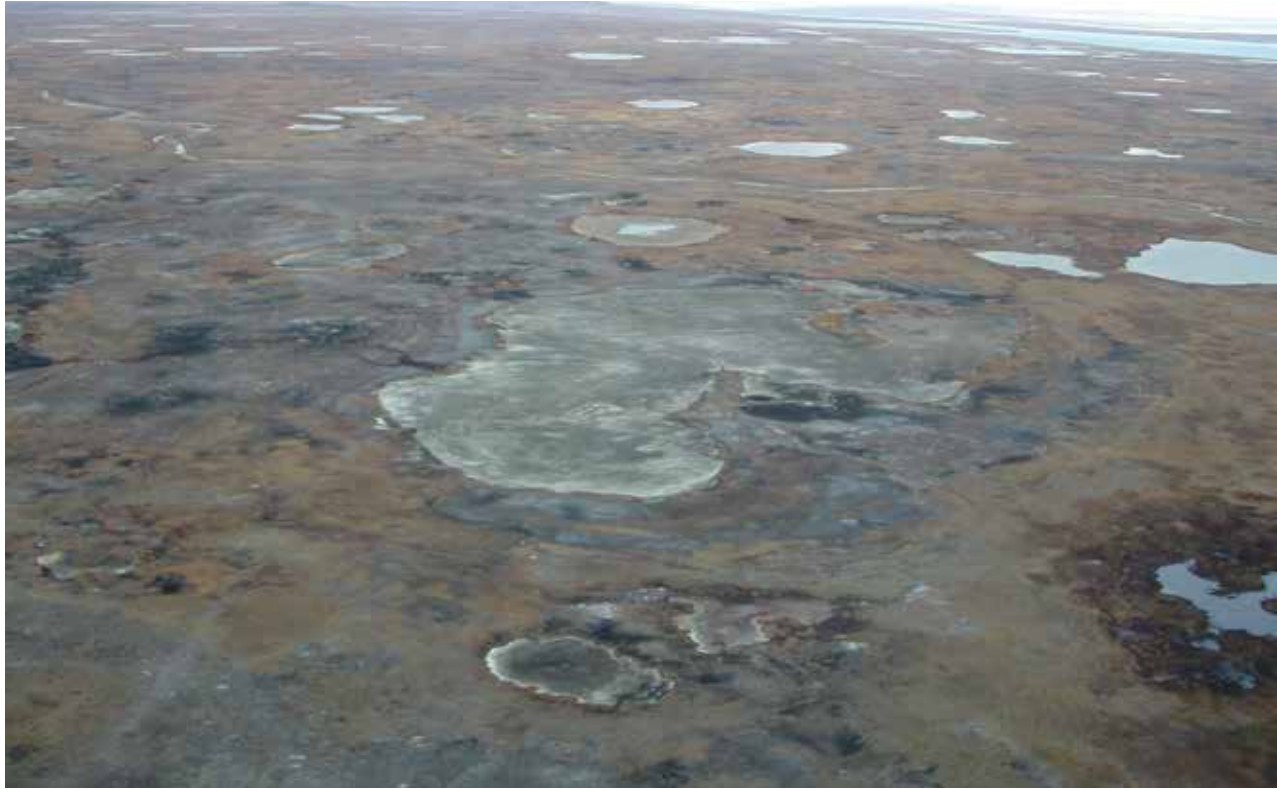


FIGURE 3. Modified from Figure 8 in Lewis and Lamoureux (2010). Modelled 21st century Julian day (JD) of first flow, JD of last flow, and number of days with flow. JD of first (and last) flow is defined as three or more consecutive days with discharge greater than (and less than) $0.05 \text{ m}^3/\text{s}$. Monitored data are shown where applicable. The hydrologic model was also run with historical modelled (CGCM 20CM3 scenario) and measured meteorological data (Mould Bay precipitation, and synthetic Cape Bounty air temperature). Symbols are monitored hydrologic data from Cape Bounty. Best-fit linear regression lines are also shown.



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FIGURE 4. Drying Ponds at Allison Inlet, Bathurst Island, after a warm dry summer late August 2011.

snow melt intensity (Lamoureux and Bradley 1996) or rainfall intensity (Lapointe et al. 2012). Glacial systems also show increasing runoff in the 20th century in many areas of the region (Lamoureux and Gilbert 2004, Lewis et al. 2002, Moore et al. 2001). These proxies suggest important changes to surface water environments in the region but long-term patterns indicate a substantial range of surface water change.

An extensive network of paleoecological studies based on fossil indicators such as diatoms have been carried out in the region and show a clear change in aquatic ecosystems interpreted to be related to increased ice-off duration, along with enhanced nutrient and/or water temperatures (Smol et al. 2005). The timing of the initiation of these changes ranges from the mid-1800 period in small pond systems to the late 20th century in larger lakes, suggesting an increasing climate effect across a wide range of pond and lake environments.

6.3.2 Changes in water quality

6.3.2.1 Observations of climate change and disturbance impacts on sediment loads

Sediment and particulate organic matter constitute an important component of surface water quality. Much of the region is covered with fine grained sediments of glacial and marine origin and as a result, sediment erosion and transport is widespread, particularly in the central and western regions of IRIS 2. The primary controls over sediment erosion are the availability, or sources of sediment, and hydrological pathways (or connectivity) to transport the sediment downstream (Orwin et al. 2012). Most research in the region has focused on the transport of suspended sediment (e.g., Lamoureux and Lafrenière 2014) and little is known about coarser bedload since the pioneering work of Church (1972). Suspended sediment comprises clay, silt and sand-sized fractions that are highly mobile in stream and river flow, and can

also travel considerable distances in lakes and ponds under ice cover (Cockburn and Lamoureux 2008). Few long term sediment transport data sets exist in the region to assess responses to climate and hydrological change. A number of studies have investigated sediment transport on a short term (1-3 year) basis and indicate a strong association between higher discharge and sediment transport and yield. In snow-melt dominated settings, this transport varies according to the quantity of snow (or SWE) in the catchment at the end of winter (Lewis et al. 2012). In years with greater snow, high discharge conditions are sustained for a longer period and result in disproportionately higher sediment transport across different landscape types (Forbes and Lamoureux 2005, McDonald and Lamoureux 2009). Summer rainfall has the potential to increase sediment transport significantly, and an intense rainfall event (c. 30 mm total) can outstrip snowmelt sediment transport substantially (Cogley and McCann 1976, Lewis et al. 2012). In glacial systems, sediment transport is sustained throughout the summer melt period and depends on specific flow pathways on, within, below and adjacent to the ice (Moore et al. 2009).

Few hydrological modelling efforts have been undertaken in the region to consider the impact of climate change on runoff and sediment transport. Lewis and Lamoureux (2010) modelled suspended sediment transport for a small High Arctic river and found the climate projections increase discharge, and have a disproportionate increase in suspended sediment transport. Their model results indicated that sediment yields would increase by 100-600% by 2100. They suggested that these estimates are likely to be minimums, as the models did not account for changes in sediment supply due to catchment disturbance by permafrost change (Lewis and Lamoureux 2010).

Landscape disturbance due to permafrost degradation is one key mechanism to increase sediment availability for erosion and transport (Figure 5). In locations where fine grained, ice-rich surface materials occur (principally the western islands and lowland coastal regions), slope failures such as thermo erosional niching and active layer detachments (ALD) (Figure 5) can substantially increase local sediment availability (Chapter 4). Lamoureux and Lafrenière (2009)

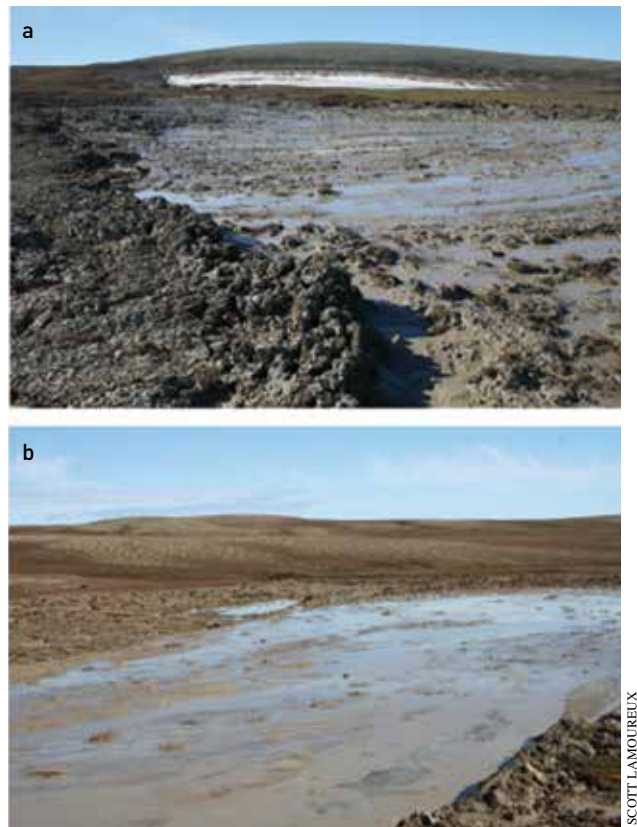


FIGURE 5. Active layer detachments (ALD) at the Cape Bounty Arctic Watershed Observatory immediately after they formed at end of July 2007. (a) Looking up slope to the initiation of the ALD. (b) Looking downslope from the same position as (a). Note the sediment slurry floor of the ALD and the high level of sediment made available for erosion.

noted that new disturbances had an immediate and large downstream impact on sediment yields, but over a longer timescale, these effects were less evident in larger river systems (Lewis et al., 2012). Sediment yields from disturbed slopes exhibited in excess of 1000 times higher sediment yields compared to undisturbed slopes. In addition to erosion of mineral sediment, research suggests that disturbance mobilizes a proportionate amount of particulate organic carbon (POC), about 1% of the mineral yield (Lamoureux and Lafrenière, 2014). Most notably, the eroded POC appears to be substantially older and has implications for downstream biogeochemical cycling and aquatic ecosystem. In a long term study of the impact of these disturbances, Lamoureux

et al. (2014) showed that the impact varies by disturbance according to hydrological conditions and flow pathways, and further demonstrated that recovery was comparatively rapid and five years after disturbance, disturbances produced much lower sediment yields. This contrasts to larger and sustained forms of permafrost disturbance such as retrogressive thaw slumps that appear to generate long term, extensive downstream sediment transport effects (Rudy et al. 2015). Given the clear association between permafrost degradation and increased sediment availability, the likelihood of increased suspended sediment yields in surface waters is substantial and could have important impacts on water quality in the region.

6.3.2.2 Climate change and permafrost disturbance impacts on dissolved loads

Solutes are the dissolved constituents in water, and in the broadest terms a solute can be any material that passes through a 0.45 μm filter. Solutes are typically examined from the perspective of several major groups of constituents:

- major ions (such as sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), bicarbonate (HCO_3^-), and sulfate (SO_4^{2-}) among others);
- nutrients (including nitrate (NO_3^-), ammonium (NH_4^+), and phosphate PO_4^{3-} (or other dissolved forms of phosphate));
- dissolved organic matter (DOM), which includes dissolved organic carbon (DOC), and dissolved organic nitrogen (DON);
- and metals, which may include common metals like aluminium (Al) and iron (Fe), as well as other trace metals (e.g., zinc (Zn), copper (Cu), mercury (Hg)) that are present in concentrations that are orders of magnitude lower than for Al and Fe, and many have important toxicological effects (see Box A).

Solutes in water are important determinants of water quality, as they can determine the suitability for the potential end use (e.g., human consumption or ecosystem support (e.g., fisheries)). The concentrations of solutes in water (usually

expressed in mg/L or ppm), as well as the total mass export, or loads (i.e., kg per season) are largely controlled by the source and amount of water, and as well as the pathway the water follows in the watershed prior to reaching the stream or river. Solute loads are therefore intimately tied to climate change, specifically through its impacts on: the amount, timing and type of precipitation (rain vs. snow); the thickness of the active layer available for storage and movement of water in the subsurface; and permafrost disturbance, which influences the nature of surface flow pathways (Figure 1).

Lewis et al. (2012) found that the source of water (snowmelt vs. rainfall) could be more important than the total volume of runoff in determining the dissolved inorganic ions and DOC yields. They found that although snowmelt typically dominates the water yields, the major ion, DOC and total dissolved nitrogen (TDN) loads can be dominated by contributions from rainfall runoff following significant late summer rainfall events. This study concludes the disproportionate solute response to rainfall runoff is a result of the input of water to the soil when the active layer is thick, which enhances the weathering and release of soluble ions from previously frozen soil.

Thermal perturbations (deep thaw) and physical disturbance of permafrost have the potential to significantly alter the quantity and composition of solutes in runoff. Thermal perturbation releases previously frozen inorganic solutes (metals and major ions), while physical disturbances remove much of the organic rich surface soil and expose the previously buried and frozen solute rich mineral soils at the surface. Lewis et al. (2012) found that localized physical disturbance had no discernable impact on the dissolved solutes (major ions, DOC, and TDN). The authors attributed the limited impact of the disturbances to the low proportion of the catchment area that was disturbed (~3%), and the limited water flow through the disturbances (i.e., disturbances were hydrologically disconnected). Subsequent research at CBAWO comparing smaller catchments with varying degrees of permafrost disturbance supports that the major ion concentrations and loads are only significantly affected by disturbance if the spatial extent of the

BOX A. Trends of mercury in landlocked char in the High Arctic and possible climate influences

Non-anadromous or landlocked Arctic char (*Salvelinus alpinus*), are the only fish species in lakes of the Canadian high Arctic islands which are isolated from the ocean (Power et al. 2008). Char are the top predator and preferentially feed on benthic chironomids (Order Diptera), the dominant invertebrate (Chételat et al. 2010, Gantner et al. 2010, Lescord et al. 2015). Their importance in lake food webs and wide distribution makes them a key sentinel species in studies of impacts of climate change on lake ecosystems. A major question being addressed is how climate warming may influence methyl mercury, the toxic and bioaccumulative form of mercury, in Arctic freshwater environments. This has been investigated using long term time series of methylmercury concentrations in arctic char (measured as total mercury (Hg)) from 6 lakes on Cornwallis Island (Amituk, Char, North, Small, Nine-Mile, and Resolute) as well as in Lake Hazen in Quttinirpaaq National Park on Ellesmere Island (82 °N). In addition, studies conducted at the Cape Bounty Arctic Watershed Observatory (CBAWO) have developed a time series (2008-2016) for mercury in char from two adjacent lakes, East Lake and West Lake. The West catchment has experienced numerous large active layer detachments during 2007-2008 as well as subaqueous slumps, turning the lake very turbid, while the East catchment has experienced relatively minor disturbances. The time series are based on annual collections of 7 to 25 adult char by gill netting in late July and early August. Further details on sampling and analysis of the char can be found in Gantner et al. (2010) and Lescord et al. (2015). Temporal trend analyses and multiple linear regression modelling was conducted with length-adjusted Hg concentrations and climate variables. Statistically significant declines in length adjusted mercury concentrations in char muscle were found for 7 of 9 lakes (Amituk, Char, East, Hazen, North, and Resolute). Annual percent declines ranged from 2.0% (Nine-Mile; 2005-16) to -8.5% (Char Lake; 2005-12). Small Lake and West Lake showed significant increases of 8.0% and 4.8% over the period 2007-2016 and 2009-2016. While Small Lake is not turbid it has higher DOC (2.2 mg/L) than all other lakes except West Lake (1.9 mg/L), which may be due to its greater area of bogs and wetland. The percent declines of mercury in char were significantly inversely related to dissolved organic carbon ($R^2 = 0.60$, $p=0.014$) (Figure 1) but not to particulate carbon ($p=0.29$) or dissolved methyl mercury in the water column, watershed-lake area ratio, or distance from the ocean. These declines are much more rapid than atmospheric Hg concentrations over the same period at Alert (north Ellesmere Island) which are about 1%/year (Cole et al. 2013). Prior to the mid-2000s Hg concentrations in char from lakes Amituk, Resolute and Hazen, where long term data (1990s to 2016)

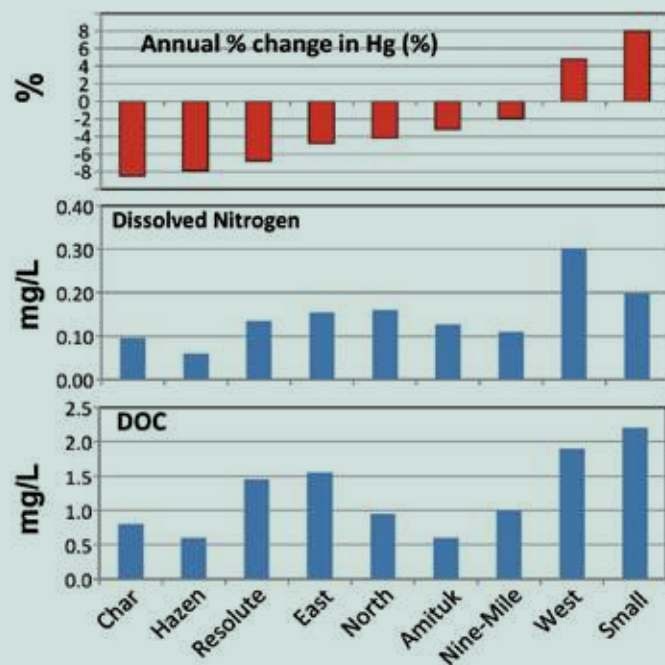


FIGURE A1. Percent annual change of methyl mercury in char muscle vs lake water chemistry. Significant correlations with Dissolved Nitrogen and Dissolved organic carbon (DOC) in lake water

disturbance is greater than approximately 6% and if the disturbance is well channelized (i.e., hydrologically connected; Lafrenière and Lamoureux 2013). Lafrenière and Lamoureux (2013) also found that thermal perturbation of the active layer, which occurs catchment wide, can have a greater impact on major ion fluxes, than localised physical disturbance. This study, as well as subsequent work by (Lamhonwah et al. 2017), demonstrate the significance of deep thaw and the hydrological connectivity provided by late summer rainfall as controls on the dissolved loads in permafrost watersheds in the region. Together these studies

highlight that understanding the timing, type and intensity of precipitation and the frequency and magnitude characteristics of projected warming are important controls on the solute and water quality response of watersheds to regional climate change (Figure 6).

Studies that have focused on the impact of climate change on dissolved organic matter and nutrients in the Eastern Canadian Arctic indicate that the thermal and physical disturbance of the active layer and near surface permafrost stand to have important impacts on the delivery of these key nutrients to aquatic ecosystems. Organic carbon and

are available, appeared to be steady or increasing. Over this longer period, Hg concentrations in char from Resolute and Hazen Lake were significantly correlated with values of the spring Pacific North-America pattern (PNA) an influential climate index in the Northern Hemisphere mid-latitudes (Hazen: $R^2 = 0.41$, $p=0.014$, $n=14$; Resolute: $R^2 = 0.29$, $p=0.026$, $n=17$) (Figure 2). Results of the multiple linear analysis for each lake showed that equations which included Previous Fall Temperature (PFT) and PNA had strong predictive power. However, the PFT term was negative in each model, suggesting

that higher temperatures result in lower Hg concentration in char. Evans et al. (2013) also found temperature term was consistently negative in their models for Hg in lake trout from Great Slave Lake. Thus the declining mercury in 7 of 9 lakes appears to coincide with higher summer and fall temperatures in the period 2005-2012. Higher temperatures are also associated with earlier ice out and may result in dietary shifts for char.

In summary, long term studies are providing information on possible impacts of climate warming on methyl mercury accumulation landlocked Arctic char and on the biogeochemistry of mercury in the High Arctic freshwater environments. Mercury may be declining in char due to warming but this may be countered by enhanced methyl mercury availability in lakes influenced by changes in their catchments such as permafrost degradation and greater wetland productivity. Higher snow accumulation and/or summer rainfall might also influence mercury in char by increasing DOC inputs to lakes. Ongoing research will attempt to address these questions.

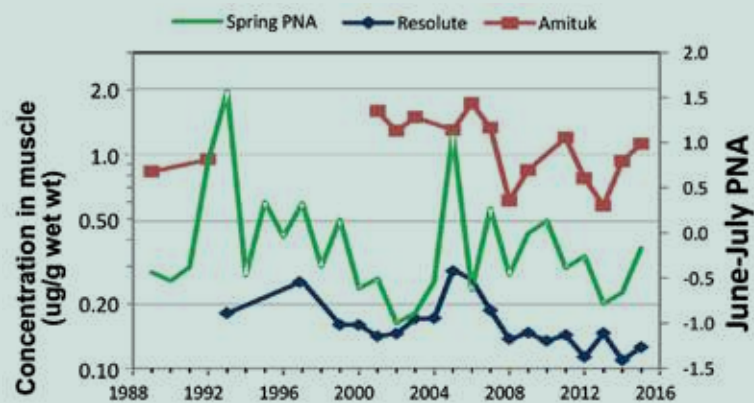


FIGURE A2. Trends of mercury in arctic char in Resolute and Amituk Lake appear to show a weak positive relationship spring Pacific North-America pattern (PNA). No relationship was seen for the Arctic Oscillation index, summer temperatures or ice coverage of nearby ocean waters

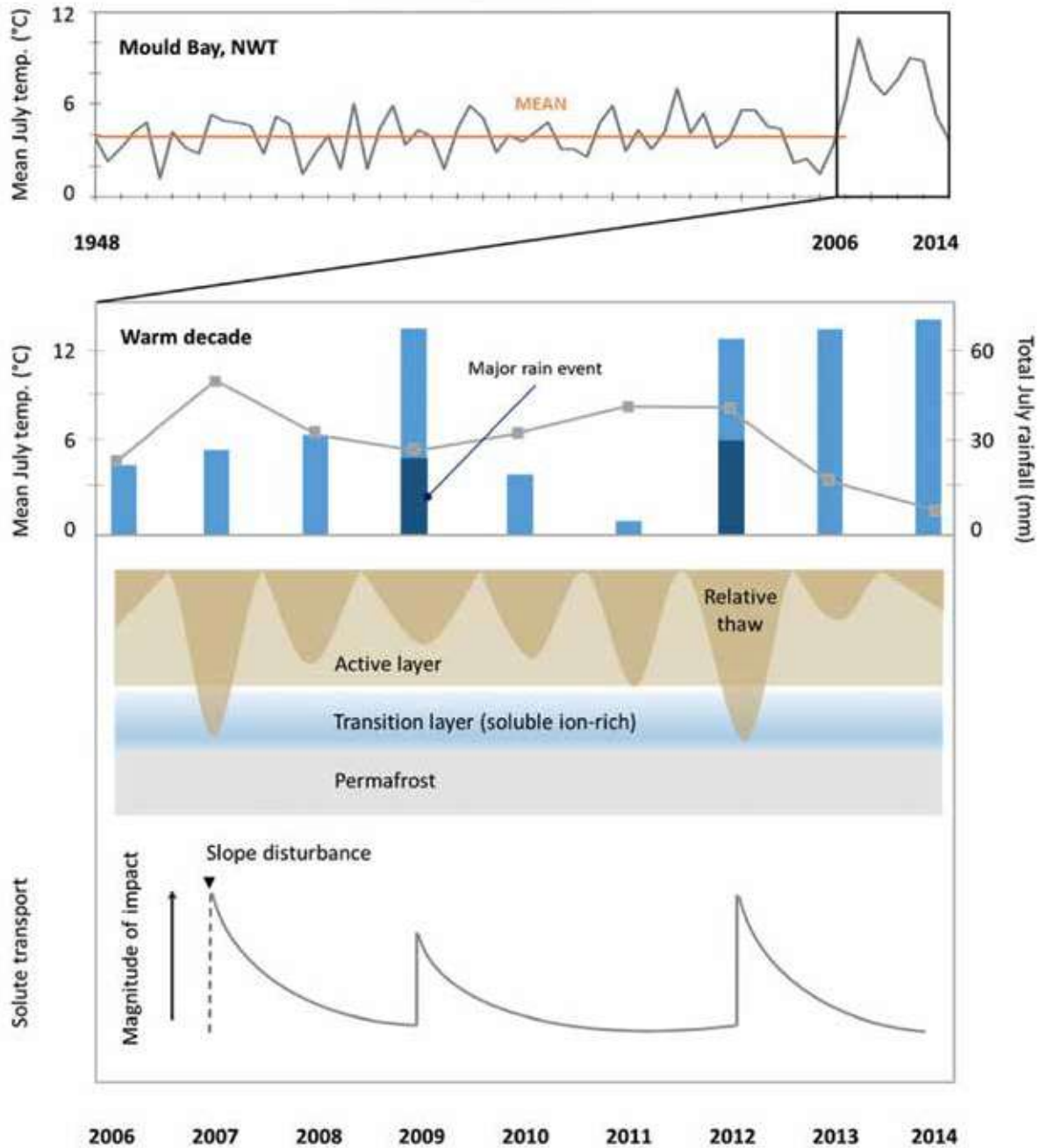


FIGURE 6. Conceptual diagram showing the relationships between late summer air surface temperatures and precipitation, relative thaw depth, proximity of thaw to the solute rich transition layer, and impacts on solute transport. Adapted from Lamhonwah et al. (2017).

dissolved nitrogen are essential building blocs for metabolism and energy transfers in the aquatic food chain. Both the amount and the type of organic matter and nitrogen are important in determining ecosystem function. Higher amounts of biologically available nitrogen (NO_3^- and NH_4^+) as well as more readily biodegradable (i.e., labile) organic matter can enhance the biological productivity of aquatic ecosystems. Studies conducted at the CBAWO following the formation of a number of slope disturbances indicate that runoff from disturbances exported suspended sediment contained older (Lamoureux and Lafrenière 2014) and more labile and less degraded organic compounds (Grewer et al. 2015), relative to undisturbed areas. Molecular analysis of the newly disturbed soils also showed that microbial activity was substantially increased when compared with undisturbed soils (Pautler et al. 2010). Similarly, a study investigating the composition of DOM in runoff from a series of catchments subject to varying degrees of disturbance, indicates that although streams from disturbed watersheds delivered slightly less DOM relative to less disturbed (or undisturbed) catchments, the composition of the DOM was more easily degradable (low molecular weight, less aromatic) and fresher (less degraded) with increasing extent of disturbance (Fouché et al. 2017). Runoff following late season rainfall events also delivered elevated concentrations of more easily degradable, and fresher DOM across all catchments (Fouché et al. 2017). A parallel study that investigated the potential impact of disturbances on the dissolved nitrogen loads, showed that the disturbed catchment exported substantially more NO_3^- than the undisturbed catchment, especially following late season rainfall (Lafrenière et al. 2017). Other work demonstrates that the additional NO_3^- was microbially derived, likely from enhanced mineralization of dissolved organic matter (Louiseize et al. 2014).

Together these investigations indicate that organic matter derived from the deeper portion of the active layer or from recently thawed upper permafrost soil is older, but more biodegradable than near surface organic matter. This is important as this indicates that organic matter mobilized from permafrost degradation could serve to stimulate biological productivity in streams and soils, and the release of old C to the atmosphere, and that the impacts of disturbance

on the composition of nutrients and DOM can persist for several years following a disturbance event.

6.4 Hydrology of wetlands and the response to climate change

6.4.1 Introduction

Wetlands are grounds that are saturated for at least a portion of the year with some types allowing hydrophilic plants to persist. In the High Arctic polar desert landscape, where vegetation is usually sparse, these often-lush vegetated sites offer a critical ecosystem for migratory birds and other fauna. Wetlands can include ponds < 2 m in depth, small strips of wet, vegetated ground alongside lakes, streams, arctic coastlines, or downslope of semi-permanent hillslope snowbeds. At the mesic to regional scale, wetlands usually comprise a mosaic of ponds of varying sizes, wet meadows, and both wet and dry ground. Often a network of low-centered and high-centered polygons exists and is indicative of massive ground ice (Woo and Young 2006). Maintenance of wetlands in the Eastern Canadian High Arctic depends on (1) the presence of permafrost and a shallow active layer (< 0.7 m), which limits the subsurface storage capacity, serving to keep water levels above or near the ground surface; (2) a regular supply of water (meltwater, ground ice melt) which exceeds seasonal losses (evaporation, seepage); and (3) the existence of peaty soils and wetland plants, including moss, which help modify water storage and thermal properties of the ground promoting ground ice formation, and in some cases permafrost growth.

The water budget is a useful framework to examine the hydrology of High Arctic wetlands. Here it is defined as:

$$P(\text{Sn}+\text{R})+\text{Gin}-\text{Gout}-\text{E}=\pm\Delta\text{S} \quad (1)$$

where P is precipitation either snow(snowmelt) (Sn) and rainfall (R), Gin and Gout are lateral inflow or outflow respectively, E is evaporation which here includes transpiration, and ΔS is the change in storage. This term can comprise fluctuating pond water levels, water tables, and soil moisture changes in wet meadows. It also includes the residual or error term for the complete water budget,

especially if wetland storage cannot be directly assessed (Young et al. 2015).

6.4.2 Emerging patterns

6.4.2.1 Snowcover

Snow continues to be an important source of water for wetland systems in the High Arctic but variability in end-of-winter snow conditions continues to be the norm, and accurate measurement of end-of-year snow accumulation (in terms of water equivalence) continues to be a significant challenge to closing the water balance in Arctic watersheds (Young et al. 2015). At Polar Bear Pass, an extensive low gradient wetland located in the middle of Bathurst Island (75° 43'N, 98° 40'W), snow receipt on low-lying ponds, wet meadows, lakes and incised polygonal ground is highly variable across space (e.g., ponds) and from one year to the next (Table 1). Nearby hillslope snowbeds and incised stream valleys continue to capture the most snow. Like other sites in the Eastern Canadian Arctic (see Godin et al. 2016) the deeply incised polygonal wetland area in the headwaters of a hillslope stream typically capture more snow than the low-gradient wetlands. Strong winds are also effective in redistributing snow from elevated regions (plateau) into the lee of hillslopes and onto the adjacent wetland (Young et al. 2013).

6.4.2.2 Rainfall

Impact of rainfall in High Arctic wetland ecosystems is strongly tied to its timing. Rain during seasonal snowmelt can accelerate melt by increasing the flux of heat into the snowpack and/or cause its dissipation through mechanical erosion. Arrival of rainfall at the tail-end of seasonal snowmelt may prolong surface runoff into ponds, lakes and wet meadows, gullies, or catchment outlets as the ground is still largely frozen (Abnizova et al. 2014, Godin et al. 2014). Episodic and minimal rainfall during the thawed season may do little to encourage runoff, especially if the storage capacity of the active layer or pond is large and evaporation demand matches or exceeds rainfall inputs (Godin et al. 2014, Young and Labine 2010, Young et al.

2015) However, frequent rainfall events, even small ones spaced throughout a season can be sufficient in maintaining or raising saturated conditions until a larger rainfall event triggers surface flow. Peak runoff from wetlands caused by summer rains can occasionally match nival levels (Miller and Young 2016, Young and Woo 2003).

6.4.2.3 Evaporation

Evaporation (including transpiration) continues to be an important loss of water from wetland surfaces including large low-gradient wetlands (see Bowling et al. 2003, Liljedahl et al. 2001, Muster et al. 2012, Young, 2017). Highest rates of evaporation from wetlands typically occur right after snowmelt when incoming radiation levels are high and water is freely available owing to a shallow thawed ground. Later in the season, evaporation rates can be modified by changes in water availability and/or energy flux. Open-water bodies, like ponds show greater losses than wet meadow sites (Young and Labine 2010). In warm, dry seasons in the High Arctic (e.g., 2011, 2012), drying of ponds is common especially in areas that do not have access to alternative water supplies (Figure 4, (Abnizova and Young 2010)). In some cases, emergent plants can inundate shallow ponds transitioning them into wet meadows (Figure 7).

6.4.2.4 Lateral inflow/outflow

Ponds and wet meadows that receive additional inputs of water either as surface inflow or groundwater at the tail-end of the snowmelt season are generally resilient against losses of water either due to evaporation losses or water seepage as the active layer deepens. These terrestrial inflows are also critical in depositing DOC and nutrients into nearby ponds (Abnizova et al. 2014). In a recent study, Young et al. (2016) showed that following the snowmelt season meltwater from a late-lying snowbed supplied groundwater to a downslope wet meadow raising water levels during both dry and wet years but these ground water inputs were not significant in comparison to seasonal snowmelt or summer rainfall in terms of the seasonal water budget. Likewise, groundwater outflow from this same wet meadow into a



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FIGURE 7. Photograph showing emergent plants in tundra pond, near Eastwind Lake, Ellesmere Island, mid-July, 2005.

nearby pond was also negligible when assessed in terms of the pond's seasonal water budget. This study along with the one by Woo and Young (2014) signaled that for some High Arctic sites, meltwater from late-lying snowbeds is no longer an important source of water for wetlands, especially in the post-snowmelt season. This finding differed from earlier wetland studies on Cornwallis Island, which showed semi-permanent snowbeds were critical in sustaining high water tables and outflow in a groundwater-fed wetland over several arctic summers (Young and Woo 2000). The Young et al. (2016) study also suggested that it is the future changes in seasonal snowcover and rainfall in High Arctic landscapes that will directly affect the resiliency of wetlands at scales from small to extensive.

Our understanding of runoff from extensive low-gradient wetlands in the High Arctic, especially in non-glacierized catchments is still inadequate. Runoff from patchy wetlands (Young and Woo 2000, Young and Woo 2003) and small polygonal wetland catchments in response to thermo-erosion gullying have been quantified (Godin et al. 2016). In Northern Canada studies suggest that streamflow is intensifying in response to recent climate warming (Dery et al. 2009). In some mainland watersheds, peak streamflow is occurring earlier because of earlier snowmelt, while baseflow is higher due in part to greater permafrost thaw which has enhanced the storage capacity of watersheds (Dery et al. 2009)

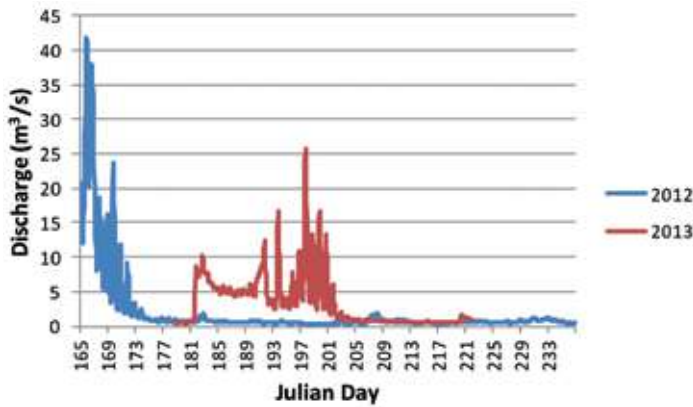


FIGURE 8. Estimates of streamflow from the Polar Bear Pass watershed [Eastern Sector-102.6 km²] in 2012 (warm/early melt) and 2013 (cool/late melt).

Stream runoff from the eastern sector of PBP (area=102.6 km²) is shown for two contrasting years (Figure 8). In 2012, owing to an extremely warm spring, peak runoff occurred by mid-June, and after a few days fell to baseflow levels where it remained for the rest of the season. Here, the early peaks are driven by snowmelt coming from the northern part of the Pass (southerly aspect) and with the secondary peaks attributed to meltwater from the southern half of the Pass (northern aspect). In 2013, runoff is delayed well into early July and while the snowmelt from the northern half of the Pass initiates runoff, it is the meltwater inputs from the southern part of the Pass that define peak runoff (Figure 9). While two years of data is inadequate to come to any defining conclusions, it is conceivable that these two contrasting years could bracket the range in responses that extensive wetlands like PBP can expect for the future as



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FIGURE 9. Photograph of the typical snow cover pattern during snowmelt across Polar Bear Pass. North part of the Pass melts out earlier than the southern part of the Pass which is still snow covered. Photo taken mid-June, 2010.

the Canadian Eastern High Arctic continues to warm and extreme climatic conditions become more common.

6.4.2.5 Wetland storage

Estimates of wetland storage are often determined as the residual in a water budget, and subsequently they will include errors in the water budget components (see Young and Woo 2004). Most wetland ponds experience negative seasonal storage as evaporation losses draw down water levels and these losses are not replenished. Wet meadows can show either negative or positive water storages, with ground ice melt often raising soil moisture levels. At the regional scale storage at PBP is much larger ranging from -52 mm (cool year) to -125 mm (warm year) (Young 2017). This estimate differs from an extensive low-gradient low arctic coastal wetland (see Bowling et al. 2003) where storage ranged from only -2 to -25 mm over two seasons. Finally, episodic thermo-erosion processes such as gully-ing (Godin et al. 2014, Godin et al. 2016), frost cracks (Abnizova and Young 2010), and erosion of polygonal rims (Boike et al. 2008) can drain ponds and polygonal landscapes quickly, thus enhancing overland flow connectivity, and ultimately altering soil moisture conditions and vegetation cover even over small areas (Godin et al. 2014, Godin et al. 2016).

6.5 Aquatic ecosystem responses to climate change in the region: Trends and uncertainties for lakes and ponds

Lakes and ponds are a major component of the northern landscape (Rautio et al. 2011, Verpoorter et al. 2014, Muster et al. 2017), and in the Eastern Canadian Arctic they occur in diverse landscape types spanning the 2500 km latitudinal gradient from 60 to 83 °N, and across the vast 2500 km east-west expanse of Nunavut. They encompass a great variety of ecosystem types, from shallow waters that melt out and mix completely each year to deep, stratified lakes that retain their ice cover through most of summer. As to be expected from these diverse settings, aquatic ecosystems in the region vary greatly in their current responses to climate change, and in their likely sensitivity to ongoing climate

impacts. This section examines current changes that have been observed in lakes and ponds within the region, and the implications and uncertainties regarding future shifts.

The most severe ecological impact of climate change is the complete loss of ecosystems and even certain ecosystem types. One mechanism of this ecosystem extinction is through changes in the hydrological balance, with shifts in the ratio of precipitation to evaporation. Many lakes and ponds in the North are shallow, yet often support large populations of aquatic organisms including zooplankton. They are maintained because of replenishment by snow-fall (in some cases by glacial meltwaters) combined with prolonged ice cover and low temperatures that ensure low evaporative losses. An additional factor is the underlying permafrost in these catchments that keeps the water table high and favours rapid transfer of meltwaters to the lake. There are likely to be large interannual variations in these shallow waters, and the biota of these habitats are adapted to sustain these changes. For example, experiments on High Arctic microbial mats, which form a layer over the base of many Arctic lakes, ponds and streams and often dominate their total ecosystem biomass, have a high tolerance to the salinity stress that would accompany evaporation (Lionard et al. 2012). However, the long term drying up of ponds will push even these hardy organisms to extinction. A pronounced shrinkage of shallow ponds has been observed in parts of Nunavut, with evidence at Cape Herschel on eastern Ellesmere Island of complete evaporative loss of some ponds (Smol and Douglas 2007).

In several parts of the circumpolar Arctic, the degradation of permafrost around thermokarst lakes and ponds (thaw lakes) is resulting in the complete drainage and disappearance of these waters, or loss by infilling. Conversely, in other parts of the Arctic, including in Nunavik, immediately to the south of Nunavut, thaw lakes are expanding in abundance and size (Vincent et al. 2011, Vonk et al. 2015). These trends have not been well assessed throughout the Nunavut, although there is evidence of recent thaw lake drainage in Nettilling Lake region on the Great Plain of the Koukdjuak (Baffin Island).

Another mechanism of climate-induced loss of freshwater environments is through changes in ice barriers that are structurally or hydrologically essential to the integrity of the ecosystem. Epishelf lakes, which are freshwater environments dammed by ice shelves, are especially vulnerable to such impacts. These ecosystems have unique physical, chemical and biological characteristics, with freshwater biota in the upper layer and marine biota at depth, in exchange with the Arctic Ocean (Van Hove et al. 2001). More than a dozen of these lakes occurred along the northern coastline of Ellesmere Island at the beginning of the last century, but with the attrition of the ice shelves, these have been mostly lost (Veillette et al. 2008). The largest was Disraeli Fiord epishelf lake, which was lost in by the fracturing of the Ward Hunt Ice Shelf over the period 1999-2002 (Mueller et al. 2003). The sole remaining epishelf lake is in Milne Fiord, which has a pronounced layering of its biological communities (Veillette et al. 2011b). This system has recently shown large year-to-year variations in its microbial community composition (Thaler et al. 2017), and the ongoing thinning of the Milne Ice Shelf implies that this ecosystem is on the brink of extinction (Hamilton et al. 2017). The surface of the Arctic ice shelves contain melt ponds with rich communities of microscopic life (Vincent et al. 2004). As in Antarctica, these have been considered as models for life on early Earth during periods of global glaciation (Vincent and Howard-Williams 2000, Hoffman 2016), but are they are now close to complete extinction as a result of climate warming.

Shifts in ice cover of Nunavut lakes are already apparent, and are likely to be much greater in the future. In a remote sensing study of 11 lakes in Nunavut over a 15 year period, from 1997 to 2011, all of the lakes showed an earlier onset of melting and ice-out; for Lake Hazen, the deepest lake in the High Arctic, the melt onset began two weeks earlier, and for Eleanor Lake on Cornwallis Island, it was more than 3 weeks earlier (Surdu et al. 2016). This extension of open water conditions has wide-ranging effects on lake ecology, including via increased exposure to direct wind induced mixing. This may entrain nutrients from deeper waters and stimulate production. For example, loss of ice in Lake A on the northern coast of Ellesmere Island resulted

in a shifting in phytoplankton species composition and an increase in picocyanobacteria (Veillette et al. 2011a). This loss of ice and mixing may also increase the residence time of contaminants in the lake by decreasing the under-ice through-flow of river inputs (Veillette et al. 2012).

An extreme example of ice loss is Ward Hunt Lake at latitude 83.1 °N. This is the most northern lake in Nunavut, and in the past was overlaid by perennial ice, up to 4.3 m in thickness. From 2008 onwards, however, this has undergone rapid thinning, with complete loss of ice cover in 2011 and 2012 (Paquette et al. 2015). This is reducing the amount of bedfast ice in winter, a trend that has been recently documented in the shallow lakes of northern Alaska (Surdu et al. 2014). This in turn increases the availability of liquid water habitats that persist under the ice during winter darkness, resulting in conditions that allow microbial production of greenhouse gases, especially methane (Figure 10, Mohit et al. 2017). An experimental study has shown that changes in light exposure in Ward Hunt Lake as a result of ice loss can result in major shifts in species composition of protists at the base of the food web (Charvet et al. 2014). A paleolimnological study of this lake showed that limnological change began more than 100 years ago (Antoniades et al. 2007), prior to this acceleration of changing ice conditions.

Loss of ice is also likely to increase the extent of lake warming, however there are no long term records for Nunavut to assess the magnitude of this effect. Global syntheses of lake temperature data show that on average lakes are warming at about the same rate as air temperature increases, but with large variations among lakes even from the same region due to differences in depth, wind exposure and transparency (O'Reilly et al. 2015). Duration of ice cover is another factor, and Nunavut lakes are likely to experience warming rates well above the global average, but with large variations among individual lakes. This change in water temperature is likely to have wide-ranging impacts on the physical, chemical and biological characteristics of northern lakes. Certain lakes such as Lake Hazen on Ellesmere Island may shift from one period of mixing per year (monomictic) to two periods each year (dimictic), which would likely stimulate primary production and



WARWICK VINCENT/CEN/ARCTICNET

FIGURE 10. Video screen shot of the microbial biofilms that grow on the bottom of Ward Hunt Lake and produce methane. These greenhouse gas-producing communities may become more common as the winter ice continues to thin over Arctic lakes and ponds in response to climate warming (Mohit et al. 2017).

perhaps all food web processes. Nunavut lakes contain diverse assemblages of microscopic life (e.g., Comeau et al. 2016, Chenard et al. 2015, Thaler et al. 2017, Mohit et al. 2017), and these communities are likely to change substantially in the future in response to shifts in the physical and chemical environment. Warming beyond the temperature thresholds of cold region biota may push certain species to extinction.

In several parts of the world, lake waters are becoming browner as a result of increases in runoff of coloured dissolved material, and in northern catchments this may be compounded by increased terrestrial plant growth (Wrona et al. 2016). Such changes can accelerate warming, as well as alter the lake biota at several trophic levels (Williamson et al. 2015). Conversely, increased soil weathering and nutrient run-off in a warmer climate may lead to the greening of Arctic lakes (Wrona et al. 2016), with potential ramifications for oxygen regimes, phytoplankton species shifts (including

to toxic species) and food supplies for higher trophic levels. Increases in lake productivity are thought to have an influence on Arctic char behaviour, with migration possibly ceasing once productivity in these lentic environments exceeds a certain as yet undefined threshold (Reist et al. 2006).

6.6 Summary and outlook

Warming air temperatures and increases in precipitation observed across the IRIS 2 region over the past 30 years or more, have had both direct and indirect impacts on water budgets, water quality and freshwater ecosystems. Although sparse and short term observations across the region substantially limit the degree of certainty, these changes are largely consistent, even if the magnitude is often still poorly constrained.

The combination of warmer air and water temperatures, enhanced precipitation, progressive active layer expansion

and disturbance of the permafrost will continue to alter the hydrological and ecological properties of surface waters in the Eastern Canadian Arctic. Observations support that evaporation and precipitation (both snow and rain) are likely to continue to increase, as well as flow duration. Runoff volumes are anticipated to increase, as it does not appear that the increases in evaporation due to warming will outweigh increases in precipitation inputs. Warming temperatures and increasing rainfall will also result in more frequent and extensive permafrost degradation including thermokarst features that have been shown to substantially alter sediment, nutrient and contaminant loads in streams and lakes. The impact of rainfall on hydrology and water quality is very difficult to predict, as this is strongly tied to the timing, frequency and intensity of rainfall, and also importantly to the extent and nature of permafrost degradation.

Observations from a number of studies across the region indicate that the cumulative effect of these changes (warming water temperatures, higher nutrients, longer runoff seasons) could result in priming freshwater ecosystems to a new equilibrium by pushing certain species to extinction, stimulating primary production and perhaps all food web processes. Wetland ecosystems, ponds and epishelf lakes appear to be particularly vulnerable to changing climate, and here the impacts can range from increases in the number of ponds due to thermokarst, to complete losses of water bodies and ecosystems, to notable changes in nutrient levels, contaminants, and ecosystem structure.

Although remote sensing methods have greatly improved our capacity to continue to monitor and observe some elements of the freshwater systems (e.g., water vapour, soil moisture, SWE), these data sets are nevertheless relatively recent and certain aspects of freshwater hydrology and quality require manual sample collection and measurements. Although much knowledge of freshwater systems has been gained from a number of multiyear research projects in the region, the temporal extent of these observations is short relative to the timeframe over which environmental change has been occurring, and the spatial extent is minimal given the size and diversity of terrain, geology and

climate in the region. There is therefore a critical need for the continuation, indeed expansion of monitoring efforts, in order to collect the observations necessary to facilitate the management of freshwater ecosystems and resources in the future.

It is however not possible to sustain a widespread monitoring effort with a handful of disparate research programs. Sustaining and expanding observation networks will necessitate the engagement and collaboration of northern communities and governments, so that research programs can help build the capacity for communities to sustain these efforts and facilitate community based assessment and management of freshwater resources and ecosystems.

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Chapter 7 Terrestrial Ecosystems: Diversity, Distribution and Responses to Climate

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Key messages

- The Eastern Canadian Arctic has the greatest diversity of terrestrial ecosystems in the Canadian Arctic, and includes all five sub zones of the Circumpolar Arctic Vegetation Map. While biodiversity of vascular plants declines with latitude, variations in topography and micro-climate result in shifts in snow deposition and soil moisture, which drives local variation in tundra vegetation.
- Inuit observations indicate vegetation is changing in the region, although the changes depend on the regional and local conditions. Near communities, people have seen new plant species and all communities report the season is getting longer, mainly because of earlier snow melt. People in the Qikiqtaaluk region have observed some increases in plant cover, including shrubs, however, the production of some berries (such as black berries) appears to be lower, and the quality has declined.
- Experimental and other observational studies have complemented the local observations and shown the increased temperatures result in earlier flowering, increased growth and seed production, and greater cover of shrubs across the region. However, the changes do not yet involve the migration of new species from southern areas.
- Tundra vegetation across all of Nunavut will generally continue to increase in abundance, which will affect the animals that depend directly on plants for food and habitat. However, there will be constraints on the increased plant cover due to local effects of permafrost degradation, and in the High Arctic, due to the lack of soil development.

Abstract

The Eastern Canadian Arctic has the greatest diversity of tundra ecosystems in Canada, and the largest area of High Arctic tundra in the world. These systems provide critical resources and services at local to global scales, and responses to the warming climate will have impacts at these scales. Inuit have observed important changes in the climate and in tundra systems including increased height and density of shrubs in southern areas, and greater plant cover in the High Arctic. Production of berry species has decreased in western inland areas, but increases have been observed near some Baffin Island communities. Experiments and long-term studies have shown the same vegetation responses, such that plants flower earlier, grow larger, and produce more and better seeds. Studies have also found that southern populations of tundra plant species do not perform as well as local populations, even in warmed conditions. Hence, greater plant cover will likely be driven by increases in growth and reproduction of the existing plants. However, the poorly developed soils, especially in the High Arctic, will restrict the rate of plant cover increase. The shift to greater shrub cover in Low Arctic areas will lower albedo and increase absorption of solar radiation, which will warm temperatures further in the region. Increased thaw depth in the carbon-rich permafrost soils will also lead to further warming as carbon dioxide and methane are emitted from the warming soils. Continued observations and studies of the ongoing changes in tundra ecosystems will be important to inform adaptation strategies and policies.

7.1 Introduction

The Eastern Canadian Arctic, which encompasses most of Nunavut, has the largest variety of tundra ecosystems in Canada, and Canada has the greatest variety of tundra systems in the world (Henry et al. 2012, Walker et al. 2005). These tundra systems span a huge latitudinal gradient (23°) from the border between Manitoba and Nunavut on the west coast of Hudson Bay to the north coast of Ellesmere Island. This region has the greatest area of High Arctic landscapes in the world, and these landscapes are predicted to change dramatically over the coming century (Pearson et al. 2013). The ecosystems are generally classified by their dominant vegetation and plant species, and vary strongly with moisture and exposure, from wetlands to polar desert landscapes. These systems provide crucial resources to wildlife and human populations across the territory, including forage for resident and migratory wildlife such as caribou, muskoxen, Arctic hare, lemmings, ptarmigan and migratory birds (Henry 1998, Massé et al. 2001). All of the terrestrial systems in this region are underlain and affected by continuous permafrost, and the soils contain enormous amounts of carbon: permafrost soils have been estimated to contain ca. 50% of the soil carbon on the planet (Tarnocai et al. 2009). As these tundra systems respond to the changing climate, there will be important

feedbacks that will affect the rate of change in the systems and the climate. This chapter reviews the diversity, distribution and importance of terrestrial ecosystems in the Eastern Canadian Arctic, the changes that have been observed over the past decades and in experiments, and the consequences of these changes for communities, the region and the globe.

7.2 Diversity of species and ecosystems

The current tundra vegetation communities in the region have developed since the end of the last continental glaciation (ca. 11,000 – 9,000 ybp), as all of Nunavut was covered by either the Laurentide or Inuitian ice sheets (Briner et al. 2016). Although there is some evidence for areas that remained ice-free and allowed species to survive (glacial refugia) in the High Arctic (Klütsch et al. 2017), the majority of species have migrated into the region since the ice retreated (Ritchie 1984). Currently, Nunavut has an estimated 630 species of vascular plants and at least as many species of lichens and bryophytes (e.g., mosses and liverworts), with the greatest diversity in southern areas, near the forest-tundra transition (Eamer et al. 2014). Vascular plant species diversity declines steadily with latitude, and is strongly related to mean July temperature (Rannie 1986). At the local or landscape scale, there are pockets of higher diversity in Arctic “oases” (Figure 1) where local climate and soils



FIGURE 1. Alexandra Fiord, a High Arctic polar oasis on Ellesmere Island.

support a larger diversity of species than expected for the region (Edlund and Alt 1989, Freedman et al. 1994). The post-glacial migration continues, and is likely affected by the current changes in climate (Alsos et al. 2007, Johnstone and Chapin 2003). Natural barriers, such as the channels between the Arctic islands and large areas of unsuitable habitat, as well as the cool short growing seasons and poor soil development have restricted the diversity of species in Arctic tundra systems. However, the warming climate will likely increase the reproductive output and success of the existing species in the Arctic (Klady et al. 2011), and increase the establishment and growth of the species currently there and species and populations that are expected to migrate to northern areas (Alsos et al. 2007).

Vegetation types in the Eastern Canadian Arctic span the diversity of complexes recognized in the Circumpolar Arctic Vegetation Map (CAVM) (Gould et al. 2003, Walker

et al. 2005), as shown in Figure 2. All of the subzones in the CAVM are represented in the region, ranging from low and tall shrub tundra along the western Hudson Bay coast in subzone E to cryptogam barrens along the northernmost shores of the High Arctic islands (subzone A). The subzones reflect the latitudinal decline in plant diversity, size, cover, biomass and productivity (Figure 3), although regional influences of the mountains in the eastern High Arctic, and the oceanic influences of Baffin Bay are seen in the northward extension of subzones B and C (Figure 2) (Gould et al. 2003, Walker et al. 2005). Tall shrubs and scattered small trees can be found in sheltered well-drained areas in the southern most areas (e.g., near Arviat; Boulanger-Lapointe (2017). Continuous plant cover is generally found in all areas of the Low Arctic region (subzones D and E), except for rock outcrops, tops of eskers, and similar upland areas that have poor soil development and are usually blown free of snow during the winter. In High Arctic areas (subzones

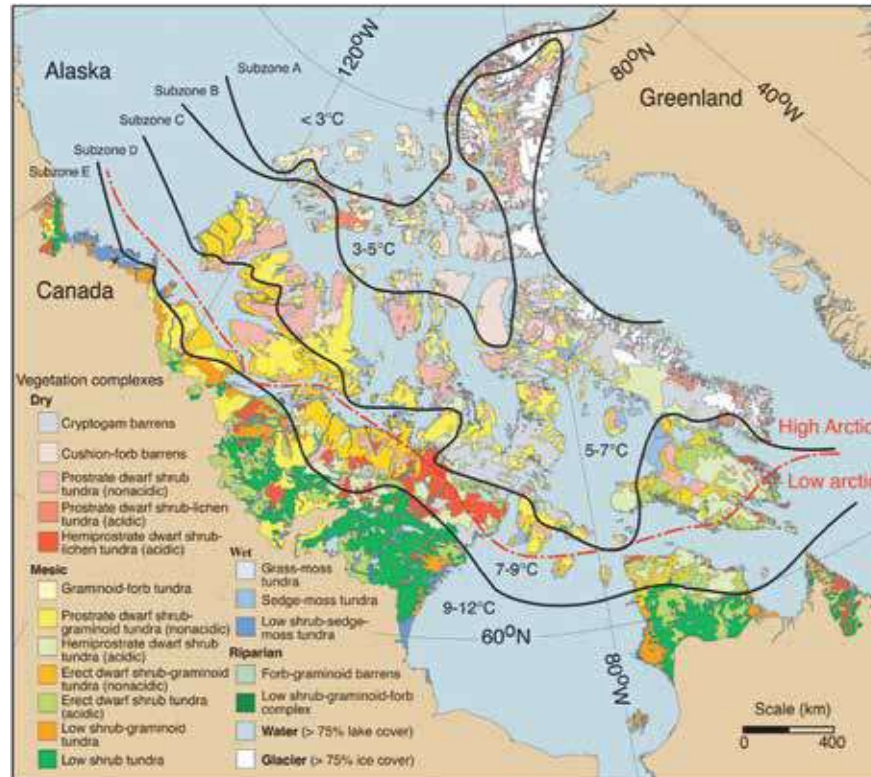


FIGURE 2. Vegetation complexes in the Canadian Arctic and the Circumpolar Arctic Vegetation Map (CAVM) subzones. The division between High and Low Arctic follows Bliss and Matveyva (1992). From Gould et al. (2003).

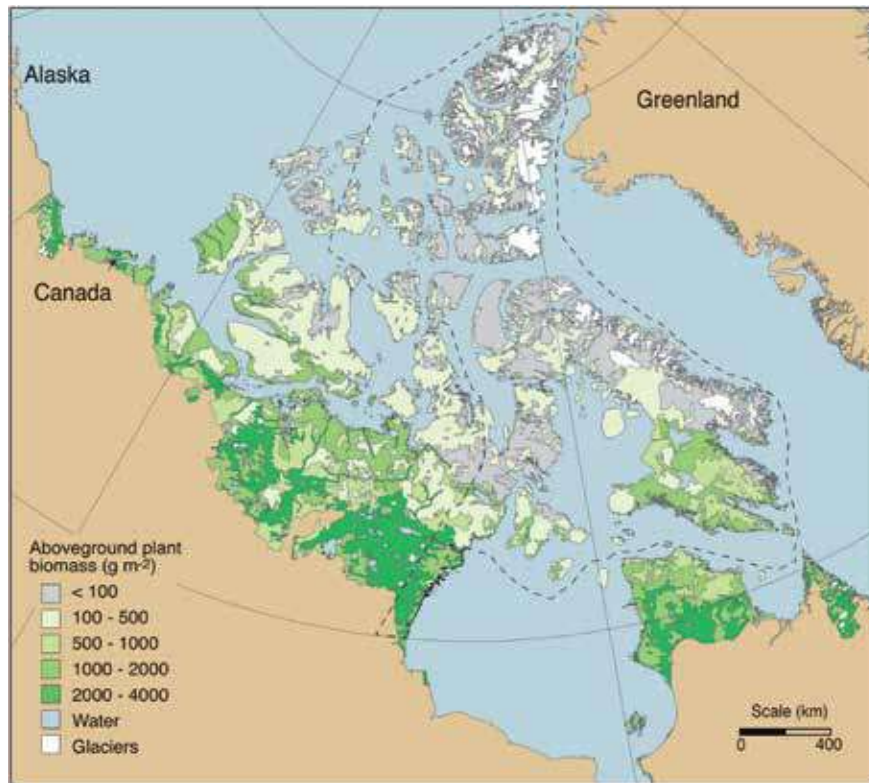


FIGURE 3. Distribution of biomass in the Canadian Arctic tundra; the dashed line represents the IRIS 2 region. The pattern follows the CAVM gradient of subzones shown in Figure 2. From Gould et al. (2003).

A, B and C), plant cover diminishes and continuous cover becomes restricted to protected lowland areas and along streams, ponds and lakes (Bliss and Matveyeva 1992, Freedman et al. 1994, Gould et al. 2003).

The lithology of the underlying rocks also strongly influences the species diversity and distribution across the Arctic (Bliss and Matveyeva 1992, Edlund and Alt 1989, Walker et al. 2005). This is especially notable in the High Arctic, where soils are very weakly developed and the characteristics of the poorly weathered underlying rocks strongly affect the pH, nutrient availability and texture of the soils. For example, in polar desert landscapes, the species composition and abundance is different on carbonate soils than on granitic soils (Figure 4) (Bliss et al. 1994).

At the local scale, ecosystem types vary along gradients of soil moisture and microclimate, generally induced by changes in topography (Figure 5). Protected areas on leeward sides of hills and eskers have deeper snow cover in winter which protect plants from freezing and desiccation, and leads to greater water supply and survivorship (Figure 6) (Svoboda and Henry 1987, Walker 2000). In some areas, late lying snow beds have a unique set of plant species, that rely on the recurrence of deep snow (Bjork and Molau 2007). In addition, snow beds are important winter nesting habitat for lemming species and caribou that use late lying snow beds for cooling off in summer and to escape from biting insects (Reid et al. 2012).



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FIGURE 4. The influence of substrate lithology on High Arctic tundra vegetation is clearly seen in this upland landscape at Alexandra Fiord, Ellesmere Island. The light area on the right is due to dolomite rocks, which has fewer plants and plant species than the darker area on the left, which is underlain by granitic rocks.

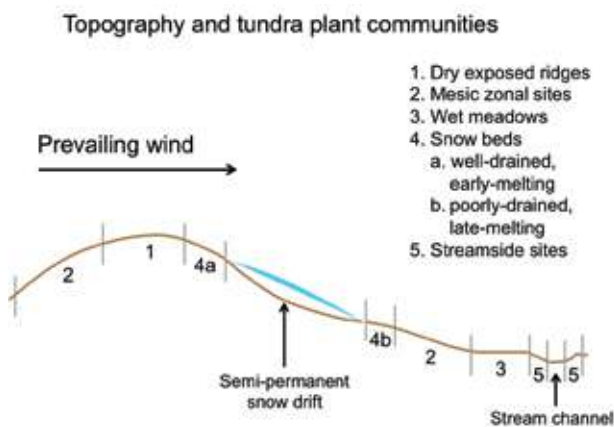
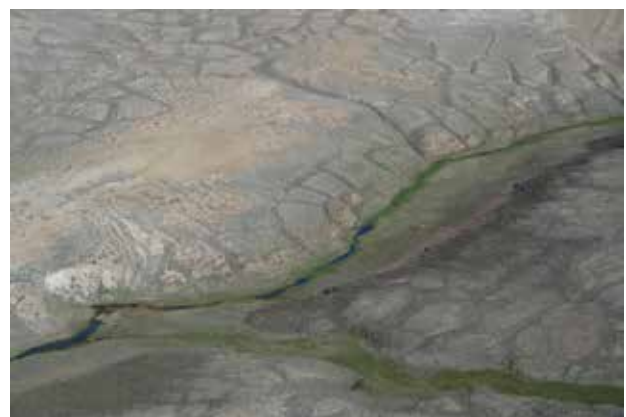


FIGURE 5. An idealized local topographic gradient for the Arctic showing five habitats: dry, mesic, wetland, snowbed, and streamside vegetation. The microtopography plays an important role in determining soil moisture status, and hence species distributions. From Walker (2000). © 2000 Blackwell Science Ltd.



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FIGURE 6. Influence of slight changes in topography on soil moisture in High Arctic tundra affects the diversity and abundance of plants. The low areas with water courses are most productive, and slightly higher areas are drier and are generally snow free during the winter, and have very few if any plants.

7.3 Production and importance of berry shrubs

While all vegetation provides direct and indirect services to animals and humans, berry producing shrub species are particularly important as a source of food and are culturally important to Inuit (Boulanger-Lapointe 2017, Desrosiers 2017, see also Box A). Across Nunavut, there are five major species used by Nunavummiut: blueberry (*Vaccinium uliginosum*), cranberry (*Vaccinium vitis-idaea*), blackberry or crowberry (*Empetrum nigrum*), cloudberry or bake apple (*Rubus chamaemorus*) and bearberry (*Arctous uva-ursi*) (Figure 7) (Boulanger-Lapointe 2017, Desrosiers 2017, Gérin-Lajoie et al. 2016). A recent study of environmental influences on production of these berry species across the Canadian Arctic found that the greatest diversity of berry shrubs occurred in Low Arctic areas, and berry productivity was highest in CAVM subzone D (Figure 8) (Boulanger-Lapointe 2017). Total berry production near the three communities in subzone D (Iqaluit and Pangnirtung in Nunavut, and Kangiqsujuaq in Nunavik) was 68% greater than those in High Arctic sites (subzone C) and 60% greater than communities in subzone E or in the forest-tundra ecotone (Boulanger-Lapointe 2017). The lack of shade by tall shrubs and tree species and relatively warm summer temperatures likely contributes to the greater productivity



FIGURE 7. Five common berry species found and harvested in Nunavut: (a) bearberry (picture taken in the autumn), (b) crowberry, (c) blueberry, (d) cranberry and (e) cloudberry. From Boulanger-Lapointe (2017).

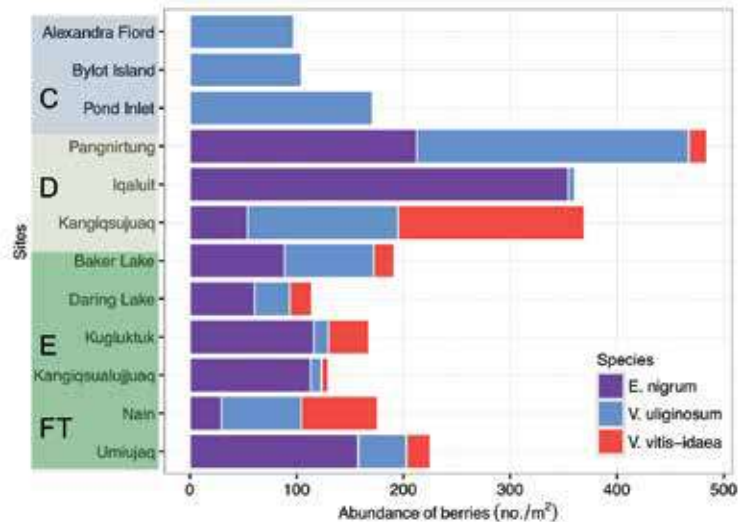


FIGURE 8. Berry abundance at sites across the Canadian Arctic arranged by subzone of the CAVM: subzone C (blue shading); subzone D (kaki shading); subzone E and FT (forest tundra) (green shading). Sites in subzone D have the greatest total abundance, although the relative abundances are different for the three species. Modified from Boulanger-Lapointe (2017).

in subzone D. Productivity of *Empetrum nigrum* was most strongly related to the mean summer (July–August) temperature in the current year, while *Vaccinium uliginosum* in the Low Arctic was most strongly related mean summer (July–August) temperature of the previous year (Boulanger-Lapointe 2017).

In a case study near Arviat, Nunavut the net annual production of berries in a 45.5 km² region surrounding the community was determined to be 400 g m⁻², with *E. nigrum* comprising the majority (90%) of the production. Collection and analysis of animal droppings for berry seeds indicated very low consumption of the total production: approximately 2% of the production was consumed by resident and migratory snow geese (Boulanger-Lapointe 2017). This is the only study to provide an estimate of the total berry production and the amount eaten by animals, and although restricted to one community in subzone E, indicates the relatively large availability of berries for human and animal use throughout the Arctic.

BOX A. Inuit observations of ecosystem change in the region

Observations by local knowledge holders in communities across Inuit Nunangat have been critical for understanding the rate and types of changes in local and regional environments. As part of a project in the International Polar Year (IPY) (Henry et al. 2012) and continued in ArcticNet, Elders and other community members were interviewed and asked for their observations and explanations of changes in the environment in response to the changes in climate (Figure A1) (Gérin-Lajoie et al. 2016). In particular, people were asked about changes in the production and quality of berries and in vegetation in their regions. The effect of the changing climate on tundra vegetation and berry production has been variable across Inuit Nunangat. Elders in Baker Lake (Qamani'tuaq) have noted less precipitation along with warming temperatures, and this has resulted in stunted shrub growth and smaller berries (Gérin-Lajoie et al. 2016). At Pond Inlet (Mittimatalik) Elders have noticed increased numbers of blueberries and blackberries, along with generally greater vegetation cover. However, they note that the berries have increased as the number of caribou has decreased and that part of the change is because the caribou are no longer trampling the plants. They have also noted new species, or rare species that have become more abundant, including species of willow. Similar changes have been noticed by Elders in Pangnirtung, where blackberries appear to be increasing in cover and growing in new places. They also have noticed a new species of dandelion and increases in grasses near the community (Gérin-Lajoie et al. 2016). Scientific observations across the Arctic match those in communities, with increasing cover of shrubs and other species, especially in areas with earlier snow melt and increased precipitation (Elmendorf et al. 2012a).

In nine communities and three research stations across the Canadian Arctic (Figure A1), plots were established to follow the production of berries of five berry shrub species (Figure 7). In some communities, such



FIGURE A1. Map of communities where Elders and community members were interviewed and where plots were established to follow berry production.

as Kugluktuk, the plots were established and are monitored by students in high school science classes (Desrosiers 2017). The students also used the opportunity to learn about berry ecology, stories and uses from their Elders in their Inuinnaqtun classes (Kugluktuk Elders and youth and Desrosiers 2016). Community members were also involved in Pond Inlet and Pangnirtung. Plots were also established near Iqaluit by students in the Environment and Technology Program at Nunavut Arctic College (NAC), where they have been monitored since 2009 (Figure A2). The record of annual berry production maintained by the students at NAC is one of the longest in the Canadian Arctic, and the first to show the wide variations from year to year, especially in production of crowsberry (blackberry).

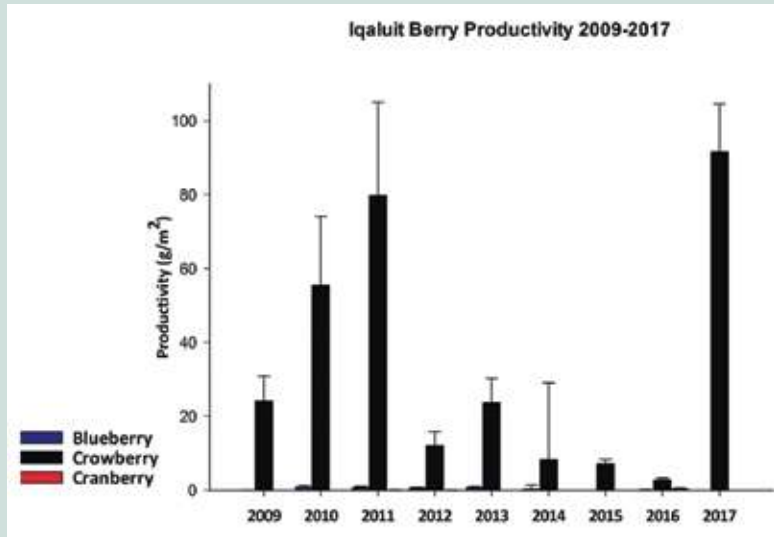


FIGURE A2. Iqaluit berry production.

One of the major goals of these community-based projects was to engage students in both science and local knowledge in an effort to show how both are equally important to understand the changes in their environments, and hopefully inspire them to become the next generation of northern scientists.

7.4 Responses to herbivory

Despite the relatively low net primary production of Arctic tundra systems, they provide forage for large numbers of resident and migratory herbivores. The greater net production in low Arctic areas (Figure 3) supports larger populations of large herbivores, including the barren ground caribou herds, muskoxen and migratory geese populations, relative to the High Arctic. Wetland areas are the most productive tundra plant communities and are important forage habitat for large herbivores (Henry 1998). The wet sedge tundra used by Greater snow geese on Bylot Island was found to support $46 \pm 10\%$ of the potential population based on the availability and productivity of the forage plants (Massé et al. 2001). Grazing by muskoxen (Figure 9) in High Arctic wet sedge tundra alters the species composition and increases available nutrients in the soil (Henry 1998). The growth of dominant species in wet sedge tundra has been found to withstand

moderate grazing by muskox and snow geese by increasing the growth and production of leaves and new shoots and the new leaves tend to have greater nutrient concentrations (Elliott and Henry 2011, Gauthier et al. 1995, Tolvanen and Henry 2000). Tundra systems have limited nutrient availability due to the low soil temperatures and short growing seasons, and the availability is strongly affected by soil



FIGURE 9. Muskoxen (*Ovibos moschatus*) on the Fosheim Peninsula, Ellesmere Island.

moisture conditions. Herbivores effectively increase the rate of decomposition by consuming the vegetation and providing nutrients directly through deposit of faeces and urine, and indirectly as the faeces are more easily decomposed than most plant litter. For example, concentrations of ammonium (NH_4) and nitrate (NO_3) were much higher in the soils of wet sedge tundra that were heavily grazed by muskoxen than in a site without muskoxen (Henry 1998), and the availability of nitrate increased in plots that had been experimentally clipped up to two times in a season (Elliott and Henry 2011). Grazing can also affect the response of tundra systems to the predicted changes in climate by reducing the encroachment of shrub species (Post and Pedersen 2008).

7.5 Ecosystem change and consequences

Recent climate warming has been most intense in the Arctic, where temperatures have increased by as much as 1 °C per decade in the past 30 years (IPCC 2013). The amplification

of warming in the Arctic is largely due to the strong snow/ice-albedo feedback (IPCC 2013, Serreze et al. 2009), with earlier snow and ice melt and later freeze-up. This is most evident in the loss of multi-year sea ice and the decreasing minimum extent in September (Wang and Overland 2012). On land, there is evidence that the area of Tundra Climate, a classification based on the cold temperature and low precipitation conditions in the Arctic, has decreased by about 20% over the past 25+ years (Figure 10) (Wang and Overland 2004). The steady decline in the area of Tundra Climate is matched by reductions in the areas with a tundra signature in primary productivity as measured by satellite-based Normalized Difference Vegetation Index (NDVI) and the strongest changes have occurred in northwest Canada in the past 25+ years, with notable changes in the Eastern Canadian Arctic (Figure 11) (Bhatt et al. 2014, Wang and Overland 2004).

The terrestrial systems of the Arctic are still recovering from the last continental glaciation, as plants and other

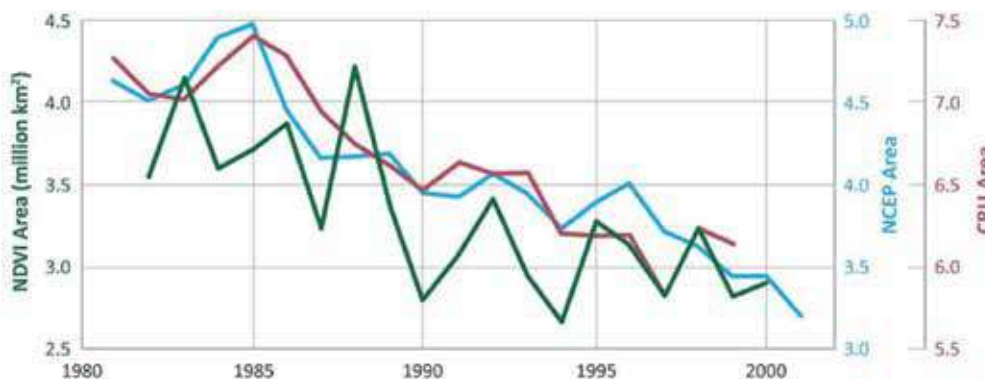


FIGURE 10. Changes in area of the Tundra Climatic zone around the circumpolar Arctic since 1982, based on NDVI (Normalized Difference Vegetation Index) and the Köppen Climate Classification System. “NCEP” and “CRU” are two datasets of monthly surface air temperatures. “NDVI” is a calculation based on light reflected by vegetation, as detected by satellite. Modified from Wang and Overland (2004). © 2004 Kluwer Academic Publishers. With permission of Springer, Wang, M. and Overland, J.E.

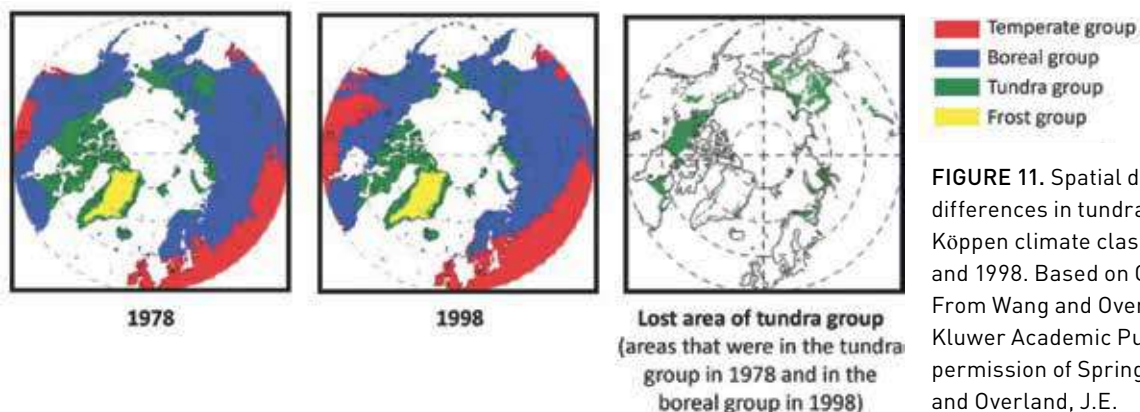


FIGURE 11. Spatial distribution of differences in tundra climate using the Köppen climate classifications in 1978 and 1998. Based on CRU climate dataset. From Wang and Overland (). © 2004 Kluwer Academic Publishers. With permission of Springer, Wang, M. and Overland, J.E.



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FIGURE 12. Passive warming experiments using open top chambers (OTCs) at Alexandra Fiord, Ellesmere Island. The OTCs allow a warm layer of air to develop over the tundra surface and increase the temperature 1-3 °C (Bjorkman et al. 2015). The OTCs are used at sites involved in the International Tundra Experiment (ITEX) (Walker et al. 2006, Elmendorf et al. 2012b).

organisms continue to disperse into the areas deglaciated between 11 000 and 7000 years ago (Alsos et al. 2007, Briner et al. 2016, Svoboda and Henry 1987). However, the rapidly changing climate over the past 50 years has disrupted and changed this progression, through changes in the physical environment and responses of organisms. With warming, there has been a strong trend to earlier phenology (timing of leaf growth and flowering) and greater growth and reproductive output of plant species. The sensitivity of plant phenology to warming is greatest in the northern Arctic areas, such as Nunavut, and flowering has

become earlier in many tundra species (Bjorkman et al. 2015, Prevéy et al. 2017). This common response had been seen in early warming experiments (Figure 12), where most species showed advanced flowering and seed set (Figure 13) (Bjorkman et al. 2015). However, the primary driver of plant phenology in Arctic plants is the date of snow melt, and an increase in snow fall leading to little or no change in snow melt date can counter the effect of warming on phenology, as was shown for plants at a High Arctic site on Ellesmere Island (Figure 14) (Bjorkman et al. 2015).

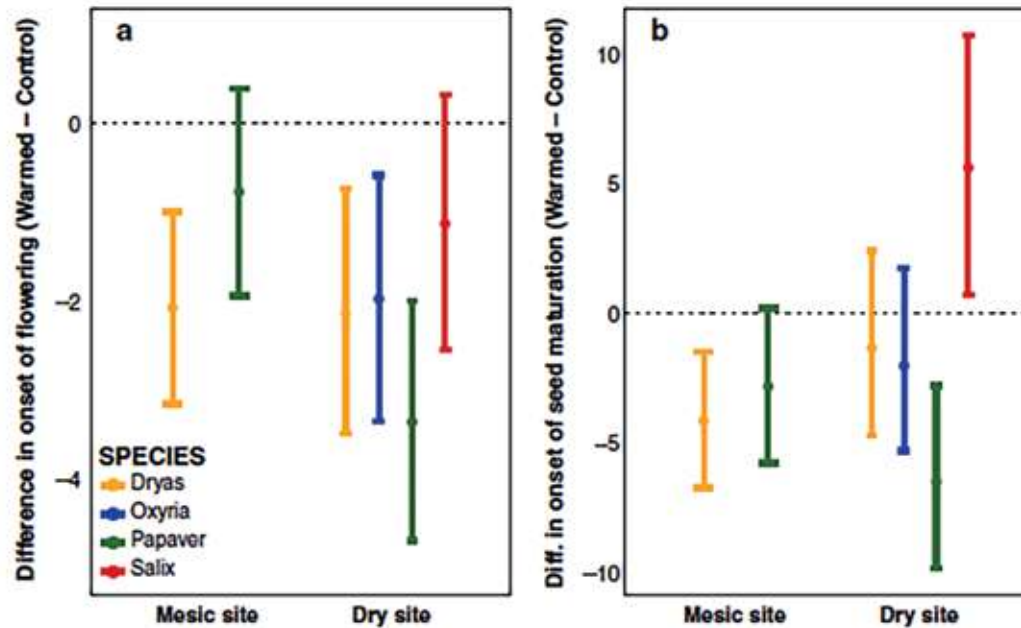


FIGURE 13. Effect of 18 years of experimental warming on phenology of four tundra plant species. The analyses show modeled difference, in number of days, in (a) flowering time and (b) seed maturation/dispersal between the warmed and control treatment for each species across all years. Negative values (below the zero line) indicate earlier flowering in the warmed treatment. Point estimates and 95% credible intervals are derived from a Bayesian hierarchical model including random effects for plot and year. From Bjorkman et al. (2015).

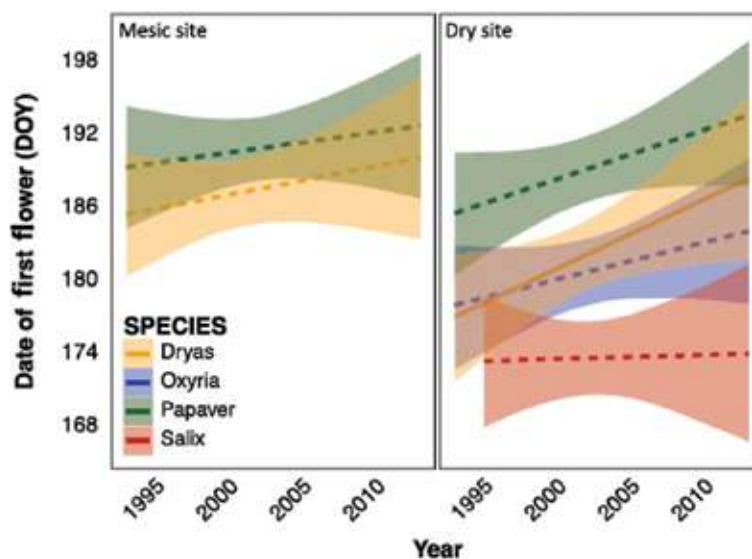


FIGURE 14. Change in predicted date of flowering time (95% credible intervals) in the control plots over the duration of the study (18 y). A dotted line indicates that the 95% CI of the slope parameter overlaps zero, and there is a weak relationship. Flowering in *Salix* includes both male and female plants but seed maturation is for female plants only. Modeled results are from a Bayesian hierarchical model with random effects for plot and year. Slopes were allowed to vary by species and site as well as the interaction between the two. DOY = day of the year. From Bjorkman et al. (2015).

The warming climate, earlier flowering and longer growing seasons will likely increase seed production in Arctic plants, which has been measured in warming experiments in the High Arctic (Klady et al. 2011). The ameliorated conditions will also allow greater number of seeds to establish and for seedlings to survive, which in turn will affect the species composition and abundance in Arctic tundra. Northern migration of southern populations could also be facilitated by the changing climate, and while dispersal barriers may be relatively low (Alsos et al. 2007), the lack of adaptation to local soil and other conditions may limit the ability of these populations from warmer areas to establish in more northern Arctic sites (Bjorkman et al. 2017). Hence, the ability of the current populations of species in northern Arctic regions, such as High Arctic Nunavut, to adapt to the changing climatic regime will likely be more important in maintaining and expanding the plant cover in these areas than migration of southern populations.

Plant growth and net primary production has increased across the Arctic, and has been noted at both circumpolar (Bhatt et al. 2014) and local scales (Gauthier et al. 2009, Hill and Henry 2011, Hudson and Henry 2009). At a long-term research site on Ellesmere Island, substantial increases in above and below ground biomass has been measured in wet sedge tundra (Figure 15) (Hill and Henry 2011), and there has been a steady increase in the biomass of shrubs and moss in a shrub heath community over a decade (Figure 16) (Hudson and Henry 2009). Similar increases in biomass have been measured at Bylot Island over a nearly 20 year period, providing more forage for the migratory snow geese and other herbivores in the region (Gauthier et al. 2009).

One of the major changes noted across the Arctic, including Nunavut, has been an increase in the abundance and height of shrub species (Bhatt et al. 2014, Elmendorf et al. 2012, Myers-Smith et al. 2011, Sturm et al. 2001). These changes have been reported for many years by both northerners and scientists (Gérin-Lajoie et al. 2016, Henry et al. 2012). The changes in shrub cover were predicted by warming experiments, which showed shrubs, grasses and sedges responded strongly to the higher temperatures (Elmendorf et al. 2012,

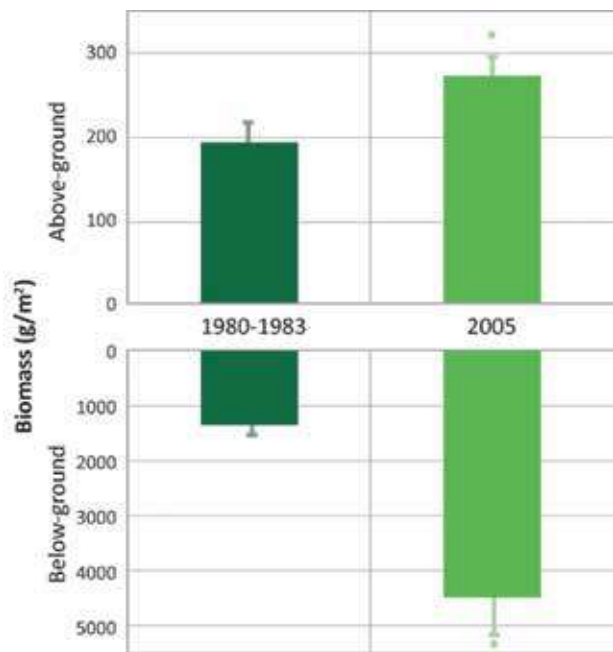


FIGURE 15. Change in above and below-ground biomass in High Arctic wet sedge tundra at Alexandra Fiord, Ellesmere Island between the early 1980s and 2005. Biomass in 2005 was significantly greater than in 1980-83 ($p < 0.05$). From Hill and Henry (2011).

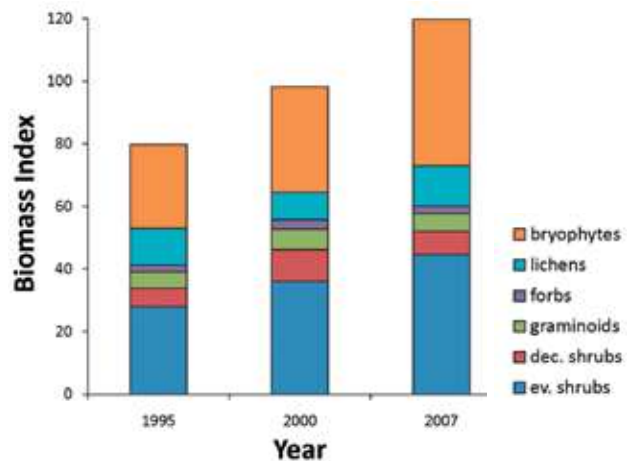


FIGURE 16. Changes in biomass index in a High Arctic dwarf shrub heath community. The biomass index is based on the total number of interceptions along 100 points in a 1 m² quadrat, using a standard point-frame technique. From Hudson and Henry (2009).

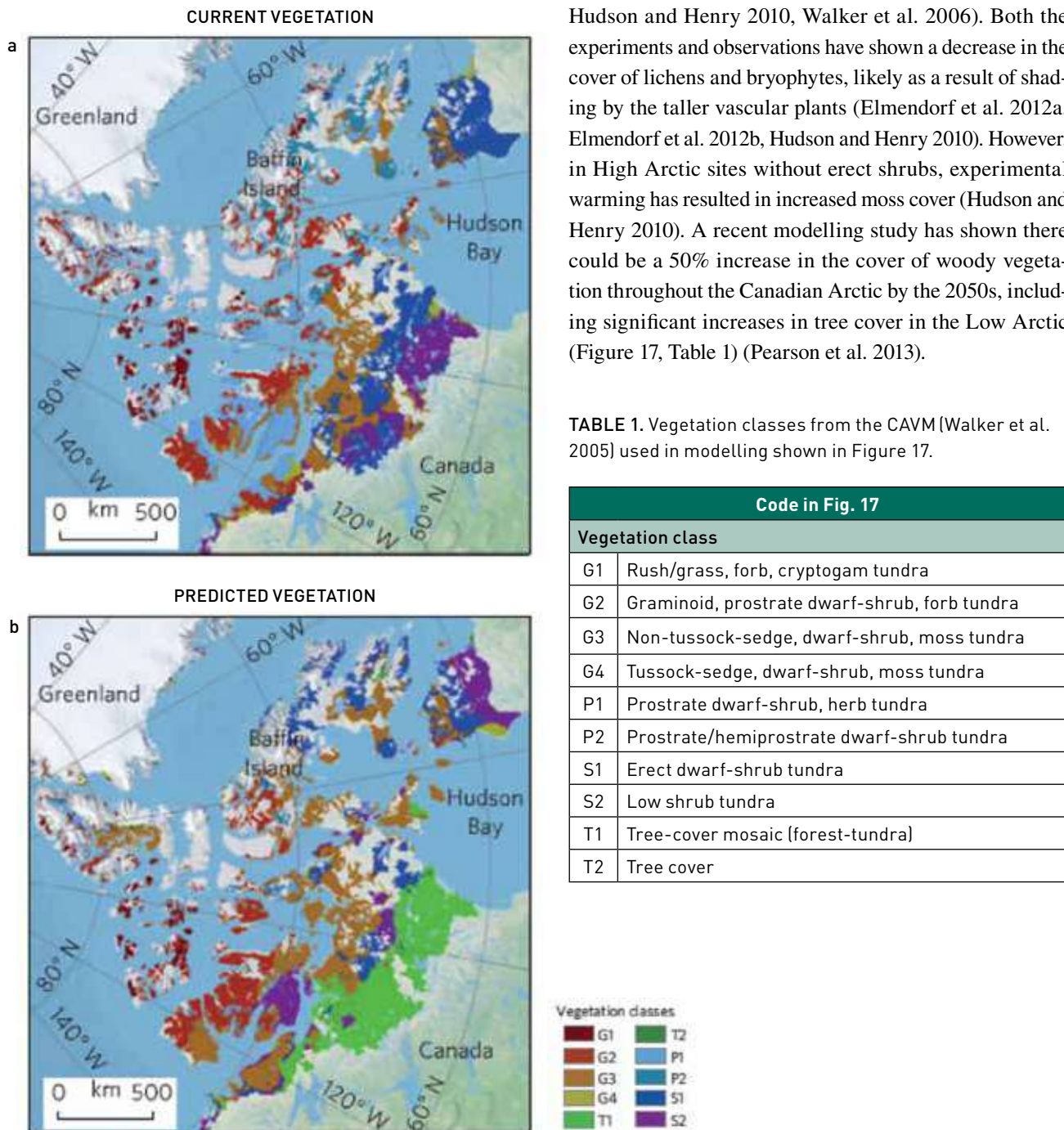


FIGURE 17. Observed (a) and predicted (b) distributions in the 2050s of vegetation classes for Arctic Canada. The vegetation classes are based on the CAVM (Walker et al. 2005). The predicted distributions for the 2050s are based on an equilibrium dispersal scenario with unrestricted colonization of trees, Random Forest model, HadCM3 AOGCM, and A2a emissions scenario. Projection: Lambert azimuthal equal area. From Pearson et al. (2013). Adapted by permission from Macmillan Publishers Ltd.

Hudson and Henry 2010, Walker et al. 2006). Both the experiments and observations have shown a decrease in the cover of lichens and bryophytes, likely as a result of shading by the taller vascular plants (Elmendorf et al. 2012a, Elmendorf et al. 2012b, Hudson and Henry 2010). However, in High Arctic sites without erect shrubs, experimental warming has resulted in increased moss cover (Hudson and Henry 2010). A recent modelling study has shown there could be a 50% increase in the cover of woody vegetation throughout the Canadian Arctic by the 2050s, including significant increases in tree cover in the Low Arctic (Figure 17, Table 1) (Pearson et al. 2013).

TABLE 1. Vegetation classes from the CAVM (Walker et al. 2005) used in modelling shown in Figure 17.

Code in Fig. 17	
Vegetation class	
G1	Rush/grass, forb, cryptogam tundra
G2	Graminoid, prostrate dwarf-shrub, forb tundra
G3	Non-tussock-sedge, dwarf-shrub, moss tundra
G4	Tussock-sedge, dwarf-shrub, moss tundra
P1	Prostrate dwarf-shrub, herb tundra
P2	Prostrate/hemiprostrate dwarf-shrub tundra
S1	Erect dwarf-shrub tundra
S2	Low shrub tundra
T1	Tree-cover mosaic (forest-tundra)
T2	Tree cover

The impacts and consequences of the changes in vegetation are and will be felt at the local, regional and global scales. In interviews with Elders in communities across Inuit Nunangat, a consistent observation was the greater cover and height of shrubs, especially in Low Arctic communities (Gérin-Lajoie et al. 2016, see also Box A). Hunters and others noted that it was becoming more difficult to travel across the land because of the greater density of shrubs in some areas. Another observation was that the taller shrubs caused a decline in berry production, although this was not found in all areas (Boulanger-Lapointe 2017, Gérin-Lajoie et al. 2016). While the warming climate has resulted in greater plant growth overall, Elders noted that the production and/or quality of berries has generally declined in their regions (Boulanger-Lapointe 2017, Gérin-Lajoie et al. 2016). The shift to a greater shrub cover will also affect wildlife, including the migration of caribou and habitat for ground nesting bird species, and may be assisting the observed increases in moose populations in Low Arctic regions of Canada (Tape et al. 2016). The increased density and cover of shrubs and trees is likely to lead to a loss of lichens in winter habitat for caribou (Cornelissen et al. 2001, Walker et al. 2006), as most of the ground lichen species, including species of *Cladina* and *Cladonia*, are shade intolerant. The loss of lichen biomass could be a concern for caribou herds if it is widespread across the current forest-tundra region. However, it is also likely that the animals will shift their migration to remain in more northern areas with abundant lichen biomass as the vegetation changes (Ferguson et al. 2001). Shrubs are an important part of the summer diet of caribou (Larter and Nagy 2004), and increased abundance of this forage may be beneficial to caribou populations. Grazing and browsing on shrubs by large herbivores may act to slow the expansion of shrubs in the Arctic, but the effect will depend on the density of the herbivores and on the palatability of the particular shrub species (Christie et al. 2015). The current decline in many caribou herds across the Arctic may actually facilitate the expansion of shrub species.

One of the major regional impacts, with global implications, will be the decrease in albedo (the reflectivity of the ground surface) with the shift from herbaceous to shrub

tundra (Pearson et al. 2013, Chapin et al. 2005). The greater density and height of shrubs will increase the amount of absorbed solar radiation, and although shrub canopy will shade the ground, the net effect will be to increase the heat transferred to the atmosphere. One estimate showed that a change from herbaceous tundra to shrub tundra could result in a warming effect similar to that of doubling the concentration of CO₂ in the atmosphere (Chapin et al. 2005), and result in further regional warming of 0.6-1.8 °C by 2100 (Bonfils et al. 2012). The shrub cover will also increase winter soil temperatures by trapping snow and increasing the snow depth beneath the shrubs. This will result in greater microbial survival and activity in the warmer winter soil which should lead to increased depth of thaw and greater nutrient and moisture availability for the shrubs, and further increases in shrub height and cover (Myers-Smith et al. 2011, Sturm et al. 2005).

Much of the vegetation change is expected to occur in the Low Arctic, especially near the Forest-Tundra ecotone, where there are responsive erect shrub species (including species of alder, birch and willow) and the sites are warm relative to the High Arctic (Elmendorf et al. 2012, Myers-Smith et al. 2015, Pearson et al. 2013). However, increases in vegetation cover is also expected in the High Arctic, where there are large areas of polar desert with <25% plant cover (Bliss and Matveyeva 1992). The cover of Polar Barrens (areas with <50% plant cover) has been estimated to be 56% of the Canadian Arctic, with the majority of these areas in the High Arctic (Eamer et al. 2014, Ahern et al. 2011). Vegetation development in these bare areas will be facilitated by the greater growth and reproduction of species in polar oases that have greater plant cover and diversity (Klady et al. 2011), and by the changes in temperature and precipitation that could lead to increased establishment of plants. Studies of vegetation development on recently deglaciated terrain on granitic substrates on Ellesmere Island (Figure 18) show the vegetation development can be relatively rapid (Figure 19), with moss species establishing within the first year of release from the ice, and herbaceous vascular plants established within the first 3-5 years (Breen and Lévesque 2006, Jones and Henry 2003). The establishment of shrub species takes 20 to 30 years

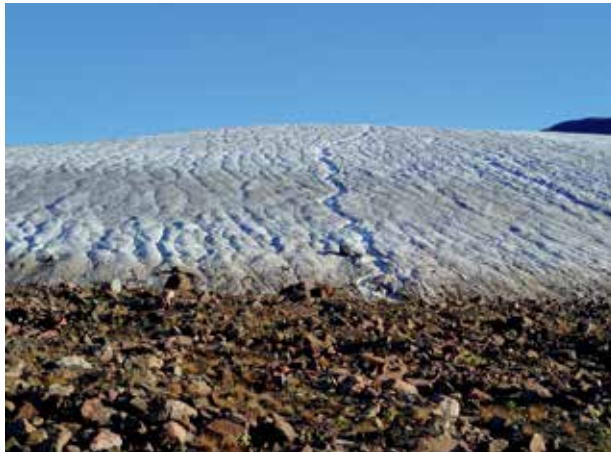


FIGURE 18. Vegetation developing on land recently released as the glacier melts and retreats.

after deglaciation, and represents an end of the sequence of species (Svoboda and Henry 1987). However, establishment of a tundra plant community similar to those in nearby areas that have developed for >6000 years since the loss of the Inuitian Ice Sheet, will likely take at least a century, as it is affected by the slow pace of soil development, especially in High Arctic polar deserts (Svoboda and Henry 1987).

The warming climate will also affect the carbon balance of tundra ecosystems: the amount of carbon that is captured by vegetation and ultimately enters the soil, and the amount lost to the atmosphere through respiration of plants and soil organisms, and lost to streams, lakes and the ocean. Increased growth and cover of vegetation will be the result of greater uptake of CO_2 in net photosynthesis. The increase in photosynthetic activity is seen in the higher values of NDVI and other indexes derived from reflected light sensed by satellite platforms (Bhatt et al. 2014). Warming experiments in High Arctic tundra have shown that changes in net ecosystem productivity (the net amount of CO_2 that flows between the land surface and the atmosphere) will depend on soil moisture. Dry tundra systems showed increases in the net flow of CO_2 into the tundra because of greater photosynthesis, while wet tundra showed a slight decrease because respiration rates increased more than photosynthesis (Welker et al. 2004).

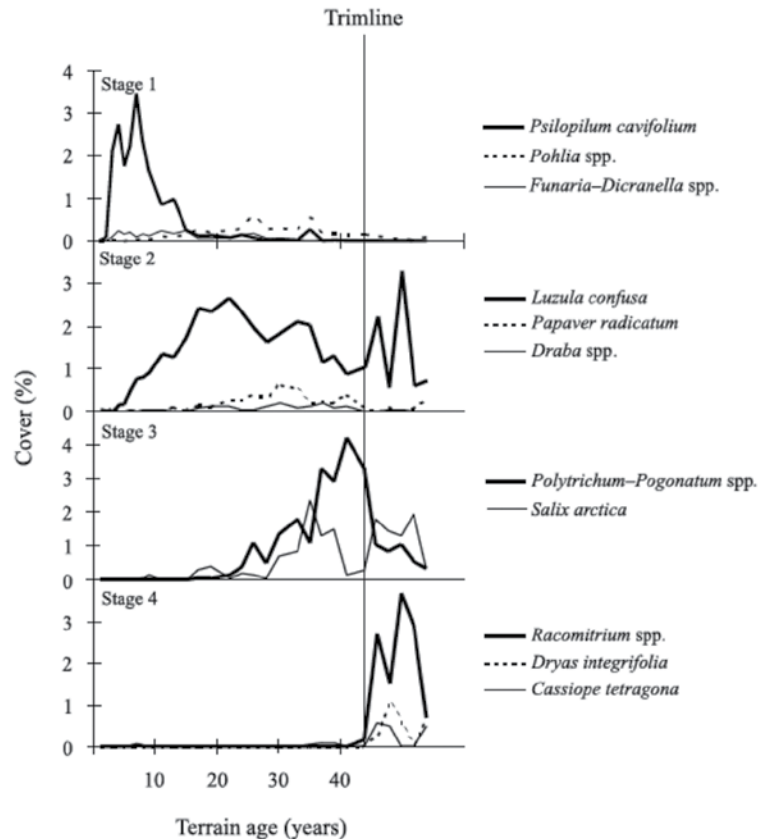


FIGURE 19. Vegetation development on a glacial foreland on Ellesmere Island over 40+ years. Four stages were recognized: Stage 1 is dominated by moss species, and occurs nearest to the glacier within the first two years of deglaciation; Stage 2 peaks between 10 and 20 years after deglaciation and is characterized by herbaceous species of forbs (*Papaver*, *Draba*) and graminoids (*Luzula*); Stage 3 is characterized by the first shrub species (*Salix arctica*) that occurs 30-40 years after deglaciation; and Stage 4 is the tundra community beyond the limit of the last glacial advance (indicated as the Triline), believed to have been during the Little Ice Age (ca. 1450-1850). From Jones and Henry (2003).

Hence, changes in soil moisture in response to climate warming will be important as it will affect the balance of CO_2 fluxes in the tundra (Oberbauer et al. 2007). Elders and scientists have already reported that areas are drier and some creeks and ponds are drying out each summer.

Permafrost soils contain about 50% of the global soil carbon (Tarnocai et al. 2009) and they could contribute significant

amounts of carbon to the atmosphere in the coming decades, exacerbating global warming. The warming climate will deepen the thaw in summer and stimulate microbial activity that will result in the increase in emissions of the greenhouse gases CO_2 , CH_4 and N_2O . Forecasting the effect of the permafrost-carbon feedback to climate warming is complex, as there will be variable responses due to the presence or absence of ice in the permafrost soils and whether the thawing leads to development of ponds as the ice in the permafrost melts and the land subsides (thermokarst) or drier tundra (Figure 20) (Schuur et al. 2015). In addition, the changes in moisture with thawing will affect the vegetation development and the carbon inputs through litter to the soils: increased thaw leading to drier soils may favour increased density of shrubs, while thermokarst in ice-rich permafrost would increase wetland vegetation. Although there would be greater input of litter

with increased deciduous shrub density, it has been found that carbon and nitrogen storage is lower in soils from shrub tundra than graminoid tundra in the same area, indicating that a shift to shrub tundra may not lead to greater inputs of soil carbon (Petrenko et al. 2016). In addition, the carbon balance of tundra systems will be affected by permafrost disturbance, such as active-layer detachments and retrogressive thaw slumps (Figure 21). These disturbances occur in ice-rich permafrost areas, and can change the tundra system from a small sink for carbon to a source of CO_2 and CH_4 to the atmosphere (Cassidy et al. 2016). Carbon also flows from the disturbances into water courses, where it can be used by aquatic microbes and lost to lake or ocean sediments (Lamoureux et al. 2009). These disturbances are increasing in frequency and magnitude (Lantz and Kokelj 2008, Lewkowicz and Harris 2005) and will be important regionally in the permafrost-carbon feedback.



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FIGURE 20. Developing thermokarst ponds in ice-rich permafrost, Fosheim Peninsula, Ellesmere Island.



FIGURE 21. A retrogressive thaw slump on the Fosheim Peninsula, Ellesmere Island. Note the ice underlying the dark tundra soil. The soil slumps down the ice and mixes with the melt water.

7.6 Conclusions

The IRIS 2 region has the greatest variety of tundra ecosystems in the Canadian Arctic, including all five sub-zones of the Circumpolar Arctic Vegetation Map (CAVM) (Walker et al. 2005). These tundra systems provide critical resources and services for northern residents and wildlife. For example, berry producing shrubs are used by humans and wildlife and are important culturally and nutritionally to Inuit, and the production of berries can be considerable near communities in the CAVM subzone D. The warming climate is changing the composition and abundance of species in tundra systems, and a general increase in shrub cover has been observed by northerners and scientists in the IRIS 2 region. The change from herbaceous tundra to shrub tundra and further to forest-tundra in the Low Arctic regions will have feedbacks to the climate through decrease in albedo, similar to the loss of sea ice. These systems also have huge amounts of carbon frozen in permafrost, which is expected to contribute to further warming with increased

carbon emissions caused by deeper thaw. These significant changes will have implications for communities across the region, but will also have effects at the global scale. Continued observations and studies by residents and scientists will help to provide needed information to improve predictions of the changes and develop better adaptation policies and strategies.

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Chapter 8 Coastal Environments and Drivers

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Key messages

- The Eastern Canadian Arctic portion of Nunavut (the IRIS 2 region) extends over 3500 km north-south from James Bay to northernmost Ellesmere Island. With a wide range of geology, relief, climate, ice conditions, and other variables, the coasts of the region exhibit a wide variety of morphology, stability, drivers of change, and coastal hazards.
- There has been near-complete loss of Ellesmere Island ice shelves and associated ecosystems over the past century, greatly accelerated in recent years.
- Greatest storm activity in the region is in the Baffin Bay and northern Labrador Sea sector, where the greatest open-water fetch can develop. There is evidence for an increase in storm activity across the region in the latter part of the 20th century.
- Sea ice serves as seasonal shore protection, but later annual freeze-up leaving more open water during the fall storm season increases the potential for storm wave activity and shore erosion in communities with vulnerable waterfront infrastructure such as Hall Beach, Pond Inlet, Qikiqtarjuaq, and Iqaluit.
- Projections of relative sea-level trends are equivocal in some places such as Iqaluit and Qikiqtarjuaq, but indicate continued sea-level fall in other communities such as Arviat, Rankin Inlet, Hall Beach, and Igloolik, where shoaling affects harbour infrastructure and navigation. The rate of sea-level fall will be reduced with a higher rate of global mean sea-level rise.
- Past flooding events in Iqaluit have resulted from extreme tides without storm activity and have flooded subsistence infrastructure with potential impacts on food security. In principle, these tidal extreme flooding events should be predictable, but absence of a tide gauge in Iqaluit is an impediment.
- Sea ice moving onshore can be a significant hazard, but damaging pile-up in communities, such as occurred in December 2005 at Hall Beach, has not been widely reported. Pile-up ridges in thick multiyear ice are widespread in the archipelago. One might postulate that thinner ice resulting from climate warming may increase the risk of shore ice ride-up.

Of particular concern to communities are the following:

- Changes and instability of coastal ice conditions, notably in the duration, thickness, and reliability of landfast ice for access to country food, particularly marine resources at the floe edge.
- Higher coastal flooding, or enhanced wave runup, affecting waterfront facilities including municipal, commercial, and residential infrastructure, port facilities, subsistence infrastructure, and archaeologically significant sites in areas of present or future sea-level rise.
- Increased coastal erosion rates in areas of stable or rising sea levels, with more open water and wave energy in and close to communities. Unanticipated local shore erosion affecting waterfront infrastructure, even on emergent coasts.
- Coastal ice dynamics, including the risk of more frequent ice ride-up and pile-up as sea ice thins and possibly becomes more mobile.
- Rapidly falling sea levels affecting subsistence boating and navigation for sealift and cruise shipping.
- Stranding of coastal infrastructure in areas of rapid isostatic uplift and falling sea levels (coastal emergence).
- Tsunami risk to coastal communities, particularly in fiords in the high seismicity region of Qikiqtaaluk.

Abstract

This chapter reviews the physical state and drivers of change on the eastern Nunavut coast, including the effects of climate and sea-level change and related hazards. Ice shelves on the north coast of Ellesmere Island have declined by 95% since 1900. Storm activity is greatest in Baffin Bay and Davis Strait, also the region of maximum fetch. Much of the coast is fetch limited by nearby land and sea ice and some parts of the archipelago have almost no wave action. While sea ice thus protects the coast, landward ice motion can severely scar the shore zone and damage coastal infrastructure. Thermal erosion of ice-rich sedimentary coasts is a lesser factor in this region than in the Western Canadian Arctic. Sea-level projections for some communities, particularly in Hudson Bay and Foxe Basin, show continuing rapid uplift and falling sea levels over coming decades. Some parts of Devon, Bylot, and Baffin islands have recent or ongoing sea-level rise, but proximity to diminishing Greenland and Canadian Arctic land ice will limit future local sea-level rise. In some cases such as Iqaluit, even the sign of sea-level change (rising or falling) is uncertain. Rising sea level can increase the risk of flooding, wave runup, and ice ride-up, while falling sea level can strand port infrastructure and impede navigation. Landfast sea ice provides an important ecological service to northern residents as a travel and hunting platform for access to country food. The declining duration and condition of landfast ice are stressing well-being and food security in northern communities. Tsunami risk is another unquantified coastal hazard in fiords of the seismically active Baffin Bay region.

8.1 Introduction

All human settlements in the Qikiqtaaluk (Baffin) region of Nunavut and all but one (Baker Lake) in the Kivalliq region are located on the coast. Baker Lake is tidal and supplied by marine transport. Residents in these regions derive a large part of their livelihood from marine resources, are highly dependent on marine transportation, and all aspects of the coastal-marine environment are central to ancient and modern Inuit culture. More broadly, the Arctic coast is a fundamental environmental and social-ecological interface, a zone of high biological productivity, sustained human use over millennia, vulnerable to natural hazards and human disturbance, and among the most rapidly changing components of Arctic landscapes (Forbes 2011). At the same time, the human footprint on high-latitude coasts is generally much lighter than in highly populated regions and was minimal prior to European contact (see, however, Viehberg et al. 2017). Tent rings, domed stone caches, blinds, and sod, stone and whalebone house structures can be found along former shorelines, many now extensively uplifted above present sea level, but the low population density and extensive use of snow structures resulted in minimal pollution, limited surviving indigenous built heritage, and negligible alteration of the coast.

Over the past century, the progressive development of trading posts, police detachments, permanent settlements, military installations, hydrocarbon and mineral exploration and production, and associated port facilities have significantly increased the physical impact of human activities on the Arctic landscape and its coasts (Lamoureux et al. 2015, NOG 1995, Walker and Peirce 2015). The risks of oil spills, particularly in ice-covered waters, have been a high-priority concern, leading to legislation (e.g., Arctic Waters Pollution Prevention Act, Canada 2017), research (e.g., Barrie et al. 1978, Taylor 1980a, Sempels 1987, Owens 1994), and consideration in environmental impact assessments for proposed industrial development. Extensive clean-up and remediation has been undertaken at former DEW Line sites and other installations. The growth of shipping already evident in the Northwest Passage and

increased bulk cargo and cruise traffic along the Baffin coast, at a time when much of the Arctic seabed remains poorly charted, have heightened concerns about potential pollution as well as impacts on sea ice and its use in the subsistence economy. Open water leads created by ship passage through fixed ice can impede subsistence access.

8.1.1 Objectives and scope

This chapter surveys the physical state of the coast in the Eastern Canadian Arctic regions (Qikiqtaaluk and Kivalliq) of Nunavut, with a focus on environmental drivers of coastal change and hazards. At a time of accelerating environment change, as the climate is warming at a faster pace in northern high latitudes, we also consider the impacts of climate change on the nature and severity of hazards and other constraints on northern livelihoods.

The Qikiqtaaluk coast ranges across 31.5° of latitude (3500 km N-S) from the southernmost island in James Bay to the northernmost tip of Ellesmere Island (Figure 1). The Kivalliq coast of Hudson Bay lies within this latitudinal envelope, which spans a wide range of solar irradiance, temperature, sea-ice duration and thickness, storm incidence, and other climatic conditions, with an associated variety of vegetation and landscapes. The Eastern Canadian Arctic coast includes a wide spectrum of coastal exposure, from parts of southeastern Baffin Island exposed to the Labrador Sea and Atlantic swell, to ice-locked shores of the central Canadian Arctic Archipelago (CAA) and the northern coasts of Ellef and Amund Ringnes, Meighen, Axel Heiberg, Ellesmere and other islands fronting the Arctic Basin. These parts of the coast facing the Arctic Ocean have the thickest (but diminishing) multiyear sea ice (Forbes and Taylor 1994, Stroeve et al. 2014) and fast-declining ice shelves along the north coast of Ellesmere Island (England et al. 2008, Mueller et al. 2008, Vincent et al. 2001).

The coastal physiography and geomorphology throughout most of the Arctic, where biology plays a minimal role relative to its influence on lower-latitude coasts, is strongly linked to the underlying geology (see Chapter 1; Wheeler

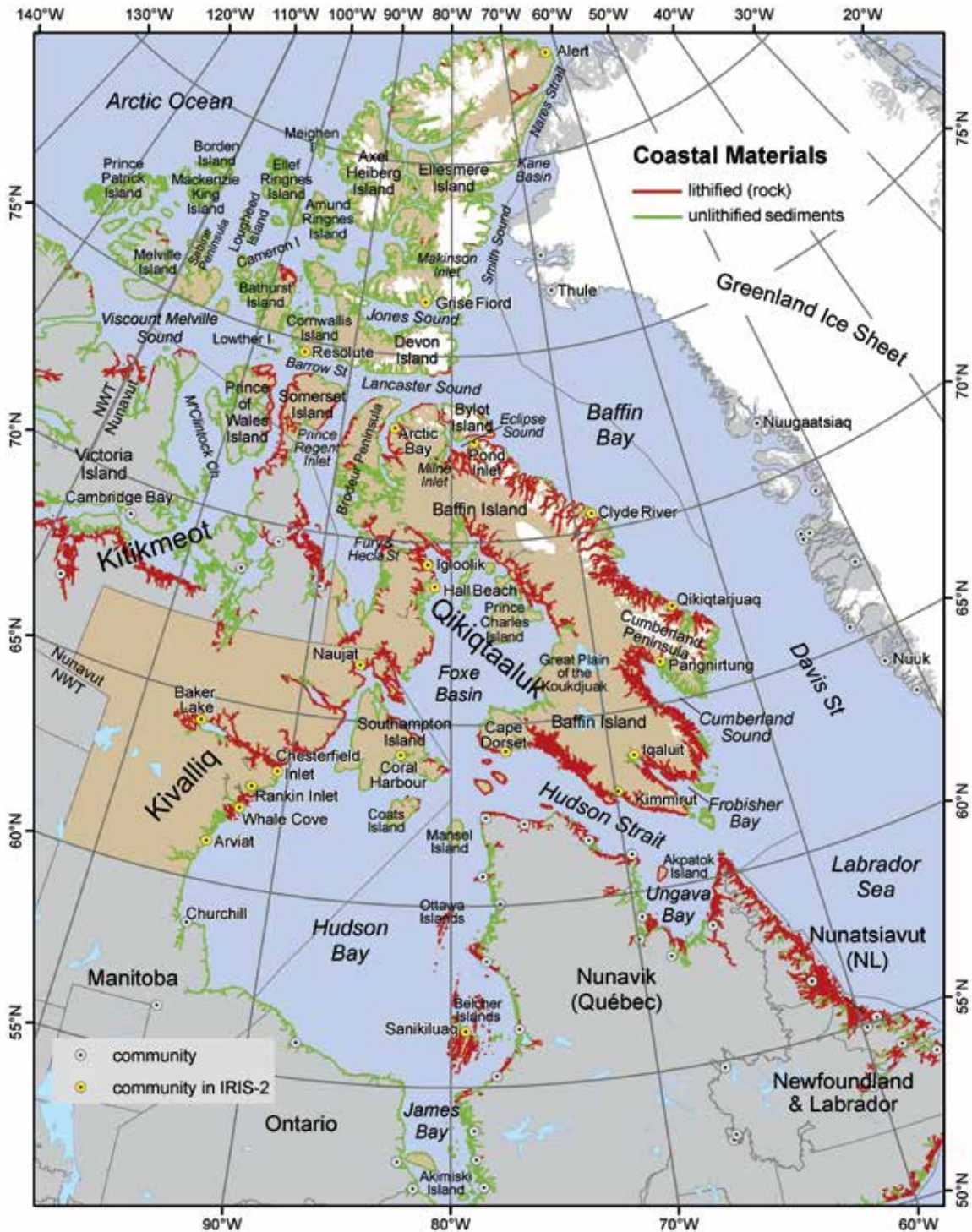


FIGURE 1. IRIS 2 region shaded brown (Kivalliq and Qikiqtaaluk), showing major geographic features, settlements, and the distribution of rock-dominated and unlithified (sedimentary) coasts.

et al. 1996, Harrison et al. 2011). This is not only the case for rock-dominated coasts (Hansom et al. 2014), which make up about 38% of the Canadian Arctic shoreline (Ford et al. 2016), but also for coasts developed in unlithified sediments (Figure 1; Taylor and McCann 1983). In other cases, cliff-base deposits or raised marine sediments in areas of isostatic uplift may lead to classification of the coast as sedimentary, despite prominent rock control of coastal topography. The antecedent landscape on which coastal drivers operate to form shorelines at the current relative sea level is largely a function of the geology, glaciation, and postglacial landscape processes.

The morphological character, materials, and stability of coasts in the IRIS 2 region show distinct variability related to the underlying geology, modified by active subaerial and marine processes, including tides, currents, storm waves, and sea-ice interaction in the shore zone (Figure 2). Relative sea-level change driven by residual viscous and present-day elastic glacial isostatic adjustment and climate-driven changes in ocean water density also play a large role. Despite the limited influence of organisms on the nature of Arctic coasts, distinctive plant communities are found in low back-shore settings where sufficient fine sediment and moisture are present, e.g., between gravel beach ridges and on



FIGURE 2. (a) Icefoot functioning as winter street, with subsistence infrastructure along the waterfront, Iqaluit, March 2011. (b) Quartz sand beach with heavy mineral placer lamination, Igloo Bay, Clyde Inlet, east coast of Baffin Island, August 2007. (c) Ekalugad Fiord, opening to Home Bay, an area of lower relief on central Baffin Island, showing terraced proglacial sandur (outwash plain and delta) in arm of fiord at right (cf. Church 1972) and moraine (emergent sill), July 2008. (d) Hamlet of Pond Inlet (Mittimatalik) on Eclipse Sound, with sandy beach at base of vegetated slope, Bylot Island in background, August 2009.

protected ice-bound shores. Sub-Arctic islands of Nunavut in James Bay have limited marsh development (Martini and Glooschenko 1984, Martini et al. 2009). Arctic coasts provide rich living resources at all levels of the food web (Bluhm and Gradinger 2008, Cusson et al. 2007, Dale et al. 1989, ICC Alaska 2015, Sakshaug 2004), including benthic organisms in shallow coastal waters (Figure 3).

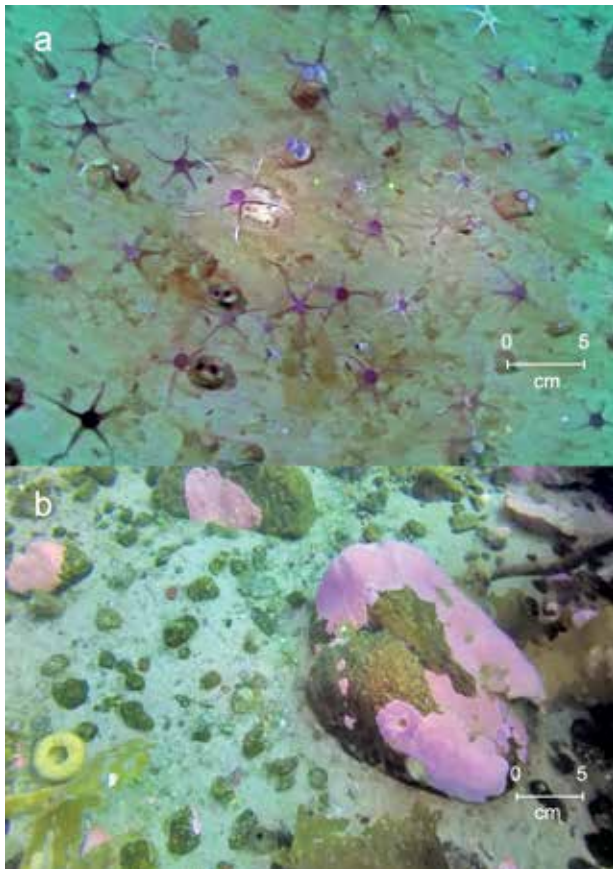


FIGURE 3. Benthic habitats in shallow waters near Qikiqtarjuaq, NU, on Cumberland Peninsula, eastern Baffin Island. (a) Sandy bottom, ~40 m water depth, south coast of Broughton Island, with abundant clam syphons (mostly *Mya* sp.) and brittle stars. (b) Sand and gravel with cobbles and boulders in Broughton Passage, ~15 m depth, with dense kelp patches and encrusting coralline algae (pink). Photos and interpretation courtesy of Ben Misiuk.

8.2 Drivers of coastal change

8.2.1 Tides and currents

Tides range from extreme microtidal (less than 0.5 m) in the northwest to extreme macrotidal in the south and southeast (Figure 4). The maximum recorded tidal range at Iqaluit in Frobisher Bay is 12.6 m (CHS 2001). The large tide has facilitated the development of extensive boulder-strewn tidal flats in inner Frobisher Bay (McCann et al. 1981). Tidal currents of 5-7 knots (2.6-3.6 m/s) are encountered in the inter-island shipping channel in the middle of Frobisher Bay (CHS 1959), as well as in other constricted channels of the intricate southeast Baffin coast. On the other hand, currents in Koojessé Inlet at Iqaluit are relatively weak, ≤ 0.8 m/s, typically much less (Dale et al. 2002, Hatcher 2013), but competent to move some sand on both flood and ebb.

The circulation in Baffin Bay is counter-clockwise, with warm water entering from the south along the west coast of Greenland and cold water flowing south (carrying icebergs) along the narrow Baffin shelf (Curry et al. 2011). There is evidence from inner-shelf sand waves for strong tidal currents near the eastern tip of the Cumberland Peninsula (Hughes Clarke et al. 2015).

In James Bay, reversing tidal currents up to 2 m/s have been reported in Akimiski Strait, between Akimiski Island and the Ontario mainland coast (Martini and Grinham 1984). In Foxe Basin, a persistent southerly flow is seen along the west coast, as revealed by current measurements at Hall Beach (Figure 5). Under non-storm conditions, tidal currents set to the north (340° - 350°) alongshore on the flood tide, and more rapidly to the south (180°) on the ebb (CHS 1959). Observed current speeds to the south (up to 1 m/s) are two to five times greater than those to the north (Manson and Forbes 2008, unpublished data). The persistence of this current just a few hundred metres offshore keeps the floe edge very close inshore at Hall Beach.

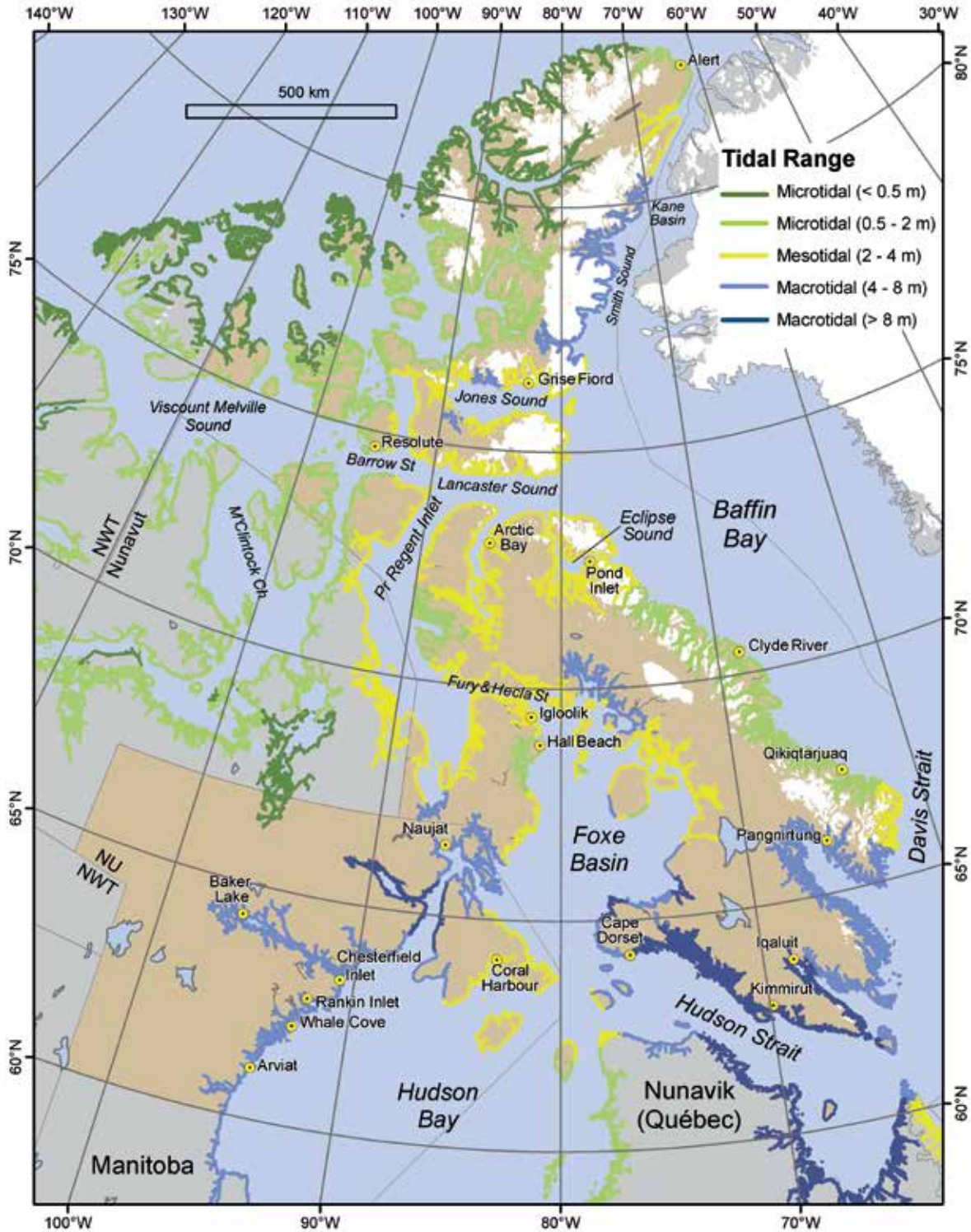


FIGURE 4. Tidal range in the IRIS 2 region (CanCoast data product, source data from Canadian Hydrographic Service).

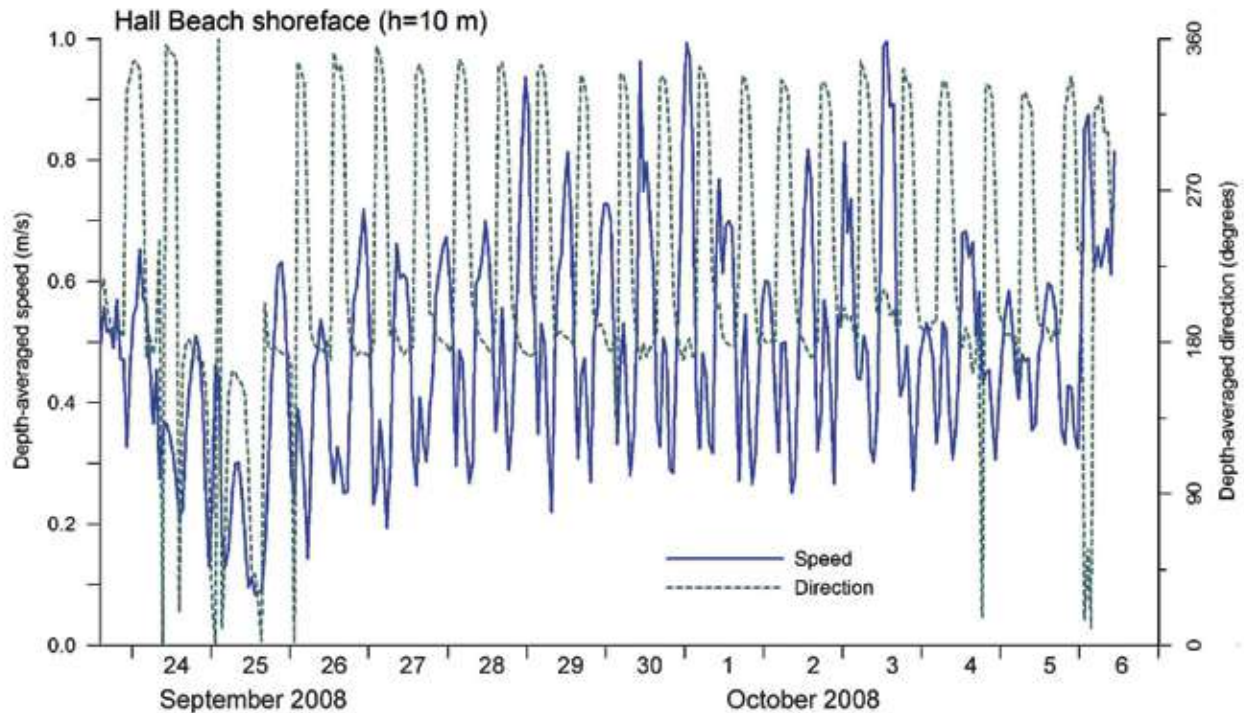


FIGURE 5. Acoustic doppler current measurements on the outer shoreface at Hall Beach, Foxe Basin, over two weeks in the fall of 2008 (Manson and Forbes 2008). Except when disrupted by storm winds, coast-parallel flood and ebb currents oscillate between north and south, with a strong southerly net flow. Peak velocities to the south are approximately 1 m/s, notably September 30, October 1, and October 3.

8.2.2 Climate and cryosphere

The climate of the study area ranges from Sub-Arctic to High Arctic, with a large annual variability in temperature. Although snow cover is present during much of the year, precipitation is concentrated in summer, with annual totals of <300 mm (with few storms) in the northwest to >1000 mm (with more frequent storms) along the Davis Strait and Baffin Bay coasts. The annual variability in solar radiation and air temperature (along with seasonal pressure and wind patterns) drives the seasonal variability in sea-ice concentration, while climate variability across the region and the climate warming trend lead to variation in sea-ice seasonal duration and thickness, and in the length of the open-water season (Figure 6).

8.2.2.1 Permafrost

Except for the islands in James Bay, the IRIS 2 region lies entirely within the zone of continuous permafrost, characterized by soil temperatures $<0^{\circ}\text{C}$ for two years or more (see Chapter 4). Sediments at shallow depth in the shore zone are typically ice-bonded (Taylor and McCann 1974, 1983, Taylor and Forbes 1987). In areas of rising relative sea level, confined in the study region to the eastern fringe of Baffin Island, Bylot Island, Lancaster Sound, eastern Devon Island, possibly Admiralty Inlet, and the northern tip of Ellef Ringnes Island, permafrost may also be present in shallow nearshore waters.

The seasonal depth of thaw limits wave erosion of beaches but is expected to increase, enabling deeper storm-wave scour in a warming climate. Measured depth of thaw is

a function of summer temperature and duration (thawing degree days) and soil or sediment properties. Thus it is not a simple function of latitude. Thaw depths as great as 0.69 m or more have been measured on Ellesmere Island (Taylor 1978b) and as little as 0.2-0.3 m late in a cold summer at Resolute (Sadler and Serson 1981). Thaw depths late in summer 2005 on Resolute beaches ranged from 0.32 to 0.81 m (St-Hilaire-Gravel et al. 2012). Taylor and Frobel (2006) compared thaw depths at numerous sites in the Barrow Strait region and detected a slow increase in the depth of thaw over three decades 1974-2005, amounting to 0.12-0.26 m. On Bylot Island beaches at the mouth of Lancaster Sound, they reported an increase of 0.3 m in the near-maximum depth of thaw from 1979 to 2005.

8.2.2.2 Sea ice and ice in the shore-zone

Sea ice is a dominant factor in the nature and use of the coast in the study region (Fig. 2a; Taylor and McCann 1983, Forbes and Taylor 1994). Using a conservative threshold of 5/10ths ice (50% cover), the decadal mean freeze-up date for 2000-2009 ranged from September 5 (the break-up date in the northwest) to 19 December, proceeding from earlier in the north and west to later in the east and south (Figure 6a). Excluding James Bay, Cape Dorset, Kimmirut, Iqaluit and Pangnirtung have the latest mean freeze-up, while freeze-up typically occurs in late October to late-November for most of the other communities in the region. The pattern of breakup is more complex and it is also highly variable from year to year (Figure 6b). The southwest coast of Southampton Island, south coast of Baffin Island, the mouth of Frobisher Bay, and central Cumberland Sound

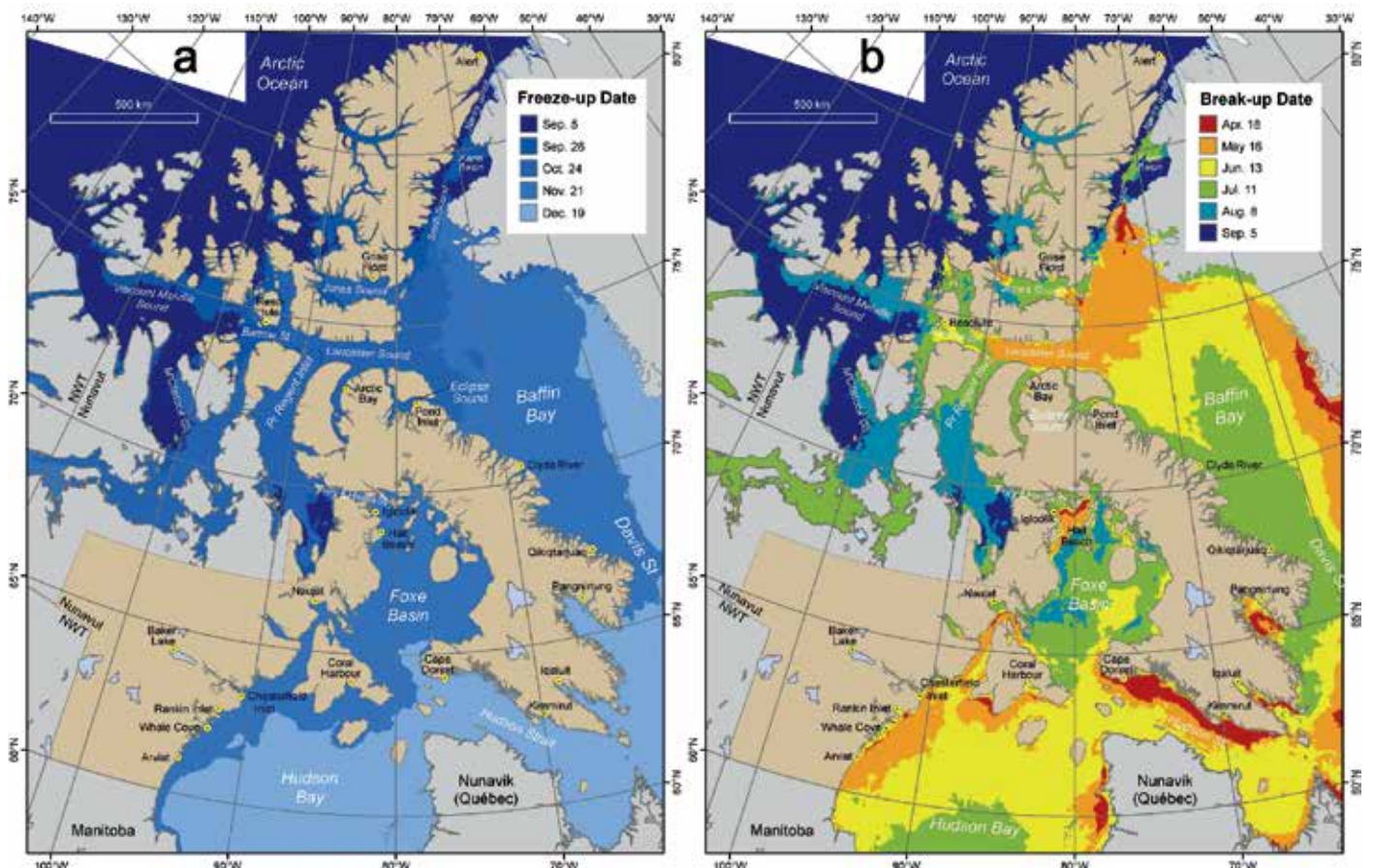


FIGURE 6. Sea-ice freeze-up and break-up dates using a 5/10ths ice-cover threshold, decadal mean 2000-2009 (CanCoast data product, source data from Canadian Ice Service). The IRIS 2 region is shaded brown.

have mean break-up (50% open water) as early as April 18. The communities along the west coast of Foxe Basin and Hudson Bay see break-up from mid-May to mid-June, but ice can persist in central Hudson Bay and the Belcher Islands as late as July. To the northwest, the interisland channels in the Sverdrup Basin have break-up coinciding with freeze-up, indicating that these areas on average do not see 50% open water at any time of the year (Figure 6b).

As the climate is warming, break-up in some places is clearly occurring earlier and freeze-up later (on average) than the 30-year climate normal. This change is captured in sea-ice charts and in the observations of northern residents with respect to long-term experience reflected in Inuit knowledge (Ford et al. 2016). St-Hilaire-Gravel et al. (2012) found that the annual duration of ice cover in the Resolute Bay area has decreased by 0.95 days/year over 30 years (1979-2009), predominantly due to a delay in the onset of freeze-up. To the east in Lancaster Sound, the length of the open-water season at Cape Charles Yorke (Baffin Island) has increased more slowly (0.57 days/year) but is highly variable because the cape acts as an anchor point for pack ice in the sound and break-up is often delayed (St-Hilaire-Gravel et al. 2015). In inner Frobisher Bay near Iqaluit, Hatcher and Forbes (2015) found a similar increase in the open-water season amounting to 1.0-1.5 days/year since 1969, with contributions both from earlier break-up and later freeze-up. Across the Canadian Arctic, the length of the open-water season is increasing by 3.2-12 days per decade (Ford et al. 2016, Howell et al. 2009, Stroeve et al. 2014).

The nature and mobility of the ice varies widely. Along the coast, extensive landfast ice develops throughout the region each winter and plays a critical role as a platform for travel and subsistence food access (Figure 7). The maximum winter thickness of landfast ice typically increases with latitude, from <1.5 m in Hudson Bay to >2 m further north, and the length of the ice season varies likewise (Forbes and Taylor 1994). The landfast ice is often smooth and easily travelled, but rough areas can occur, particularly where wind has compressed young ice during the 'setup' period, before the ice assumes a more stable arrangement for the winter. In areas of large tidal range, as in Frobisher Bay at Iqaluit,

the periodic lifting and settling of ice on a boulder-strewn tidal flat produces a very rough maze of ice that is difficult to traverse (Figure 8a; Forbes and Taylor 1994, Hatcher and Forbes 2015, McCann and Dale 1986, McCann et al. 1981). Thin ice is a hazard both early in the year and in the spring and early summer as melt begins to take place.

Nearshore anchor ice typically forms in a narrow zone, within about 5 m of the lower low-water line (Sadler and Serson 1981). An icefoot generally forms higher on the shore, building up to the higher high-water line (Figure 2a; Forbes and Hansom 2011). These two ice bodies may become amalgamated and, in some cases, are buried by sediment and persist well into summer, if not later (Blake 1975).

Sea ice serves a seasonally protective role on most Arctic coasts. In some areas with negligible open water (or very short seasons with limited fetch), ice can severely limit or virtually eliminate wave action, as seen in parts of the CAA such as the Sabine Peninsula (Melville Island) or Loughheed Island (Forbes and Taylor 1994, Taylor and Forbes 1987). Elsewhere, more energetic waves remould beaches and build storm ridges during the open-water season (St-Hilaire-Gravel et al. 2010). Furthermore, the presence of ice floes interacting with surf in the near-shore can enhance the erosional impact of a storm by 'ice wallow' (enhanced hydrodynamic scour) on the shoreface and more irregular wave action at the beach (Taylor 1981).

Ice can also move against the coast under wind stress (or stress transmitted through the ice pack), scouring the shoreface and driving sediment onshore (Reimnitz et al. 1990, Taylor and McCann 1976). Ice ride-up and pile-up phenomena are common, widespread, and sporadically destructive (Forbes and Taylor 1994). Most of the region's coastline is susceptible to this hazard, but some areas are particularly prone. Ice ride-up involves direct encroachment of an ice sheet with limited deformation and, in some cases, can penetrate 100 m or more and severely damage infrastructure such as aids to navigation (Kovacs and Sodhi 1980, Taylor 1978a). When the ice sheet is fractured by buckling

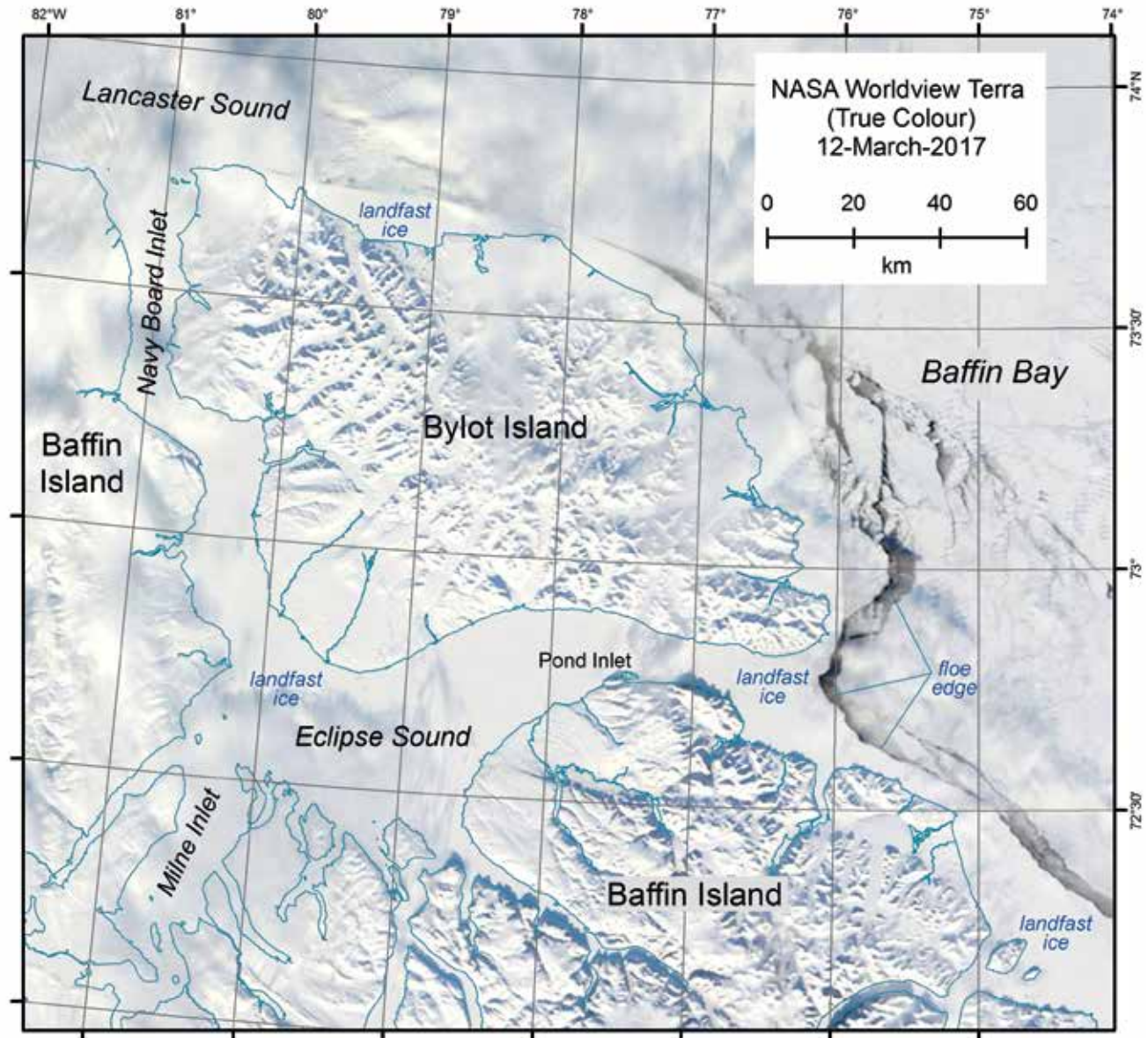


FIGURE 7. Landfast ice filling Eclipse Sound (including Pond Inlet) and forming a travel platform 10-20 km wide along the east coast of Bylot and Baffin islands, with flaw lead (open water) in the shear zone beyond the 'floe edge' (edge of landfast ice), 12 March 2017 (Terra satellite data from NASA Worldview, <https://worldview.earthdata.nasa.gov>). The width of the landfast ice diminishes westward along the north coast of Bylot Island; it may even be discontinuous in the northwest but is obscured there by cloud.

or crumbling failure, it can form a pile-up ridge, frequently 10-20 m or more in height (Taylor 1978a, Taylor and Forbes 1987). Sverdrup (1904) reported an ice ridge approximately 36 m high off the southwest coast of Axel Heiberg Island in April 1900. Ice pile-up events can be damaging, occur rapidly, and pose a safety risk if they occur on a populated shorefront, as happened at Hall Beach in December 2005 (Figure 8b).

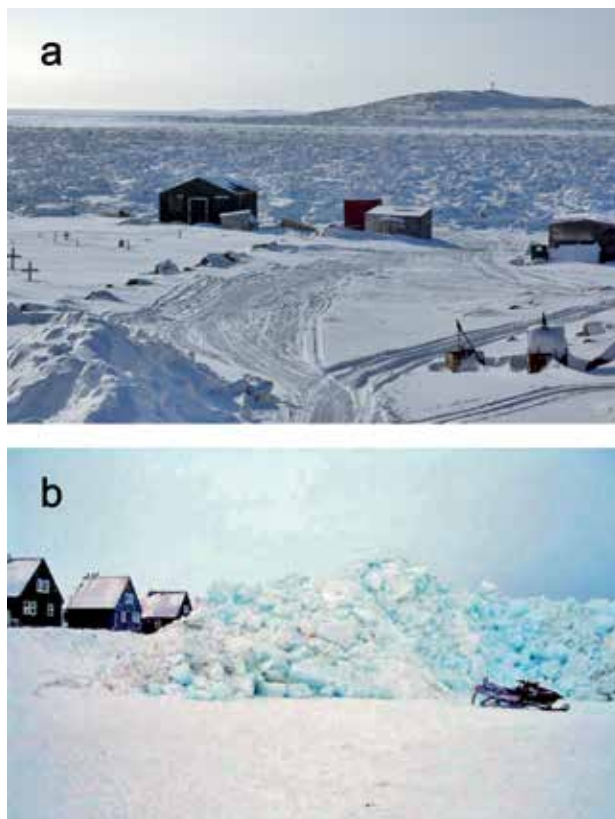


FIGURE 8. (a) Rough ice over the tidal flats, Iqaluit, March 2011 (DLF). (b) Ice pile-up on the beach at Hall Beach, 1 December 2005 (courtesy of C. Hotson).

8.2.2.3 Storms and wave climate

Atkinson (2005) analyzed the storm climatology for seven sectors of the Arctic Ocean over 50 years (1950–2000) and showed that the storm count for the CAA and Greenland sector was much lower than for any other part of the Arctic margin (Forbes 2011). This work was focused on the Arctic Basin and did not include more southern

parts of the CAA including the most populated areas of Qikiqtaaluk and Kivalliq. Zhang et al. (2004) considered cyclonic activity throughout the northern mid- to high latitudes, using a ‘cyclone activity index’ that integrates information on cyclone intensity, duration, and frequency. They found higher storm activity in the Labrador Sea to Baffin Bay sector of the Canadian Arctic, as would be expected from knowledge of storm tracks and weather data. Using 55 years of data (1948–2002), they found an increase in Arctic storm activity in the second half of the 20th century and suggested that a shift in storm tracks had occurred to bring more and more intense storms into the Arctic, particularly in summer (Zhang et al. 2004), when sea ice is approaching its annual minimum and open-water fetch is increasing.

Ice is a critical factor in determining the impact of storms on coastal stability and hazards (St-Hilaire-Gravel et al. 2010). A storm climate analysis for seven years of field studies (2003–2009) at Resolute found that only 35% of the 46 storms identified had the potential to generate wave activity at the coast (St-Hilaire-Gravel et al. 2012). Of these storms (restricted to ‘open-water season’ late July to early October), open-water fetch ranged from zero to 230 km or more and hindcast significant deepwater wave heights exceeded 2 m in 12 events, with a maximum of 5.2 m from the east in the storm of 4–7 August 2008. The nearshore wave energy generated by storms depends not just on fetch length but also on shoreline orientation, wind direction, and shoreface bathymetry, such that the same storm may have different impacts on adjacent parts of the coast or opposite sides of islands (St-Hilaire-Gravel et al. 2010).

Until recently, there were very few data sets with wave observations in the region and coastal wave measurements remained scarce. Advances in reanalysis and satellite data time series are beginning to provide a better picture of the regional wave climate in Arctic waters. For 1955–2004, Swail et al. (2006) hindcast a 99th percentile significant wave height between 4 m and 6 m in Davis Strait and <3 m in northern Baffin Bay. Stopa et al. (2016), using satellite altimeter data and wave hindcasting for 1992–2014

(a shorter but more recent period than the other study), showed the 99th percentile significant wave height ranging from >5 m in Davis Strait to about 3 m off the mouth of Lancaster Sound, and about 2 m in Smith Sound, Lancaster Sound, and Barrow Strait. In Hudson Bay, observed monthly maximum significant wave heights as of the mid-1990s ranged from 1.5 to 8.2 m (Shaw et al. 1998).

In Foxe Basin, limited wave records were obtained in three depths across the shoreface at Hall Beach over two weeks in September–October 2008 (Manson and Forbes 2008). Figure 9 shows the 2008 wave record from the outer instrument at Hall Beach in 10 m water depth. During this period, there were several storm events with onshore waves and significant wave heights >1 m (in one case >3 m), at a time in the fall when open-water fetch to the northeast, east, and southeast in Foxe Basin was effectively unlimited.

Wave records have also been obtained at several locations on the tidal flats at Iqaluit, for approximately nine weeks in late summer and early fall of 2010 and 2011 (Hatcher and Forbes 2015, Hatcher et al. 2014). The most frequent wind direction in summer is from the southeast, the direction of maximum potential fetch (approximately 50 km), but the large tidal range reduces the probability of storm events with high waves reaching the high-tide line. Dale et al. (2002) reported a storm in which “waves 1 m in amplitude” pounded the beaches at the head of the bay and transported a substantial volume of sand alongshore and seaward.

While projecting future impacts of climate change on coastal processes in the region remains extremely challenging, anticipated increases in open-water fetch, storm frequency and intensity, and depth of thaw may combine to reinforce each other in promoting more substantial shore remodelling and potential impacts on infrastructure.

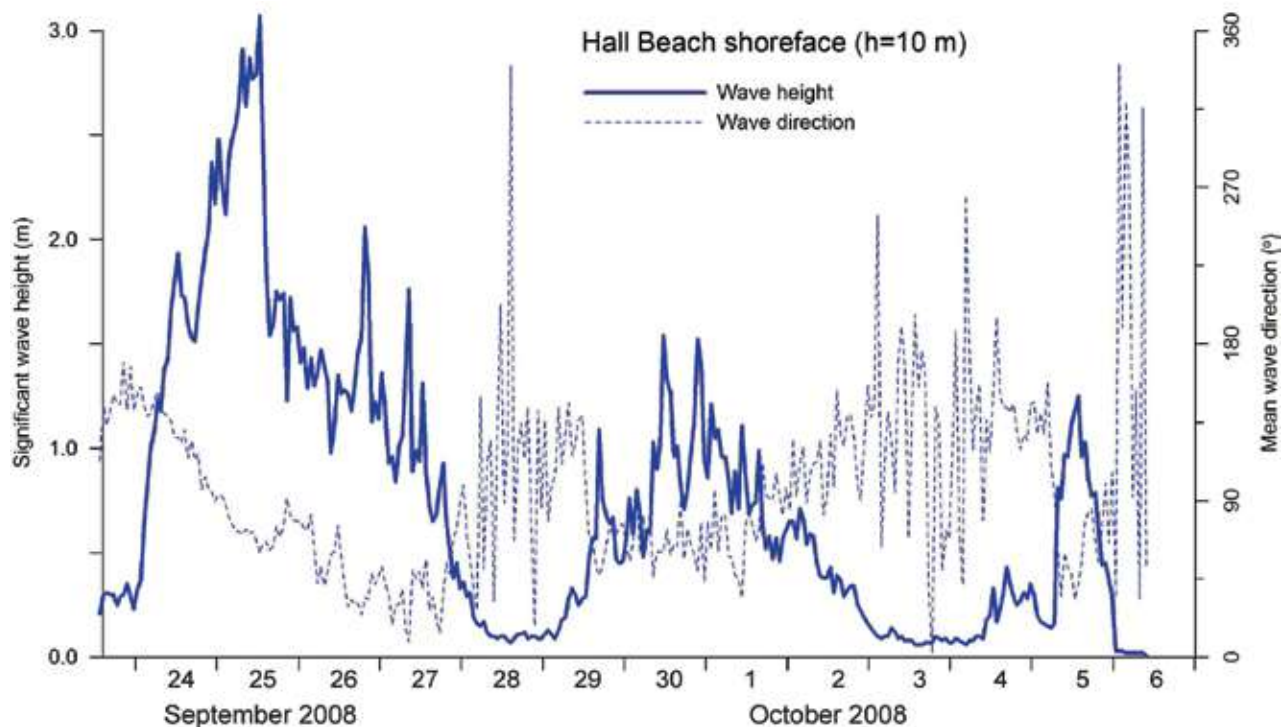


FIGURE 9. Acoustic doppler wave measurements on the outer shoreface at Hall Beach, Foxe Basin, over two weeks in the fall of 2008 (Manson and Forbes, 2008).

8.2.3 Glacial history, isostatic adjustment, and relative sea-level change

Northern North America has a history of multiple continental-scale glaciation, culminating in the Laurentide Ice Sheet at the last glacial maximum (LGM), about 25 000 years ago, when most or all of the region was buried in ice. Some parts of the region have been ice-free for more than 10 000 years, while others were deglaciated much more recently, including the area surrounding existing extensive glaciers and ice caps. The formation of thick and extensive ice sheets removed water from the ocean basins, lowering global sea levels by about 120 m, while the resulting ice mass depressed the crust, except in marginal regions where limited uplift occurred. As the ice sheets diminished over many thousands of years, global mean sea level rose and the crust and underlying mantle rebounded in a process known as glacial isostatic adjustment (GIA). The elastic response to unloading of the crust was nearly immediate on deglaciation, but the viscous readjustment of the mantle has a time scale of the order of 10^4 years, so that many coastal communities in the region are still experiencing GIA uplift at rates equivalent to or faster than regional sea-level rise (James et al. 2014, 2015).

The highest local evidence of sea level on land since the last deglaciation is known as the ‘marine limit’. In the study region, this ranges up to nearly 170 m along the Kivalliq coast near Arviat (Figure 10; Simon et al. 2014) and over 100 m in many parts of the region. Land below the marine limit is former seabed, modified by shore processes as it emerged above sea level and subsequently reworked by weathering, freezing, downslope movement, sediment transport, and, in some cases, development of an organic cover. The emergence and cooling of saline marine clay and silt (initially unfrozen on the former seabed) has important implications for the stability of permafrost. Many communities are founded on these marine sediments and are affected by saline permafrost (cold sediments with limited excess ice and weak ice bonding), which can compromise the stability of building foundations (Hivon and Segó 1993, Smith et al. 2012a,b,c).

Coasts affected by isostatic uplift exceeding the rate of sea-level rise (thus falling ‘relative sea level’ – level with respect to the land surface) have varying expressions of raised former shorelines (see Chapter 1; Figure 7a, c), which in some cases (where shore processes are active) form dramatic sequences of beach ridges (sometimes referred to as ‘staircases’) on the backshore slope below the marine limit (e.g., Blake 1975, St-Hilaire-Gravel et al. 2012). Emergent coasts also display terraced deltas, which occur in a range of settings from fiord-head proglacial outwash (Figure 2c; Church 1972) to the terraced finger deltas of the Sverdrup Basin (Forbes and Taylor 1994).

From a natural hazards perspective, the most important implication of GIA is its role in reinforcing or inhibiting sea-level rise due to climate change. Where the land is currently sinking, local relative sea-level rise will be greater than the projected climate-induced sea-level rise, because the effect of subsidence is to raise relative sea level. Where GIA uplift prevails, the emergence will act in opposition to climate-induced sea-level rise and reduce the expected local relative sea-level rise. If the rate of uplift exceeds the rate of regional sea-level rise, relative sea level will fall, as is anticipated for some parts of the Canadian Arctic, including communities such as Igloodik (Figure 11; Ford et al. 2016, James et al. 2014, 2015). An additional consideration for the Eastern Canadian Arctic is the gravitational effect of the Greenland Ice Sheet (and, to a lesser extent, Canadian glaciers and ice caps) that acts to counteract rising sea level in the region. This has a strong and clear effect on projected sea-level rise at Iqaluit and in northern Ellesmere Island (Figure 11).

On some parts of easternmost and northern Baffin Island, Bylot Island, and eastern Devon Island, relative sea level is rising from a postglacial minimum associated with a former forebulge (Figure 10) (Andrews 1989, Forbes et al. 2004). Relative sea level is also currently rising along the northwestern margin of the CAA, including Borden Island and northern Ellef Ringnes Island (Atkinson and England 2004). The implications of rising sea level for coastal stability and hazards include higher storm flooding and potential marine ice incursion, increased frequency of

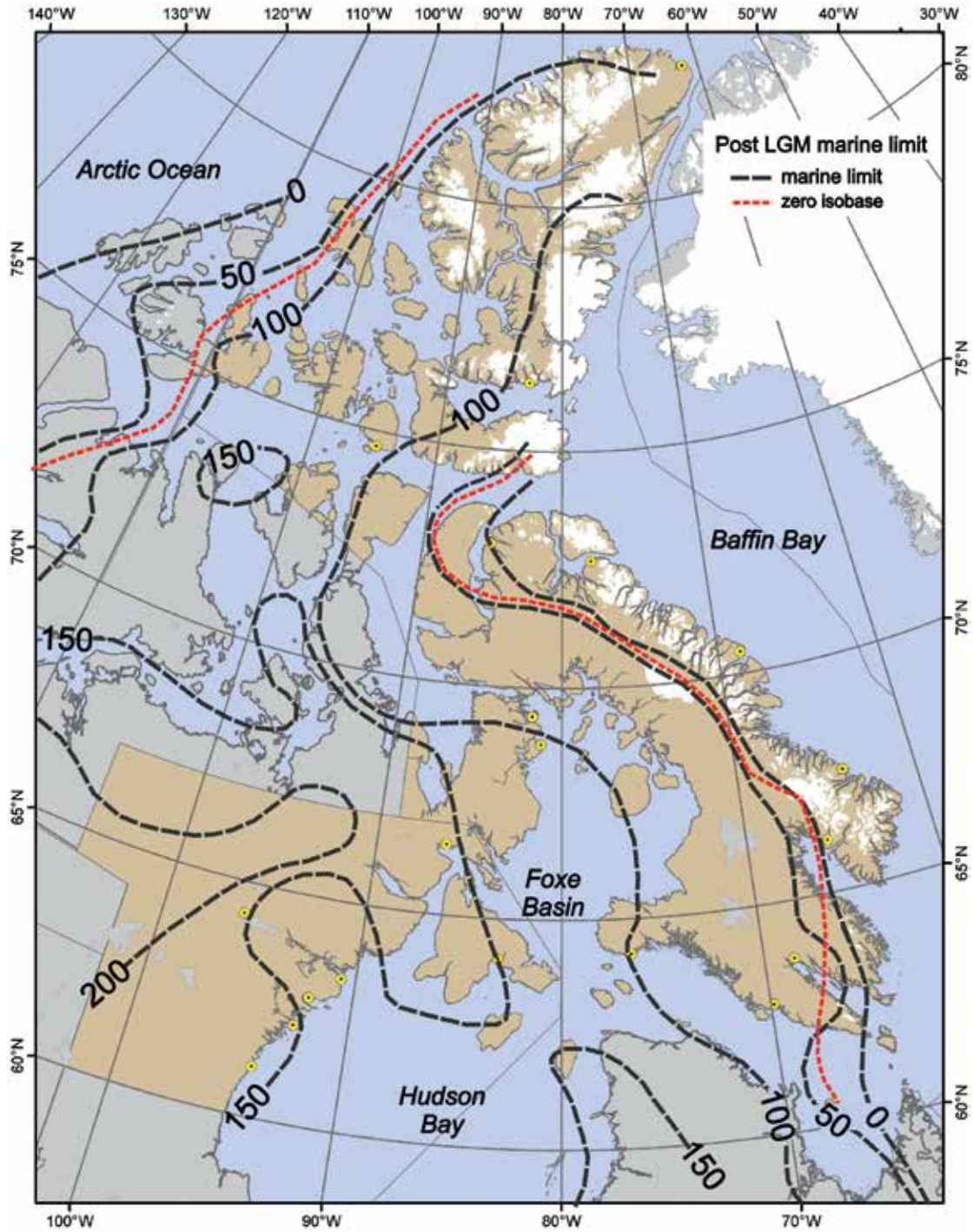


FIGURE 10. Approximate marine limit (highest sea level) since the Last Glacial Maximum (in metres above present sea level) and present zero isobase (modified after Andrews 1989). The marine limit has varying age and the zero marine limit is not necessarily coincident with the present locus of zero vertical motion.

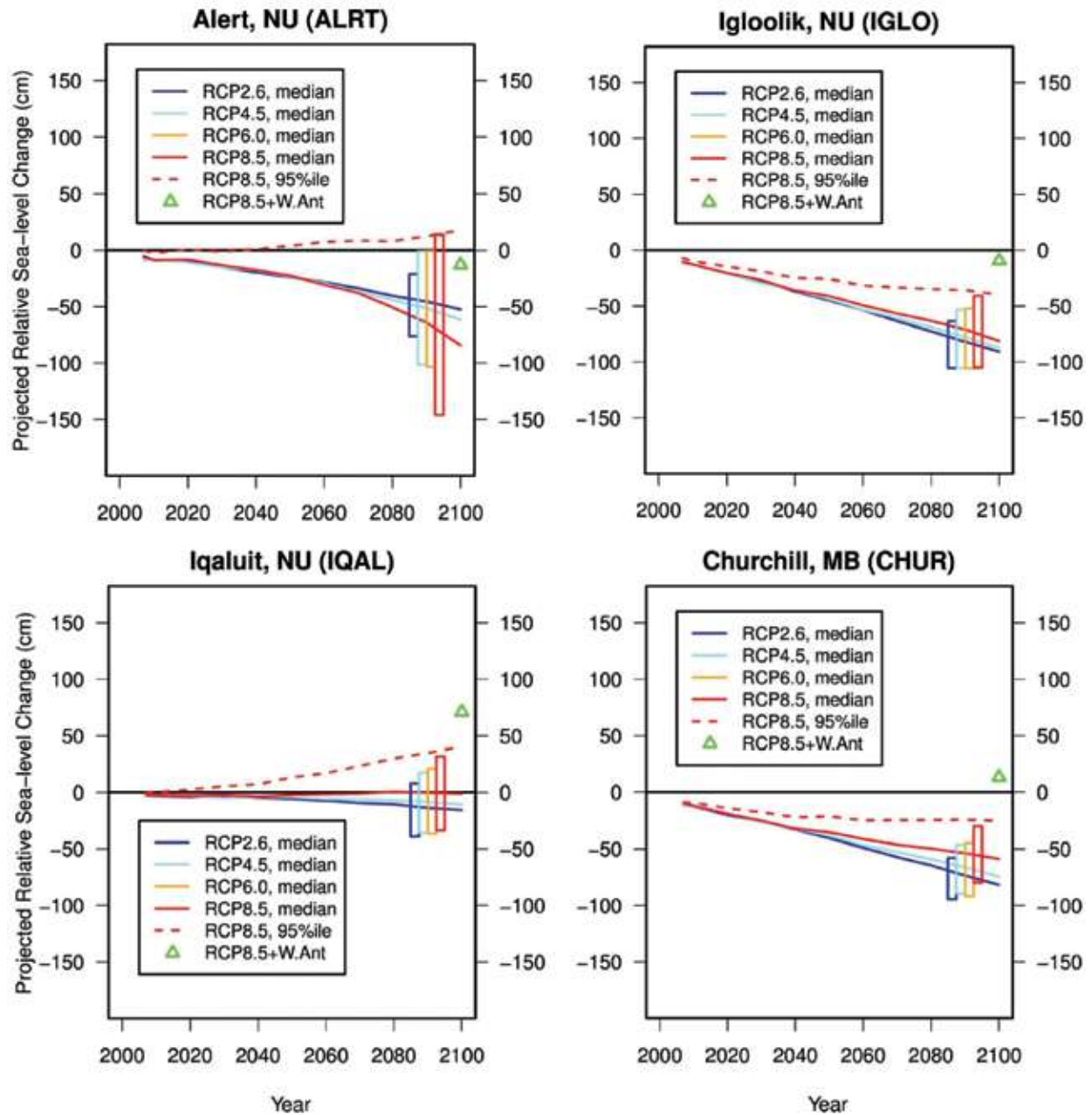


FIGURE 11. Relative sea-level projections incorporating global and regional sea level change, GIA, ocean dynamics and gravitational effects for selected sites in the IRIS 2 region (adapted from James et al. 2015). These show a possible rise in relative sea level at Iqaluit and Alert, but continued fall in relative sea level at Igloolik and Churchill. The latter is 270 km south of Arviat and provides the best available projections for that part of Kivalliq. The RCPs ('representative concentration pathways') are scenarios of emissions and greenhouse gas concentrations leading to different radiative forcing and climate change (Moss et al. 2010), as adopted for the global climate and sea-level projections of the IPCC Fifth Assessment Report (IPCC 2013, James et al. 2014).

flooding, inundation of low-lying land (including cultural heritage sites), landward movement of coastal landforms such as barrier beaches, and increased risk of coastal erosion. Where local relative sea level is falling and expected to continue that trend, as is currently happening in Hudson Bay and Foxe Basin communities, among others, there are other implications, including shoaling challenges for navigation and sealift operations.

8.3 Coastal geomorphology and shoreline change

The Canadian Arctic coast as a whole has been described in varying detail in a number of books and reports, including Bird (1967), Forbes and Hansom (2011), Hansom et al. (2014), Owens (1994), and Shaw et al. (1998). Detailed regional studies have included Barrie et al. (1978), Dowdeswell and Andrews (1985), Martini and Morrison (2014), and Taylor (1980a). In this section, we provide a brief overview of coastal geomorphology and stability in various sub-regions of the IRIS 2 region.

8.3.1 Ellesmere and Axel Heiberg, northern and eastern Devon Island

This region includes the hamlet of Grise Fiord (Ausuittuq), the Canadian Forces base at Alert, and a research, monitoring, and logistical base at Eureka, all on Ellesmere Island, as well as a number of historical sites. It also includes Quttinirpaaq National Park. The Arctic Ocean coast and northern inter-island channels are microtidal, while much of the rest of the region more open to Baffin Bay is mesotidal; macrotidal conditions occur on the central east coast of Ellesmere Island facing Kane Basin and Smith Sound and in a small area of Jones Sound west of Grise Fiord (Figure 4). Except for extreme southeastern Ellesmere Island and eastern Devon Island, which border on the North Water Polynya, the region has very short or absent open-water season (Figure 6).

The coast of Ellesmere Island comprises four distinct sectors: (1) exposed, moderate to high-relief mixed rock and sedimentary shores in the southeast facing onto northern

Baffin Bay and Jones Sound; (2) the less exposed and fiord-indented coast along Nares Strait, Kane Basin, and Smith Sound; (3) the indented Arctic Ocean coast along which once-extensive ice shelves are rapidly disappearing, exposing new shorelines for the first time in millennia; and (4) the sheltered mountain, fiord, and lowland western shores of the island.

The coast of Axel Heiberg Island has similar relief but has not been mapped in any detail. On the south side of Jones Sound, central Devon Island is a largely ice-free dissected plateau and the Devon Ice Cap covers most of the east end of the island, which forms part of the Churchill Province. These islands (Ellesmere, Axel Heiberg, and Devon) discharge approximately 2.6 billion tonnes/year of glacial ice to the ocean, while the output from Baffin and Bylot amounts to 0.26 billion tonnes (Ford et al. 2016, Gardner et al. 2011, van Wychen et al. 2014).

Apart from work on the northern ice shelves (e.g., Copland et al. 2007, 2017, Mueller et al. 2008, Vincent et al. 2001, White et al. 2015) and some work on tidewater glaciers on Devon Island (Bachelors et al. 2016, Burgess et al. 2005, Taylor and Frobel 1984), there has been relatively little study of coastal morphology and processes in this region. Blake (1970, 1975) reported in detail on a raised beach sequence at Cape Storm on the south coast of Ellesmere Island (Jones Sound). Blake (1975) also described the ice-foot that develops each winter and persists though most of the summer, and illustrated a case in which an exceptionally high tide breached the barrier and inundated the icefoot to a depth of 0.5 m in late July 1970. Taylor (1978b) reported on a detailed study of Makinson Inlet, a large fiord on the east coast of Ellesmere south of Smith Sound. The main stem of Makinson Inlet reaches 96 km inland. It is bounded in part by up to 1000 m high talus-banked rock cliffs interspersed with numerous tidewater and land-terminating glaciers emanating from the Inglefield Mountains and Prince of Wales Ice Cap on the north and extensive ice on the peninsula to the south. A shorter southwest arm extends into dissected plateau terrain with several large deltas and raised beaches.

Much of the south coast of Jones Sound on eastern Devon Island is characterized by steep, talus-banked, rock cliffs 300-480 m high, interspersed with tidewater glaciers. The latter occupy some 30% of the coastline east of Brae Bay, where the Sverdrup Glacier is the westernmost outlet glacier from the Devon Ice Cap that descends to tidewater (Taylor and Frobel 1984). West of Brae Bay, a succession of narrow coastal lowlands occurs over 50 km west to Sverdrup Inlet.

8.3.2 Northwestern Canadian Arctic Archipelago

There are no permanent settlements in this area, but it was a region of extensive oil and gas exploration by Panarctic Oil beginning in the late 1960s, with production and shipping of oil from Bent Horn (Cameron Island) from 1985 to 1996. There were major camps at Rae Point and Drake Point on Melville Island and a number of onshore and offshore well sites. The former weather station of Isachsen is located on Ellef Ringnes Island.

This region includes mostly sedimentary and well-lithified rocks of the Parry Island Fold Belt on Bathurst, Byam Martin, and Melville islands in the south, and softer sedimentary units of the Sverdrup Lowland to the north. The entire region has minimal tides (<0.5 m), a low incidence of storms, and very low to absent wave energy because sea ice remains in place for most or all of the year (Figure 6).

Along the southeast coast of Melville Island and the west side of Byam Martin opposite, McLaren (1982) distinguished three shore types: deltas, sandflats, and gravel beaches. Braided streams draining parts of the Parry Island Fold Belt deposit sandy deltas at the present coast. Sub-ice currents and occasional wind-driven waves and currents redistribute the sand to form a thin nearshore veneer out to 7 m water depth. Sand is also transported to adjacent coastal segments, where it accumulates to form the very low-angle foreshore of the sandflat coast. The gravel beach coasts occur where sand is scarce. Ice scour moves sediment onshore to form thin, steep ($>8^\circ$), gravel beaches and small storm ridges are formed when locally forced

waves develop in the short open-water season. The gravel is derived in part from winnowing of ice-scoured glacial-marine sediments and in part from erosion of local bedrock in the nearshore and foreshore (Taylor and McCann 1983). Flights of isostatically raised gravel beaches in this area rise to about 30 m above present sea level.

North of the fold belt, the poorly or non-lithified sediments of the Sverdrup Basin occur on Melville (Sabine Peninsula), Loughed, Mackenzie King, King Christian, Ellef and Amund Ringnes, Cornwall, and other islands. In this region of very subdued relief, there is little gravel and the shore-zone is characterized by sand or mud (Owens et al. 1981). Sea-ice cover is almost perennial in the inter-island channels, with very limited open water in shore and flaw leads. As a result, wave action is minimal to absent and coastal reworking is ice-dominated (Forbes and Taylor 1994, Taylor 1980a, Taylor and Forbes 1987, Taylor and McCann 1983). Four distinct shore types can be recognized: deltas, sandflats, partially vegetated (low-energy) mudflats, and ice-scarred mud shores.

Terraced finger deltas have developed in the absence of wave reworking, projecting as much as 4 km offshore (Figure 12; Forbes et al. 1986). Stream incision under forced regression (uplift and falling sea level), limited by ice-bonded sediments in the channels and banks, leads to self-confinement, which promotes the seaward extension of the delta. The formation of individual terraces appears to be controlled by channel diversion on the active delta fan, influenced by the formation of ice-pushed ridges, which help to define the shape of the terrace edges (Figure 12). The sandflat shore type is widespread and characterized by small swash bars or subtle berms up to 0.5 m high, incised by rill drainage across the low-angle backshore, with ice-bonded sediments at shallow depth and anchor ice underlying foreshore deposits near the water line (Taylor and Forbes 1987). The vegetated mudflat shores occur in the most sheltered locations on finer-grained formations and where the nearshore slope is so shallow that ice grounds offshore and cannot ride up. They are characterized by algal mats, with sparse, salt-tolerant grass and carpets of moss in the backshore, and show almost no morphological

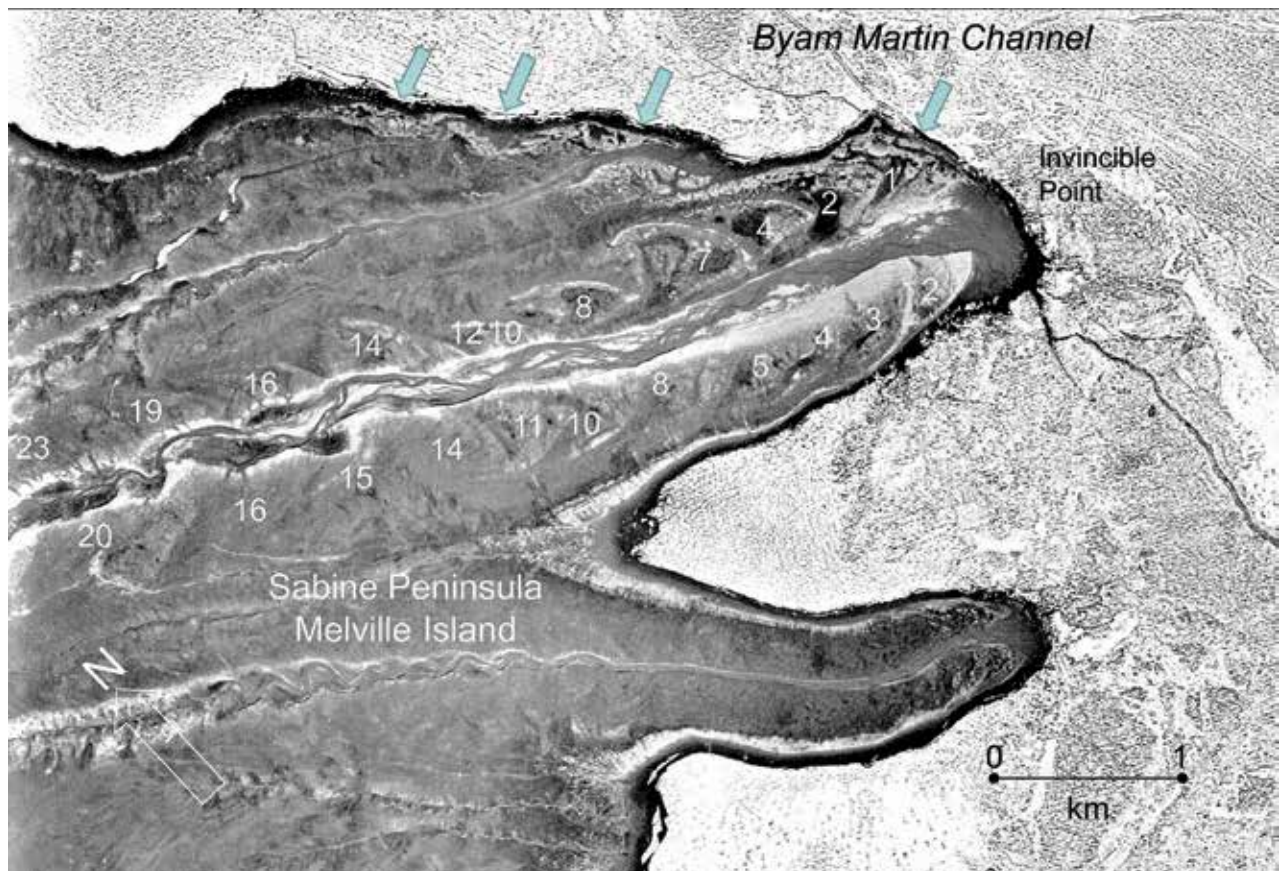


FIGURE 12. Terraced finger deltas on east coast of Sabine Peninsula, Melville Island, detail from 1959 airphoto A16764-2 © HM the Queen in Right of Canada (Natural Resources Canada); terrace elevations in metres above present sea level reveal a history of falling relative sea level in this area (Forbes et al. 1986). Note predominant orientation of ice pressure (blue arrows) and better defined terrace edges facing that way.

expression of the shoreline (Forbes and Taylor 1994). Where muddy sediments occur along coasts with steeper nearshore bathymetry, sea ice moving onshore creates chaotically scarred foreshore and backshore mounds, pits, and ridges, indicating that any infrastructure placed along such shorelines would be subject to severe ice hazards (see Chapter 1; Figure 7d). Whereas the scarred morphology is preserved on ice-bound shores of the Sverdrup Lowland, ice deformation of beaches in other areas is largely erased by waves (St-Hilaire-Gravel et al. 2010, 2012, 2015). Along many of the coasts of the CAA, but especially in the northwest, very large pile-up ice ridges line the nearshore and persist throughout the summer months (Taylor et al. 2011, Taylor 1978a).

8.3.3 Barrow Strait, Lancaster Sound, and Eclipse Sound

The coasts of this region, particularly those fronting on Barrow Strait and Lancaster Sound, have attracted a number of research projects over many years. This was helped by the establishment of the Polar Continental Shelf Project base at Resolute in the 1960s. Besides Resolute Bay (Qausuittuq), other communities in this area include Arctic Bay (Ikpiarjuk) and Pond Inlet (Mittimatalik), as well as the former mine and town site of Nanisivik. Baffinland Iron Mines Corp. operates a port at Milne Inlet for shipment of ore from the Mary River mine. Besides a number of historic sites, the area includes two national parks:

Qausuittuq on Bathurst Island and Sirmilik on northern Baffin and Bylot.

Early work was focused in the Radstock Bay area of south-western Devon Island (McCann and Owens 1969, 1970, McCann and Taylor 1975, Owens and McCann 1970) and along the north coast of Somerset Island (e.g., Taylor 1975, 1978a, 1980b). The northern coast of Bylot Island provided insights into ice interaction with exposed beaches under storm conditions in northern Baffin Bay (Taylor 1981). More detailed work was undertaken on a number of small beaches in Eclipse Sound in connection with oil-spill studies in the 1980s (Sempels 1987). Over the past 15 years, largely with support from the Geological Survey of Canada and ArcticNet, coastal monitoring and process studies have been directed to the coasts of Cornwallis, Griffiths, and Lowther islands in the west (St-Hilaire-Gravel et al. 2010, 2012, Taylor and Frobel 2006) and northern Baffin Island in the east (St-Hilaire-Gravel et al. 2015) as well as continued monitoring of sites on northern and eastern Bylot Island and northeastern Baffin Island, including Pond Inlet in Eclipse Sound (Figure 2d; Taylor and Frobel 2006, Taylor and St-Hilaire-Gravel 2013).

Bylot Island and Eclipse Sound lie within the Churchill Province of the Canadian Shield (see Chapter 1; Figure 6), most of Lancaster Sound and Barrow Strait fall within the Arctic Plateau province. Prominent rock cliffs fringe many of the larger islands (see Chapter 1; Figure 7a) and smaller islands such as Prince Leopold and Lowther, which has one short section of high cliffs (see Chapter 1; Figure 7b). In embayments between the cliffs and on lower-relief coasts, beaches are well developed, predominantly gravel, and in most areas backed by sequences of raised beach ridges rising to the postglacial marine limit (see Chapter 1; Figure 7c). Locally, where less resistant rocks are exposed, as in the Peel Sound lowland west of Cape Anne (northern Somerset Island), sand can predominate (Taylor and Frobel 2006). Sandy beaches with minor gravel also occur in more protected settings, such as at Pond Inlet (Figure 2d).

In the absence of active wave and sediment transport processes reworking the modern beach, glacial isostatic uplift

and emergence will cause a seaward migration of the shoreline. The ubiquitous flights of raised beaches attest to this dominant trend on most emergent or formerly emergent coasts in the region. Coastal progradation can be further enhanced by landward ice push feeding nearshore sediment to the beach, or even leading to the formation of shoals, which can then be reworked by waves and may initiate new barrier islands or beaches separated from the previous beach by shallow lagoons (Figure 13; Taylor and Frobel 2006). Over several years of beach monitoring at Sight Point and in Allen Bay at Resolute, waves reworked the ice-push features each summer and the beaches responded to storm events, but the dominant long-term trend was slow progradation resulting from a combination of emergence and longshore sediment transport (St-Hilaire-Gravel et al. 2012).



FIGURE 13. New island ~800m long and 100 m wide, formed by ice push approximately 500 m off the lowland coast of north-central Somerset Island, just east of Irvine Bay, August 2005. From Taylor and Frobel (2006).

At the eastern end of Lancaster Sound, including Bylot Island, eastern Devon Island, and northeastern Baffin extending as far west as Admiralty Inlet, postglacial isostatic subsidence has resulted in rising relative sea level (see zero isobase in Figure 10). This enables the formation of transgressive gravel barriers backed by lagoons or low backshore, migrating landward with rising sea level (Figure 14). Over time, beach reorientation can occur, with erosion at one end and progradation at the other, as observed at Bathurst Bay on Bylot Island (Taylor and St-Hilaire-Gravel 2013). However, where sediment supply is abundant, beach progradation can occur in spite of rising sea level, as on the Cape Charles Yorke foreland on northernmost Baffin Island (St-Hilaire-Gravel et al. 2015). Here initial postglacial emergence, documented by raised beaches, was followed by a shallow lowstand and then a lengthy period of sedimentation under rising relative sea level to build a beach-ridge sequence with crest elevations rising seaward (Figure 15).



FIGURE 14. Barrier beach and lagoon across front of proglacial outwash plain sourced from Glacier E67 in the background, northeast coast of Bylot Island, Baffin Bay (Figure 1); Eclipse Sound in left background; trimetrogon airphoto T235L-100, 1947, © HM the Queen in Right of Canada (Natural Resources Canada).



DONALD FORBES

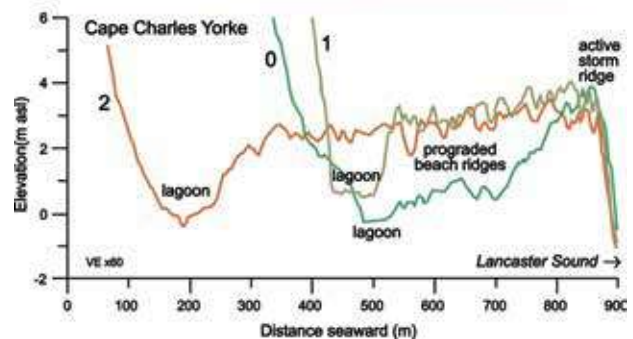


FIGURE 15. Cape Charles Yorke foreland seen from the northeast, August 2009, with three surveyed transects, showing seaward-rising beach-ridge crests (after St-Hilaire-Gravel et al. (2015).

8.3.4 Baffin Island fiords and outer coast

This region, which overlaps in the north with the preceding one, includes a number of coastal settlements on Baffin Bay, Davis Strait, and Hudson Strait: Clyde River (Kangiqtugaapik), Qikiqtarjuaq, Pangnirtung (Pannirtuq), Iqaluit, Kimmirut, and Cape Dorset (Kingnait). There are several North Warning stations, including Kangok Fiord, Cape Hooper, Broughton Island, Cape Dyer, Cape Mercy, Brevoort Island, Loks Land, and Resolution Island, off the mouth of Frobisher Bay. Auyuittuq National Park is located on the Cumberland Peninsula between Pangnirtung and Qikiqtarjuaq. Most of the northeast coast of Baffin Island is microtidal, but the tidal range increases southward around the Cumberland Peninsula to extreme macrotidal in Frobisher Bay and Hudson Strait (Figure 4). While much of the indented coast is fetch-limited in protected embayments, strong winds and local waves can develop in fiords

and the outer coast is exposed to virtually unlimited fetch in Baffin Bay or the Labrador Sea during the open-water season, when heavy Atlantic swell can propagate through Davis Strait into Baffin Bay. The southward current along the Baffin coast carries large volumes of icebergs into the Atlantic from calving ice fronts and ice shelves in Canada and Greenland (e.g., Williamson et al. 2008).

The highly indented fiord coast of Baffin Island has high relief above and below water. Dowdeswell and Andrews (1985) identified 227 fiords longer than 5 km on Baffin Island, excluding the largest bays and sounds such as Eclipse Sound, Cumberland Sound, and Frobisher Bay. They measured 29 dimensional and shape parameters (mean \pm standard deviation [range]), including:

- fiord length: 27.9 ± 24.7 [5-121] km
- fiord mouth width: 6.5 ± 5.8 [1-39] km
- fiord mid width: 2.5 ± 1.4 [0.4-8] km
- fiord surface area: 105 ± 158 [3-953] km²
- maximum adjacent elevation: 787 ± 396 [229-1905] m.

They documented a maximum depth of 950 m (mean 330 m), based on data from 44 fiords predating the advent of multibeam mapping, and recognized that this underestimates the depth of glacial erosion to bedrock, as most fiords contain thick sequences of ice contact, glacial marine, and postglacial sediment (e.g., Syvitski and Hein 1991). In many but not all cases, the deepest part of the fiord is close to the location of maximum sidewall elevation (Løken and Hodgson 1971). For the full sample of 227 fiords, 'fiord density' (the number fiords within 50 km along the coast on either side, is 4.7 ± 2.5 [0-12]). The largest embayments on Baffin Island are at least in part structurally controlled (e.g., Frobisher Bay and Cumberland Sound are half grabens with fault control on south and north sides, respectively), but multibeam mapping shows evidence of glacial scour and presumably additional deepening (e.g., Dowdeswell et al. 2016a,b).

Proglacial or paraglacial outwash (sandur) plains and deltas are present at the heads of most fiords (e.g., Figure 2c),

incised into terraces of earlier proglacial deltas. In the outer Cumberland Peninsula, where sea level was lower than present, submerged proglacial delta terraces are found in the heads of many fiords. The fiord floor basins are relatively flat and flanked by steep slopes with basal debris cones formed by rockfall, debris flows, and slides, many originating higher up on the valley wall above present sea level (Figure 16).

The south end of Baffin Island (Hall Peninsula and Meta Incognita Peninsula) has lower relief than further north. Frobisher Bay is a structural basin overdeepened by glaciation (Hodgson 2005). It has an irregular and highly indented shoreline. Several islands sit astride the bay near its midpoint, separating the inner basin on which Iqaluit is located from the outer bay. These provide protection from Atlantic swell and reduce the risk of storm surge. The tide is semidiurnal with a range of 11.1 m at springs (7.8 m mean tide) and a maximum recorded range of 12.6 m (CHS 2001). The twice-daily rise and fall of the tide has important implications for sediment transport, ice formation and stability, and coastal hazards.

The surficial geology in the vicinity of Iqaluit includes wave-washed, glacially scoured monzogranite, a discontinuous till blanket or veneer, and proglacial outwash deposits, including raised delta terraces located at the head of the inlet underlying the airport and at Apex (Allard et al. 2012). Very extensive boulder-strewn tidal flats have accumulated in shallow embayments around inner Frobisher Bay. Sand and mixed sand-gravel beaches have developed at the high-tide line in exposed locations (Figure 17), attesting to occasional high-energy waves reaching the high-tide line and above. The tidal flats in Koojesse Inlet at Iqaluit are the best studied example (e.g., Dale et al. 2002, Hatcher and Forbes 2015, Hatcher et al. 2014, McCann et al. 1981). These flats appear to have formed under falling relative sea level by progressive erosion of underlying, stiff, proglacial muds and winnowing of coarse material to produce a thin veneer of sand, gravel, and boulders (Hatcher 2013). Glacial marine muds are also present on the seafloor in the inner bay, where they are involved in several hundred submarine slope failures (Mate et al. 2015).

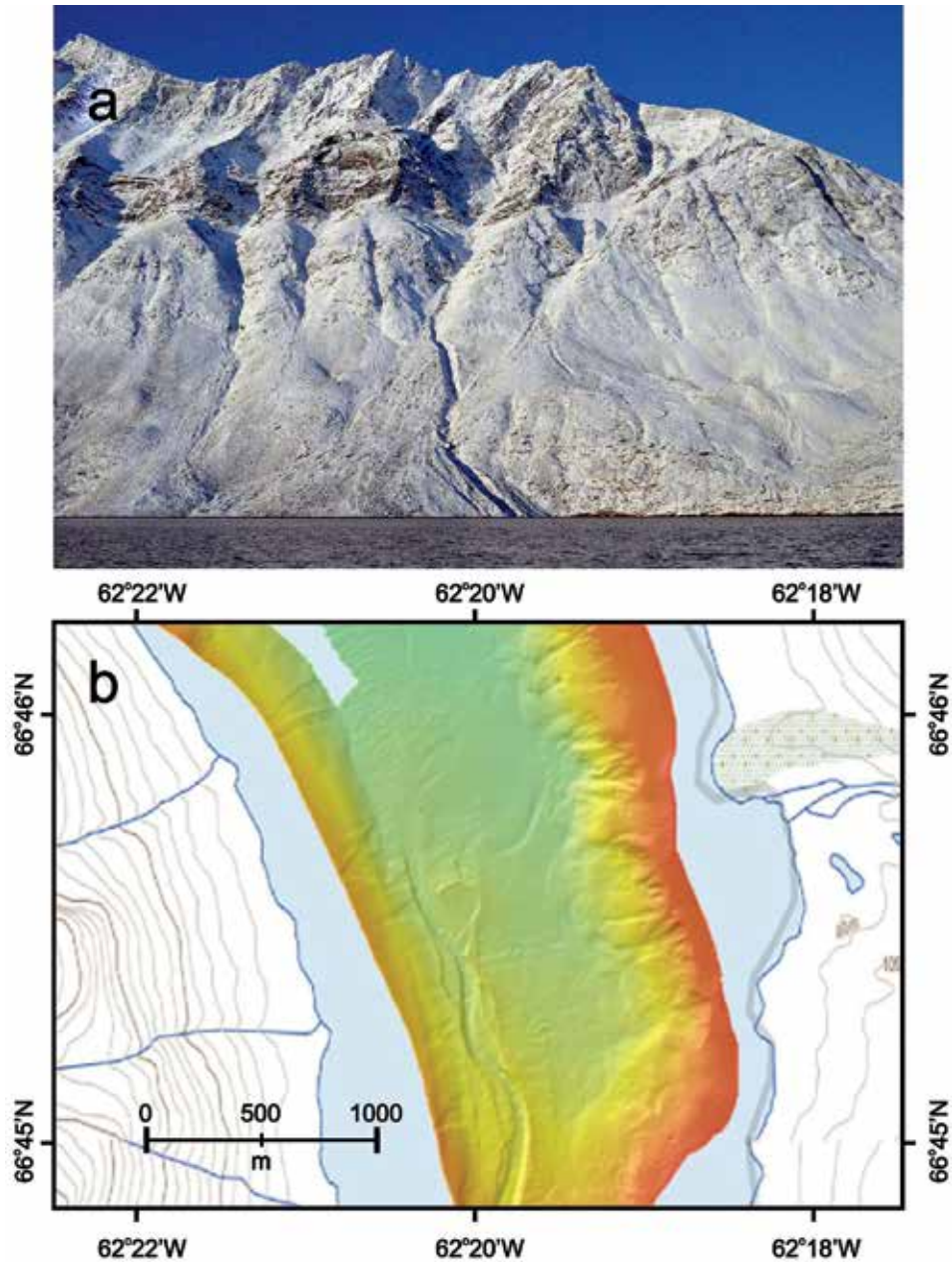


FIGURE 16. (a) Rock cliffs, chutes, and colluvial cones with debris flow channels on the valley side wall of Mermaid Fiord, Baffin Island, October 2012 (DLF). (b) Multibeam imagery of inner basin ~130 m deep near the head of Southwind Fiord, Baffin Island. After cruise report appendix in Cowan (2015). Note numerous slide scars and debris cones, as well as axial channel emanating from the fiord head.

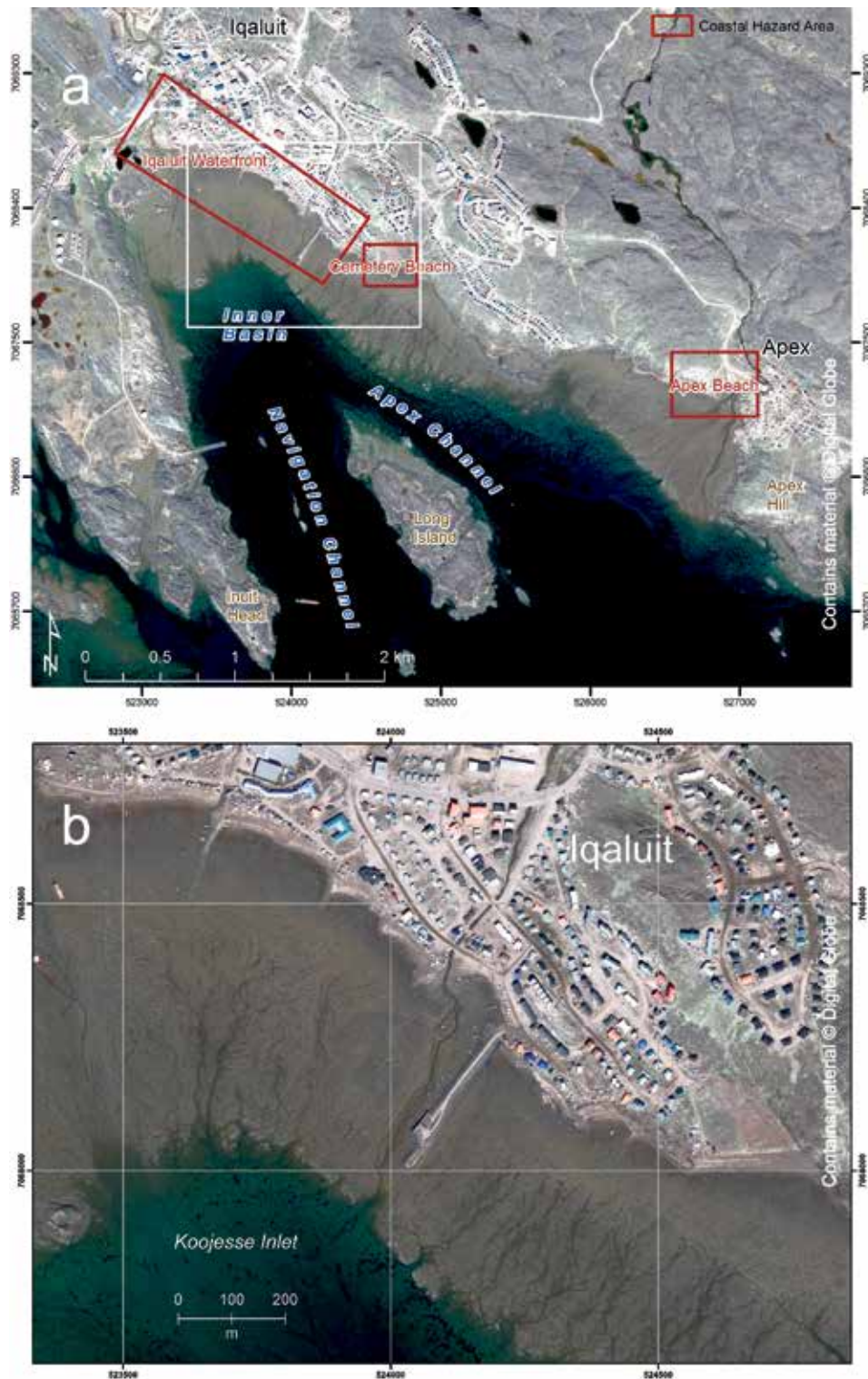


FIGURE 17. (a) Koojesse Inlet at Iqaluit, NU, showing boulder-strewn tidal flats at mid-tide. Red boxes delineate areas of the waterfront in which important infrastructure or cultural heritage resources are at risk of flooding (Hatcher and Forbes 2015); white box shows location of Figure 16b. (b) Detail of waterfront in downtown Iqaluit, showing extensive bouldery tidal flats, tidal drainage network, and high-tide beaches realigned by groynes.

Flooding of the Iqaluit waterfront has occurred twice in recent time under extreme tides, without associated wind events (Hatcher and Forbes 2015). The projections of relative sea-level rise for this site are equivocal, but the range of uncertainty includes a rise of more than 0.7 m from 2010 to 2100 including plausible meltwater contributions from West Antarctica (James et al. 2015). If this occurs, critical infrastructure will have a freeboard of 0.3-0.8 m above high spring tide, putting it at risk of flooding, wave impacts, and ice ride-up (Hatcher and Forbes 2015). The large tidal range, limited fetch, and wide intertidal flats, which dissipate some wave energy by shoaling, limit the potential wave energy at the beach, but observations of large-wave events at high tide by Dale et al. (2002) and more recently in video of a storm in 2010 (D. Mate, pers. comm., 2011), demonstrate that wave hazards do need to be considered.

The tidal range diminishes northward along the Baffin coast, to about 7 m large tide in Cumberland Sound (including Pangnirtung), 1.6 m at Qikiqtarjuaq, and 1.2 m at Clyde River, before increasing again to 2.3 m in Milne Inlet (Eclipse Sound) (CHS 2001). A well-developed boulder barricade is present at Pangnirtung (Forbes and Hansom 2011, Forbes and Taylor 1994, Gilbert and Aitken 1981, McCann et al. 1981). Assuming that relative sea level previously dropped below present and has since been rising again, Gilbert and Aitken (1981) postulated the existence of a buried boulder barricade below the present-day flats. McCann et al. (1981) distinguished sediment-starved conditions at Iqaluit (excluding the Apex River fan) from the setting with ongoing sediment supply at Pangnirtung. By contrast, at Qikiqtarjuaq, where the tidal range is currently 1.6 m and no modern boulder barricade is present, a submerged boulder ridge is interpreted as a relict boulder barricade 16 m below present sea level, in front of the proposed large-vessel wharf (Cowan 2015). Former shoreline features, including proglacial deltas, beaches, and spits are found at varying present water depths down to about 50 m below present sea level east of Qikiqtarjuaq on the outer Cumberland Peninsula (Cowan 2015, Hughes et al. 2015). If the tidal range has diminished over time, this may be a factor, although both relict and active modern boulder barricades, albeit small and subtle, have been observed

in Patricia Bay at Clyde River (Figure 18), where the tidal range is even smaller (Forbes and Manson 2012). Here, shallow submerged delta and nearshore terraces show that relative sea level was slightly lower in the late Holocene, has risen since then and may still be rising slowly, although proximity to the Greenland Ice Sheet and elastic response to ablation of the Barnes Ice Cap and Baffin mountain glaciers may counteract that.

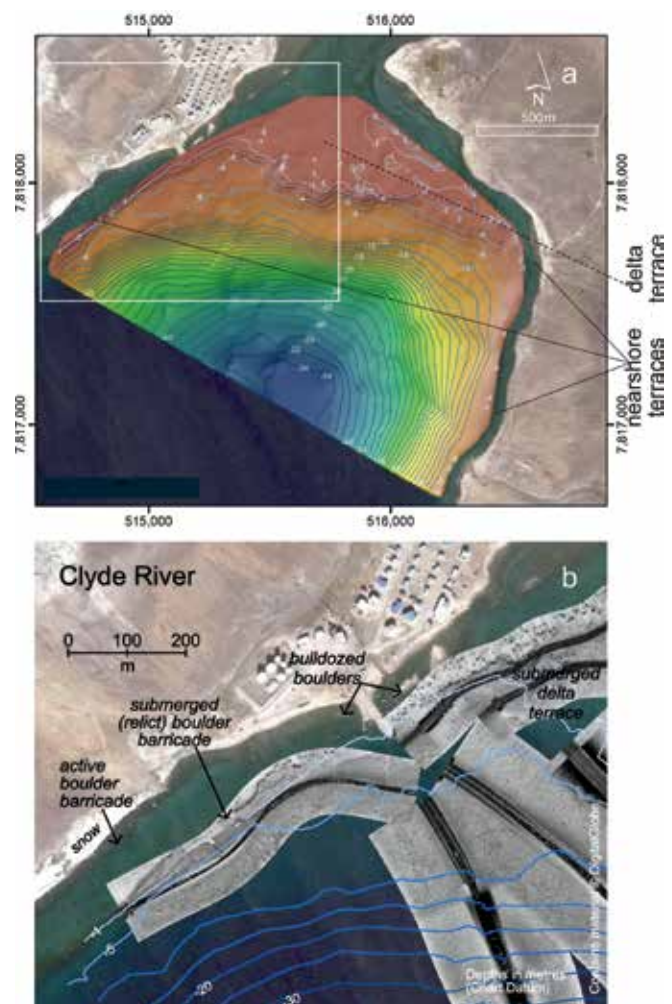


FIGURE 18. (a) Bathymetry in the river mouth at the head of Patricia Bay, Clyde River, showing submerged delta and nearshore terraces (Forbes and Manson 2012). (b) Sidescan sonar mosaic of the area in the box above, showing relict (submerged) and small active boulder barricade in a microtidal setting.

Although gravel beaches are common on the outer Baffin coast, local sources of sandy outwash deposits can feed extensive sand beaches, locally with placer concentrations of garnet or magnetite (Forbes and Hansom 2011). Well-developed sandy beaches are also found locally in fiord-margin embayments in Clyde Inlet and Inugsuin Fiord (Figure 2b). North of Clyde River, sediments of the Clyde foreland are exposed in coastal cliffs 8-35 m (typically 10-20 m) high extending for 35 km along the coast north of Cape Christian (Figure 19a; Miller and Andrews 1977). Southward longshore transport of sand from these cliffs fully exposed to Baffin Bay has fed broad and gently-sloping sandy active and raised beaches with a partial cover of aeolian sand on the outer coast near Clyde River (Figure 19b,c,d).

The south coast of Baffin Island along Hudson Strait has postglacial raised deltas at the mouths of some rivers in coastal embayments (Hodgson 2005), but is mostly rocky, irregular, and rugged (Shaw et al. 1998).

8.3.5 Foxe Basin

There are two coastal settlements in the northwest corner of Foxe Basin: Igloolik (Iglulik) and Hall Beach (Sanirajak). In addition, there are several former DEW Line sites, now part of the North Warning system, on or near the coast at Hall Beach, Rowley Island, Bray Island, and Longstaff Bluff (Baffin Island).

Foxe Basin is underlain by flat-lying carbonate sedimentary rocks forming part of the Arctic Platform (see Chapter 1;



FIGURE 19. (a) Cliffs in unlithified glacial and interglacial sediments north of Cape Christian, outer coast near Clyde River, Baffin Island, NU, August 2007 (DLF). (b) Icebergs off the sandy beach at south end of cliff exposures, Cape Christian, August 2008 (GKM). (c) Stream-cut section in sandy berm on beach at Cape Christian, August 2007 (DLF). (d) Heavy-mineral sorting in swash deposits in berm-cut shown in adjacent photo (DLF).

Figure 6). Large parts of the basin are characterized by lowland limestone coasts (much of the east coast of Melville Peninsula, the Baird Peninsula on Baffin Island, and almost all the islands: Jens Munk, Koch, Rowley, Bray, Foley, Prince Charles, and Air Force). The southern and northernmost Melville Peninsula coasts, including Fury and Hecla Strait, are developed in moderate relief rocks of the Churchill Province, as is much of the west coast of Baffin Island, where the relief is lower and the glacial signature is more prominent (King and Buckley 1967, Martini and Morrison 2014). The Quaternary surficial cover is very thin, so that bedrock is everywhere very close to the surface. Foxe Basin is a former glacial ice centre and is therefore subject to rapid isostatic rebound. This has been ongoing for the past 5000-7000 years and has led to emergence of the postglacial marine limit to elevations of about 80-160 m above present sea level (Figure 10; Dredge 1991, 1995).

Relative sea-level projections for Igloolik, in the northwest corner of the basin, indicate that this coast will remain emergent through to the end of this century, even with the most extreme of the scenarios (Figure 11; James et al. 2015). The 95th percentile for RCP8.5 would see 26 cm relative sea-level fall from 2010 to 2100 (the projected drop in sea level for the median value of RCP4.5 over the same time interval is 75 cm). Thus, ongoing rapid emergence and the formation of new gravel beach ridges is to be expected.

Martini and Morrison (2014) distinguished three distinct shore types in Foxe Basin:

- erosional rocky coasts with pocket gravel beaches, bouldery ice-push ridges, and mixed sand-gravel beaches;
- coasts dominated by active and emerged gravel beach ridges;
- low-energy muddy coasts on wide coastal plains and very low-energy embayments.

The first shore type is associated with low- to moderate-relief coasts of northern and eastern Foxe Basin with resistant rocks. These shores are exposed both to direct ice impacts and variable open-water fetch enabling some wave reworking of sand and gravel beaches.

The lowland carbonate shores of the central, northwestern, and southeastern basin are characterized by a multiplicity of well-formed active and emergent gravel beach ridges, interrupted locally by steeper, slightly scarped shores, or muds on very low-angle coastal plains (primarily in the southeast). The beach ridges form striking successions of pebble-cobble gravel with intervening organic silts in troughs between the ridges. The sediment cover, including bouldery till and pockets of marine mud or sand, is generally thin. The width and height of the beach ridges reflect local wave energy (storm climate and ice conditions) at various times in the past (St-Hilaire-Gravel et al. 2010), while a long-term progressive reduction in ridge height in some areas may be related in part to progressive reduction of potential fetch as isostatic rebound creates new sheltering islands (King 1969, Martini and Morrison 2014).

Carbonate rock is exposed in occasional backshore scarps or in the foreshore. Frost shattering of emergent limestone or dolomite in the shore zone is the predominant sediment source for the gravel storm ridges (Dredge 1992, Hansom et al. 2014, cf. Taylor 1980b). In some areas, there is more sand, largely derived from the till, and beach sand can accumulate in the foreshore, while longshore transport by waves can move sand into shoaling embayments, as at Hall Beach.

Even in areas of rapid emergence, limited coastal erosion can form low (1-2 m) scarps in carbonate rock or till. These localized erosional zones may result from one or more interrelated causes:

- changing wave refraction patterns, as the bathymetry progressively changes under falling sea level;
- variable beach width and longshore migration of gravel creating local zones of sediment deficit that promote shore erosion; or
- growth of sinuosity (cell formation) on drift-aligned portions of the shore.

An erosion problem threatening a number of shore-front homes at Hall Beach shows elements of all three processes, but notably involves the longshore migration of gravel

over several decades (Figure 20; Forbes and Manson 2012, Manson and Forbes 2008).

Low-energy muddy coasts occur in meso- to macrotidal embayments of emerging islands or the vast, almost flat, emerging lowlands in the southeast (Martini and Morrison 2014). They may take the form of intertidal flats on islands in the central bay or of vast tidal flats, several kilometres wide, fringing the Great Plain of the Koukdjuak. In both cases, they are subject to ice-rafting, which introduces some gravel and boulders, and the upper intertidal supports

algal growth which is intermixed with or gives way landward to patchy *Puccinellia phryganodes*, grading landward into wet sedge (*Carex* sp.) meadows and moss-, forb-, and grass-dominated tundra (Martini and Morrison 2014).

8.3.6 West coast of Hudson Bay in Kivalliq

The Kivalliq coast of Hudson Bay includes several large and small communities: Arviat, Whale Cove (Tikirarjuaq), Rankin Inlet (Kangiqtiniq), Chesterfield Inlet (Igluligaarjuk), Baker Lake (Qamani'tuaq) [inland],

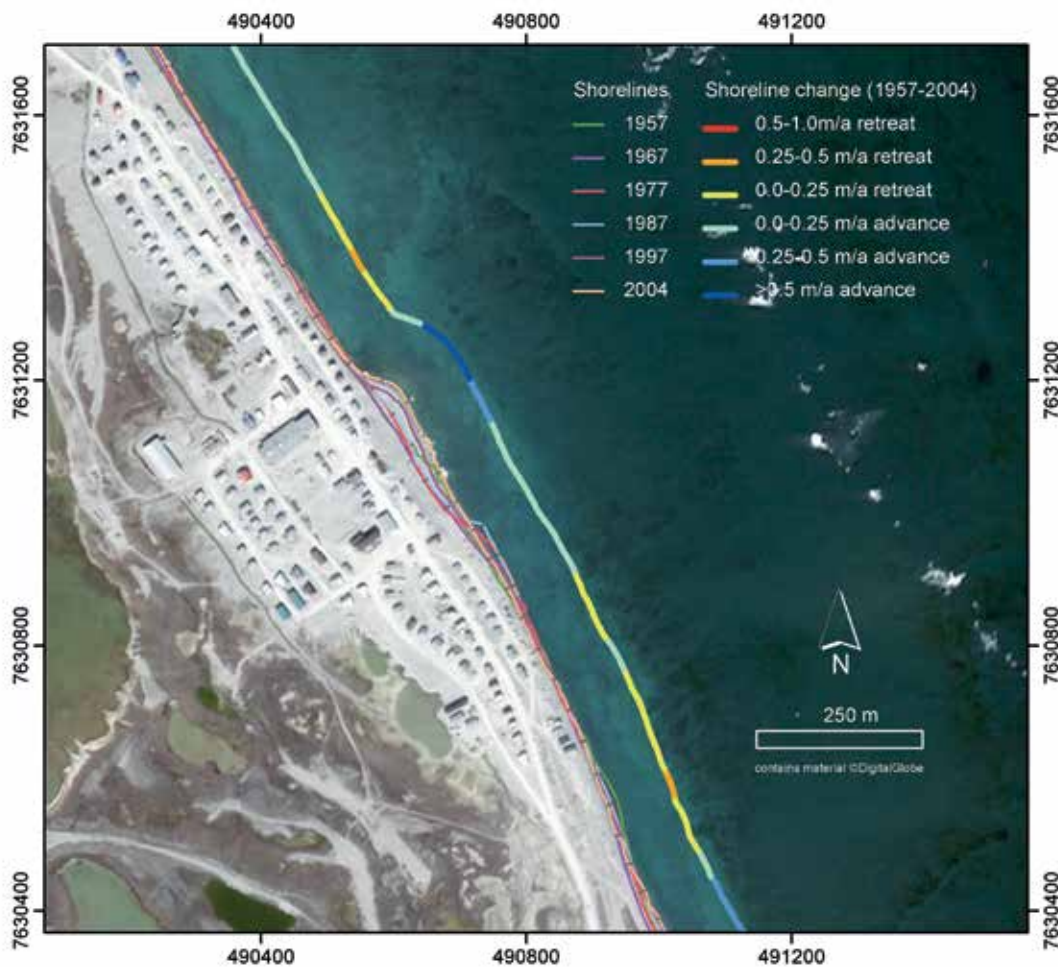


FIGURE 20. Shoreline time series and retreat/advance rates over almost 50 years (1957-2004) in the central part of the Hamlet of Hall Beach on Foxe Basin. Data derived from decadal repeat aerial photography 1957-1997 and QuickBird satellite imagery from 2004. A small gravel foreland located at the mid-point of the image until the 1980s moved abruptly north to its present position, where an erosional hotspot developed, threatening a number of houses.

Naujaat, and Coral Harbour (Salliq) on Southampton Island. The entire mainland is macrotidal, with extreme macrotidal conditions on the west side of Southampton island (Figure 4). The southeast part of the island and Coats and Mansel islands are mesotidal. The entire region is emergent (Figures 10, 11), with progressively shallower nearshore waters creating hazards for navigation and complicating sealift deliveries.

The Hudson Bay coast can be subdivided into three regions. All lie on resistant shield rocks of the Churchill Province (see Chapter 1; Figure 6) but the coastal morphology is largely a product of the sediment cover and the landform legacy of glaciation. The southern region from Arviat to

the Manitoba border and beyond is characterized by broad tidal flats grading landward into poorly defined shore-parallel beach ridges with progressively thicker peat cover landward as the age since emergence increases. The peat-covered emergent shorelines on the south side of Arviat are typical of this subregion (Figure 21a; Forbes et al. 2014). From Arviat to Whale Cove, the coast is highly indented with long narrow peninsulas formed by emergent eskers or glacial fluting, extending several kilometres into Hudson Bay (Figure 21b, d). In places the shoreline pattern is further complicated by De Geer or other recessional moraines normal to the grain of the promontories (Figure 21c). From Whale Cove north, the surficial cover is more limited, with increasing proportions of rock outcrop in the shore-zone



FIGURE 21. (a) Hudson Bay tidal flats backed by peatland, looking south from Arviat, NU. (b) Community of Arviat, looking east over peninsula defined by two emerged eskers, the northern one of which underlies the urban core in the foreground. (c) North-south oriented recessional moraines flanking an west-east oriented esker ridge just north of Arviat. (d) Indented coast in glacially fluted terrain 20 km west of Whale Cove, west coast of Hudson Bay between Arviat and Rankin Inlet. All photos July 2009 (DLF).

(Hansom et al. 2014) and gravel shores are found in pocket beaches (Allard et al. 2014). The relief is higher north of Chesterfield Inlet, where the indented coast is predominantly resistant rock (Shaw et al. 1998). On the west coast of Southampton Island opposite, the tidal flats are up to 6 km wide (Dunbar and Greenaway 1956). Southern and western Southampton Island, Coats Island, and Mansel Island are underlain by Paleozoic rocks of the Hudson Bay Platform (see Chapter 1; Figure 6), and have low relief with continuous beaches and raised beach ridges. Precambrian rocks of the Churchill Province form 200 m high cliffs on northeastern Coats Island and higher relief on northern Southampton Island (Shaw et al. 1998).

The eskers in the Arviat area provide sound foundation sites, convenient road bases, and large volumes of aggregate for gravel pads and other infrastructure projects (Forbes et al. 2014). Large coastal dunes have developed on the esker adjacent to sandy tidal flats on the south side of Arviat. Permafrost and ground ice development are highly variable and evolving as new land emerges from the sea to be freshly exposed to the cold atmospheric climate. Ground freezing and segregated ice formation are strongly influenced by the grain size and permeability of surficial deposits, and associated drainage conditions. Decreasing sea-ice duration and rapidly falling sea levels in this region complicate projections of coastal change and the planning of coastal infrastructure. Despite the rapid coastal emergence, localized erosion does occur (as in Foxe Basin) and has affected road access at the outer point in Arviat, but the probability of runup to any given level decreases rapidly with falling sea level, even with shorter sea-ice duration and more open water in Hudson Bay. As a result, any erosion problems should be short-lived. On the other hand, the falling sea level has converted shallow passages behind islands to dry land in living local memory, requiring more lengthy and exposed boat routes to sites along the coast to the north of Arviat. The falling sea level makes coastal shoals progressively shallower over time, affecting ship access, and can strand wharves and other coastal infrastructure, requiring progressive lengthening or replacement (Allard et al. 2014).

8.4 The Eastern Canadian Arctic coast in a warming climate

Evidence of a warming climate is already abundant on northern coasts, where break-up is occurring earlier, freeze-up is coming later, landfast ice is less reliable, higher runup and flooding are encountered in some places, and the once-extensive ice shelves of northern Ellesmere Island (90 000 km² in 1906) have declined precipitously to only 5% of their former extent (Copland et al. 2017).

A Canada-wide index of coastal sensitivity to climate change has been developed in CanCoast, an initiative of the Geological Survey of Canada, building on an earlier analysis of coastal sensitivity to sea-level rise (Shaw et al. 1998). This shows that on a five-point rating system, virtually none of the Eastern Canadian Arctic coast ranks as ‘extremely high’. While several areas rank ‘high’, likely because of a combination of rising relative sea level and high exposure (Baffin coast), high exposure and soft sediments (southwestern Hudson Bay), or the potential for reduced sea ice in an area with high susceptibility to wave reworking (Sverdrup Basin), most of the region’s coast ranks ‘moderate’ or ‘low’ on the CanCoast scale (Atkinson et al. 2016).

The high sensitivity of the low-energy, ice-bound coasts of the Sverdrup Basin, particularly the vulnerability of the finger deltas to the initiation of open-water wave activity, is well understood, but the channels choked with multiyear ice in that region may be among the last to see a significant reduction of sea ice. In addition, apart from past hydrocarbon exploration and production and rare subsistence hunting activity, there would be little human impact of changes in that area. Likewise the loss of ice shelves on the north coast of Ellesmere Island, while catastrophic for the Arctic cryosphere and unique ecosystems dependent on the ice-shelf environment, will have little impact on Nunavut communities.

The extent of changes to be expected in coastal ice remains difficult to project, but we see clear evidence from several parts of the region for a reduced ice season attributable to

earlier onset of spring melt (and eventual partial or full break-up), of later initiation of fall freeze-up, or both (e.g., Ford et al. 2016, Hatcher and Forbes 2015, St-Hilaire-Gravel et al. 2012). Observed changes in the open-water season have occurred over several decades and there is potential for an acceleration of these changes.

As open water becomes more extensive and lasts longer, particularly into the fall storm season when fetch may be near its seasonal maximum, some acceleration of coastal erosion can be expected. Several IRIS 2 communities, including Arctic Bay, Pond Inlet, Clyde River, Hall Beach, and Arviat are known to have erosion issues, but most are minor or reasonably manageable. Processes of rapid, thermo-mechanical erosion of ice-rich sediments, as observed in the Beaufort Sea region and elsewhere, are much less a factor in the Eastern Canadian Arctic. In addition, it is not clear that enhanced erosion is entirely or primarily attributable to climate change in some settings, as exemplified by the roles of beach dynamics or wave refraction and focusing at Hall Beach. Variability in open-water wave energy can influence the size of beach ridges (St-Hilaire-Gravel et al. 2010) and cause short-term erosion of sedimentary coasts (Taylor 1981, Taylor and Froebel 2006, St-Hilaire-Gravel et al. 2015, 2012), but the long-term coastal trend on emergent coasts is seaward migration of the shoreline. The challenge for some Arctic communities such as Resolute and other sites with modest rates of glacial isostatic uplift is the possibility of a shift from falling to rising relative sea level as the rising global mean sea level accelerates through this century.

Changing storm patterns bringing more cyclonic systems further north (Zhang et al. 2004) may bring about changes in prevailing and dominant winds, as reported by Inuit research partners in Hall Beach, and such changes could alter longshore transport patterns in particular situations. Alternatively, rare events from particular sectors may drive changes in beach configuration, such as the jump in location of the small foreland at Hall Beach, which involved northward longshore transport, counter to the prevailing coastal current on the outer shoreface and inner shelf (Figures 5 and 20). Changing bathymetry with rapid

coastal emergence may also have affected wave shoaling and refraction patterns in that area.

Waterfront flooding of homes, offices, and subsistence infrastructure (sheds and other structures) has occurred under storm conditions at Pond Inlet (Taylor and St-Hilaire-Gravel 2013) and without storms at extreme high tides in Iqaluit (Hatcher and Forbes 2015). In the latter case, development had occurred in an area where a pre-development flooding event in 1964 was not considered or remembered. While the likelihood of enhanced flooding at Iqaluit may be low, numerous storage sheds and other structures supporting access to country food are located on the beach crest (Figure 2a), at risk of flooding with today's sea level, and are vulnerable to wave impacts. The uncertainty of the current sea-level projections (Figure 11) suggests the advisability of precautionary planning strategies (Hatcher and Forbes 2015).

An additional coastal hazard with no clear connection to climate change is the risk of tsunami waves from local sources, either submarine slope failures or subaerial landslides running into the water (e.g., Pedersen et al. 2002). The seafloor of inner Frobisher Bay bears the imprint of >250 submarine slope failures, for which there may have been a range of triggers (Deering et al. 2015). The observed failure scars are small enough that they may not pose a hazardous tsunami threat, but a proper risk analysis requires a better understanding of the trigger(s) and the maximum potential displacement volume. Steep fiord walls may pose a more severe threat, highlighted by the 2017 destructive tsunami at Nuugaatsiaq, Greenland (Bessette-Kirton et al. 2017), which took four lives. Rockslides are a known hazard and historical cause of tsunamis and fatalities in other fiord regions, including Chile and Norway (e.g., Blikra et al. 2006, Harbitz et al. 2014, Sepulveda and Serey 2010). Removal of glacial buttressing even thousands of years ago can create instability in fiord walls. Combined with the high seismicity of the Baffin Bay region, this creates a hazard with a potential trigger. The steep rock walls of many Baffin fiords are flanked in places by debris ramps or cones, with the latter in many cases lying beneath high rock chutes and marked by debris flow channels and levees

(Figure 16a). Submarine fiord wall slopes also show evidence of extensive failure (Figure 16b). Destructive tsunami-generating slides are likely to be larger than these features, but the evidence from Greenland, Norway, and Chile demonstrates the need for a more thorough analysis of this hazard in the Baffin region.

8.5 Summary and conclusions

The region is very extensive (3500 km north-south) with a wide spectrum of permafrost and ground ice conditions, sea-ice characteristics and seasonal duration, open-water season, storm climate, fetch and wave energy, tides and currents, coastal materials, and underlying geology. Although the population of the Eastern Canadian Arctic is small relative to southern coasts, the cultural and material dependence of Arctic residents on sea ice and marine resources highlights the importance of the coast for all communities in the region.

8.5.1 Coastal issues

Following are among the issues of most immediate concern to communities:

- Changes and instability of coastal ice conditions, notably the duration, thickness, and reliability of landfast ice for access to country food, particularly marine resources at the floe edge.
- Higher coastal flooding, or enhanced wave runup, affecting waterfront facilities including municipal, commercial, and residential infrastructure, port facilities, subsistence infrastructure, and archaeologically significant sites in areas of present or future sea-level rise.
- Increased coastal erosion rates in areas of stable or rising sea levels, with more open water and wave energy in and close to communities. Unanticipated local shore erosion affecting waterfront infrastructure, even on emergent coasts.
- Coastal ice dynamics, including the risk of more frequent ice ride-up and pile-up as sea ice thins and possibly becomes more mobile.

- Rapidly falling sea levels affecting subsistence boating and navigation for sealift and cruise shipping.
- Stranding of coastal infrastructure in areas of rapid isostatic uplift and falling sea levels (coastal emergence).
- Tsunami risk to coastal communities, particularly in fiords in the high seismicity region of Qikiqtaaluk.

8.5.2 Key findings

- There has been near-complete loss of Ellesmere Island ice shelves and associated ecosystems over the past century, greatly accelerated in recent years.
- Greatest storm activity in the IRIS 2 region is in the Baffin Bay and northern Labrador Sea sector, where the greatest open-water fetch can develop, enabling the generation of large storm waves. There is evidence for an increase in storm activity across the region in the latter part of the 20th century.
- Sea ice serves as seasonal shore protection, but later annual freeze-up leaving more open water during the fall storm season increases the potential for storm wave activity and shore erosion in communities with vulnerable waterfront infrastructure such as Hall Beach, Pond Inlet, Qikiqtarjuaq, and Iqaluit.
- Projections of relative sea-level trends are equivocal in some places such as Iqaluit and Qikiqtarjuaq, but indicate continued sea-level fall in other communities such as Arviat, Rankin Inlet, Hall Beach, and Igloolik, where shoaling affects harbour infrastructure and navigation. The rate of sea-level fall will be reduced with a higher rate of global mean sea-level rise.
- Past flooding events in Iqaluit have resulted from extreme tides without storm activity and have flooded subsistence infrastructure with potential impacts on food security. In principle, these tidal extreme flooding events should be predictable, but absence of a tide gauge in Iqaluit is an impediment.
- Sea ice moving onshore can be a significant hazard, but damaging pile-up in communities, such as occurred in December 2005 in Hall Beach, has not been widely

reported. One might imagine that thinner ice resulting from climate warming may increase the risk of shore ice ride-up, but pile-up ridges in thick multiyear ice are widespread in the archipelago.

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Chapter 9 Education in Nunavut

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Key messages

- Residential schools and practices of assimilation have negatively impacted Inuit students creating mistrust of education.
- High school graduation in Nunavut has been increasing steadily between 1999 and 2015, although graduation rates remain the lowest in Canada.
- In Nunavut, Inuit are less likely to undertake post-secondary education than non-Inuit.
- While 47% of non-Inuit in Nunavut hold post-secondary diplomas and degrees, only 2% of Inuit hold this level of qualification.
- Creative programs at the school and post-secondary levels have helped to demonstrate the ability of Inuit to succeed educationally.
- A National Strategy on Inuit Education, led by the national organization Inuit Tapiriit Kanatami, is drawing together the four Inuit regions of Canada to collaborate with plans to improve education.

Abstract

Formal education in Nunavut remains a recent endeavor with a residential school past. This colonial period continues to negatively impact student attendance, high school graduation rates and levels of participation in post-secondary education though improvements are obvious with a rising graduation rate and increased participation in post-secondary education. These improvements can be explained by the *Education Act* that legislates Inuit values and knowledge as the basis of curriculum and a National Strategy on Inuit Education which holds promise for the future as it brings together all four Inuit regions in Canada. The Nunavut Teacher Education Program continues to graduate more and more bilingual Inuit teachers who speak an Inuit language as well as English. However, consistent implementation of these changes is difficult to achieve due to high turnover of non-Inuit teachers and school leaders.

9.1 Introduction

It is important to acknowledge the complex educational history of Canada's Eastern Arctic region, a history that involves traditional practices of both 'informal' and experientially-based Inuit education. Less than 100 years ago, traditional knowledge honed over millennia was passed on by parents, grandparents, extended families, and Elders and shaped Inuit society. The younger generation was taught life skills and values appropriate to their culture and context. In the colonial period, missionary schooling, which included residential schools, emerged in the communities, along with the more 'formal' education system in the form of Federal Day Schools and later Territorial Day Schools. The effects of colonial control, social disruption, and loss of culture are still being felt. Today, Inuit in Nunavut are starting to reshape formal education in a way that better reflects Inuit culture, language and values, while also striving to offer students a high standard of Canadian mainstream education to ensure that high school graduates have broad opportunities for future leadership in diverse careers. The process of reshaping education from pre-school through kindergarten and into secondary and post-secondary levels is one of the current challenges facing Nunavut with implications that significantly impact the future of the territory.

9.2 Brief Historical Overview

Between the establishment of the first school for Inuit children in Shingle Point (Yukon) in 1922 and the Second World War, the Anglican Church, the Oblate missionaries and the Grey Nuns (both Catholics) controlled the education of Inuit. The colonial attitude of the Canadian Government toward the education of the Inuit during this period was ambiguous at best. On the one hand, Federal and Territorial governments provided financial assistance to religious congregations so they could run day schools and residential schools. On the other hand, school was not mandatory and many bureaucrats in Ottawa wondered "why should the government squander public money on dotting the Arctic with well-equipped primary schools that

will give the children of Eskimo fur-trappers the same education as white children receive, when these Eskimo children will themselves become mere fur-trappers as they grow up?" (Jenness 1964).

At the end of the Second World War, the Canadian government decided that it had the responsibility to educate Inuit and provide them with the same opportunities to participate in the life and activities of the country as other Canadians had (Lesage 1955). In 1949, the first three Eastern Arctic federal elementary schools were opened in Lake Harbour, Coppermine and Coral Harbour (Jenness 1964, Damas 2002). In 1955, a residential school was established in Chesterfield Inlet where a Catholic mission school had existed for decades. The following year, a federal school was opened in Cape Dorset (Weissling 1991), followed by Frobisher Bay, *Ikpiarjuk* (Arctic Bay) and *Qausuittuq* (Resolute) in 1959, *Kangiqtugaapik* (Clyde River) and Iglulik in 1960, *Aujuittuq* (Grise Fiord) and Padloping in 1962, *Kimmirut* (Lake Harbour) (again) in 1963, as well as *Sanirajak* (Hall Beach) in 1967 (Damas 2002).

High school education was available to young Inuit, but they had to move away from home to residential schools established in Yellowknife (1958), Inuvik (1959) and Churchill, Manitoba (1964). Between 1951 and 1961, the number of Inuit students went from 245 to 2,600. The proportion of young Inuit who were going to school also increased from 10% in 1951 to 63% in 1961. By 1966, there were 61 schools in the Northwest Territories (NWT) (Damas 2002).

For the Canadian Government, education was a means to assert sovereignty and prepare Inuit to participate in the development of the resources of the NWT (Tester and Kulchyski 1994). For this reason, the Territorial authorities favoured "an education that would lead to vocational training and prepare them for work 'in the white man's economy'" (Duffy 1988). Accordingly, vocational programs started in the 1960s through Frontier College, which sent adult educators to northern communities to teach English and civic literacy courses. In 1968, the Adult Vocational Training Centre, which later became the Arctic College and

then the Nunavut Arctic College in 1999, was created to provide vocational programs and courses locally to Inuit.

In the 1960s and 1970s, cooperative manager training was also offered to Inuit in communities across the NWT as part of an attempt by government to educate northern Indigenous peoples about democracy and local self-government.

In the early 1970s, one of the most long-standing northern programs, the Teacher Education Program, was established, supported by the Donner Foundation and certified by McGill University. The number of vocational programs offered by Adult Education Centres increased during this time as communities began to prepare for major resource development projects and increases in community infrastructure.

Following the publication of a Government of Northwest Territories report, *Learning Tradition and Change in the Northwest Territories* in 1982, Nunavut Arctic College was established and had expanded to include three campuses, with community learning centres located in every Nunavut community. The number of courses and programs offered proliferated as well and reflected many of the labour force needs at the time. For example, in 1985 Arctic College ran 81 programs in 30 communities across the NWT.

The Nunavut Land Claims Agreement, signed in 1993, led to the establishment of the territory of Nunavut in 1999, but largely overlooked the matter of education in this new territory. However, the first major task of legislators was to initiate a process to address the education system in Nunavut and make it more culturally appropriate and responsive to the needs of the majority Inuit population. This process was initiated through the creation of regional school boards in the 1980s, with some success (McGregor 2010, O'Donoghue 1998), but following their dissolution shortly before the creation of Nunavut, the new *Education Act* (Government of Nunavut 2008a) needed to provide structure, direction and resources to enable the educational system to address the goals of bilingualism and culturally-grounded schooling (McGregor 2010).

The *Education Act*, which took several years to develop and involved extensive consultation, was given assent in 2008. The Act legally grounds education in Nunavut in the principles of *Inuit Qaujimajatuqangit* (IQ), Inuit social values, and bilingualism (Inuit languages and English). IQ principles emerge from Inuit knowledge and values; “knowledge that has proven to be useful in the past and is still useful today” (Laugrand and Oosten 2009). Incorporating IQ principles as the foundation of education in Nunavut, along with meeting mainstream academic standards, is a priority for Nunavut educators and administrators and is understood as central to building leadership capacity among Inuit.

In his report to the Federal Government as part of the Nunavut Land Claims Agreement implementation process, Justice Thomas R. Berger argued the need for more highly educated, bilingual Inuit to fill the leadership positions in government and meet the key provision of the Nunavut Land Claims Agreement, Article 23, that required representative numbers, (85%) of the Inuit population to be employed in Nunavut's public sector by 2020 (Berger 2006). As he indicated, the problem is not one of demand but one of supply, as there are presently insufficient numbers of qualified Inuit to fill the professional positions available (Berger 2006, Poelzer 2009). Berger (2006) highlighted the need to increase high school graduation rates and improve bilingual education as key factors in addressing this challenge. It is also clear that improved university access is fundamental to addressing the shortage of highly skilled and professionally qualified Inuit.

Unlike every other circumpolar country, there is no university in Canada's Arctic region, and access to university courses requires partnerships between Nunavut Arctic College and/or the Nunavut Department of Education and educational institutions in the South. Several successful partnerships have started to address the need for college and university-educated Inuit in Nunavut, but many more are necessary if significant change is to take place. For example, several post-secondary initiatives have been offered either by the accreditation of local college programs (i.e., University of Manitoba's Inuit Language and

Culture Program), by delivering courses on location, (i.e., University of Victoria’s Akitisiraq Law Program, University of Prince Edward Island’s Master of Education in Nunavut), a hybrid program, (i.e., Athabasca University and University of the Arctic) or through other hybrid models supplemented by learner support (i.e., Carleton University’s Nunavut Certificate in Public Service Studies). Present partnerships do not provide Inuit students with the diverse range of options to address academic and professional programming necessary to develop Inuit leadership in both the public and private sectors (Poelzer 2009).

9.3 Recent trends in education in Nunavut

From 1999 to 2010 the number of high school graduates in Nunavut increased 88% from 128 to 241. By region, during this same time interval, the number of graduates increased

by 68% and 196% in the *Qikiqtani* (Baffin) and *Kivalliq* (Keewatin) regions, respectively (Figure 1) (Nunavut General Monitoring Plan, unpublished data).

Overall, high school education attainment within Nunavut has shown significant improvement over the past decade and the 2008-09 school year saw the high school graduation rate rise to 39% from 28% in 1999 (Figure 2) (Nunavut General Monitoring Plan, unpublished data).

Nevertheless, high school graduation rates remain the lowest in Canada for an Indigenous population (Canadian Council on Learning 2009, Richards 2008, Statistics Canada 2006). With the exception of 1999, 2001, and 2010, more than half of the secondary school graduates have been females (Figure 3) (Nunavut General Monitoring Plan, unpublished data).

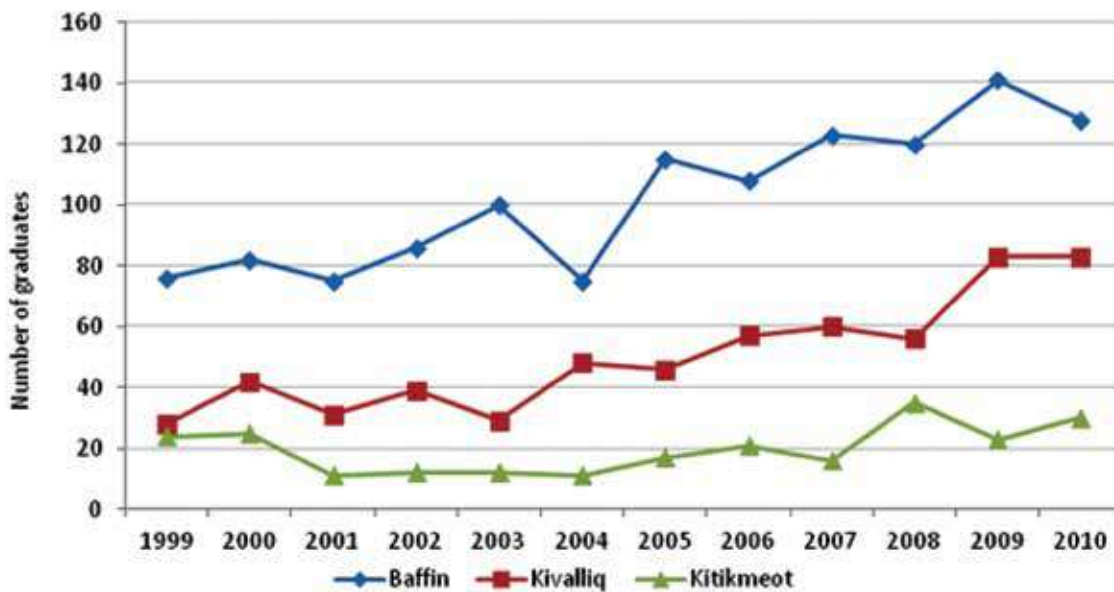


FIGURE 1. Secondary school graduates by region - Nunavut (1999-2010). [Adapted from Nunavut General Monitoring Plan (unpublished data)].

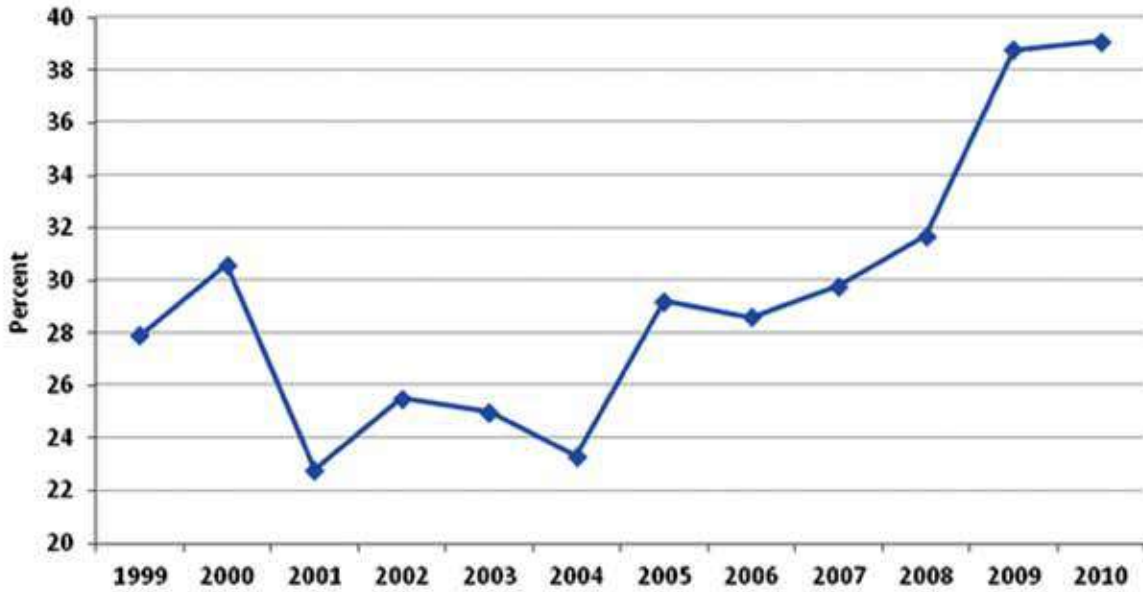


FIGURE 2. Graduation rate in Nunavut (1999-2010). (Adapted from Nunavut General Monitoring Plan (unpublished data)).

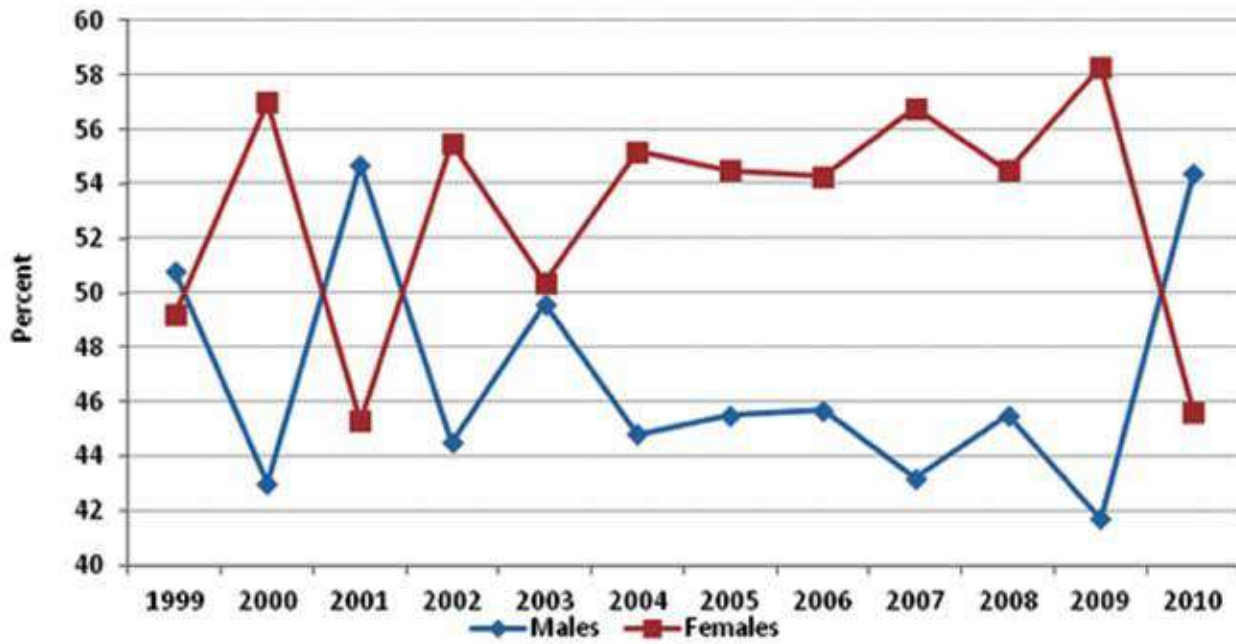


FIGURE 3. Secondary school graduates by gender in Nunavut (1999-2010). (Adapted from Nunavut General Monitoring Plan (unpublished data)).

According to the 2011 census, (Nunavut Bureau of Statistics, 2013), out of the 14 280 Nunavummiut aged 25 to 64 (Table 1):

- 46% (6570) had no certificate, diploma or degree. Among them, 6370 were Inuit, 170 non-Inuit.
- 12% (1770) had a high school or the equivalent. 1230 were Inuit, 500 non-Inuit.
- 10% (1425) had an apprenticeship, trade certificate or diploma. Among them, 1160 were Inuit, 250 were non-Inuit.
- 17% (2420) had a college or other non-university certificate or diploma. 1625 were Inuit, 750 were non-Inuit.
- 2% (230) had a university certificate or diploma below bachelor degree. Among them, 95 were Inuit, 120 were non-Inuit.
- 13% (1860) had a university certificate or degree at bachelor's level or above. 195 were Inuit, 1,615 were non-Inuit.

There is a significant discrepancy in educational attainment between Nunavut Inuit and non-Inuit and only 36% of Inuit students graduated from high school in 2011 (Office of the Auditor General 2013). This means that due to a complex variety of factors, over 60% of Inuit in Nunavut have not completed a high school certificate or equivalent. While 1% of Inuit hold a university certificate or diploma below a bachelor level, 4% of non-Inuit hold this level of education. Finally, while 2% of Inuit hold a university certificate, diploma or degree at a bachelor's level or above, 47% on non-Inuit hold diplomas or degrees above this level. Inuit are far less likely to graduate from high school than their Nunavummiut non-Inuit peers and go on to complete diplomas or degrees.

9.4 Identifying the challenges

9.4.1 High school education in Nunavut

Systemic challenges cause disengagement from school, including high levels of staff turnover, and struggles to implement bilingual education continue to limit the ability of Inuit to participate fully in the knowledge economy (Berger 2006) and prepare for the impact of climate change on Inuit society. Recent territorial and national legislative and policy developments, however, bring hope and provide a framework for change, creating opportunities for Inuit to build a school system based on Inuit language, culture and values (McGregor 2010). After the creation of Nunavut in 1999, Inuit set a number of priorities for the new territory, including making Inuktitut an official working language by 2020 and, as previously mentioned, increasing the proportion of Inuit in the government's workforce to 85% (Government of Nunavut 1999). The Government of Nunavut (GN) has passed legislation to create an environment favourable to change, including the *Education Act* (Government of Nunavut 2008a), the *Inuit Language Protection Act* (Government of Nunavut 2008b) and the *Official Languages Act* (Government of Nunavut 2008c), all based on the principles of IQ. This legislation and the policies now being implemented across communities and schools in Nunavut call for innovation in the way curriculum and Inuit languages are taught in schools. The new vision for Inuit education in Nunavut also includes an enhanced role for parents through locally elected education committees, District Education Authorities (DEAs), and the territorial DEA Coalition.

Case studies of high schools in Pangnirtung, Clyde River, Rankin Inlet, and Kugluktuk help to provide a snapshot of the formal education system across Nunavut from 2000/2001 to 2009/2010 (McGregor 2011, 2012). They provide historical background and statistical profiles of the high schools in the four communities. The profiles cannot provide a full statistical picture for a number of reasons. It is difficult to access information about rates of attendance, graduation, staff turnover, and numbers of Inuit staff numbers, as in the past the standardized systems of

TABLE 1. Highest level of educational attainment for the population aged 25 to 64, 2011 counts and percentage distribution, for Nunavut. (From Nunavut Bureau of Statistics (2013).

Proportion of the population 25 to 64 Years by Highest Certificate, Diploma or Degree, for Nunavut, Regions and Communities, 2011 National Household Survey							
	Total – Population 25 to 64 Years	No Certificate, Diploma or Degree	High School Certificate or Equivalent	Apprenticeship or Trades Certificate or Diploma	College, CEGEP or Other Non-University Certificate or Diploma	University Certificate or Diploma Below Bachelor Level	University Certificate or Degree at Bachelor's Level or Above
Nunavut	100	46.0	12.4	10.0	16.9	1.6	13.0
Baffin Region	100	42.4	13.1	8.8	18.4	1.9	15.4
Arctic Bay	100	55.6	9.5	14.3	14.3	0.0	3.2
Cape Dorset	100	59.2	12.5	10.0	10.0	1.7	8.3
Clyde River							
Grise Fiord	100	33.3	16.7	16.7	16.7	0.0	16.7
Hall Beach	100	65.1	7.0	9.3	16.3	0.0	0.0
Igloolik							
Iqaluit	100	24.3	15.9	7.7	23.4	3.0	25.8
Kimmitut	100	48.7	15.4	10.3	17.9	0.0	7.7
Pangnirtung							
Pond Inlet	100	59.7	11.2	9.0	13.4	0.0	6.0
Qikiqtarjuaq	100	52.9	9.8	9.8	15.7	0.0	9.8
Resolute	100	35.0	15.0	15.0	20.0	0.0	0.0
Sanikiluaq	100	69.8	7.9	9.5	6.3	0.0	3.2
Keewatin Region	100	51.1	12.4	10.8	14.7	1.2	9.9
Arviat	100	53.1	10.1	10.1	16.8	1.1	8.4
Baker Lake	100	56.4	14.7	9.6	9.0	1.3	8.3
Chesterfield Inlet							
Coral Harbour	100	60.9	7.8	10.9	10.9	0.0	6.3
Rankin Inlet	100	33.2	16.6	10.4	22.3	1.4	15.6
Repulse Bay	100	70.3	6.3	12.5	4.7	0.0	3.1
Whale Cove	100	63.3	6.7	13.3	13.3	0.0	0.0
Kitikmeot Region	100	50.0	10.2	12.7	15.7	1.4	9.8
Cambridge Bay	100	37.7	15.7	10.7	17.6	3.1	15.7
Gjoa Haven	100	56.0	6.0	15.0	17.0	0.0	7.0
Kugaaruk	100	69.1	5.5	18.2	5.5	0.0	3.6
Kugluktuk	100	45.3	10.9	11.7	21.1	0.0	10.9
Taloyoak	100	64.2	7.5	11.9	9.0	0.0	4.5

maintaining records across the region, including in individual schools and in the Nunavut Department of Education, were inconsistent. Each community experiences different circumstances with respect to the stability of staff, availability of funding and DEA support which makes data comparison challenging. In spite of these limitations, however, the research offers important initial indications of the realities facing Nunavut high schools and identifies practices that offer promising directions for student engagement and success (see Chapter 22).

9.4.2 Inuit educators and professional development

The gradual increase in the number of Inuit staff in schools, including language instructors, teachers, administrators, and support staff, in some schools offers evidence of improvement in Nunavut education. The number of Inuit teachers in Nunavut schools has increased from an estimated 90 Inuit teachers and 190 Inuit staff in 1995, to an estimated 218 Inuit teachers, (38% of total employed teachers) and 246 Inuit staff in 2007-2008. The number decreases to 223.5 Inuit staff in 2009-2010 (35%), possibly due to some retirements and access to employment opportunities within GN departments (McGregor 2011). The increase is due in part to improved access to professional training programs in the region, including more accessible teacher education programs, offered through community-based Nunavut Teacher Education Programs (NTEP), now certified through a partnership with the University of Regina. The University of Prince Edward Island (UPEI) Master of Education (MEd) program has graduated 37 Inuit educators in two iterations of the program. There were 21 graduates in 2009 and 13 graduates in 2013, with two additional Inuit graduates having completed theses and one other having completed the MEd degree on campus. The Nunavut Department of Education continues to offer a leadership program, now offered as a five-course university-credited Certificate in Educational Leadership in Nunavut (CELN) through UPEI. These programs are making university-level professional and higher education more accessible and culturally appropriate for Inuit educators.

In spite of efforts to train Inuit teachers, rates of staff turnover in Nunavut schools remain high, particularly for non-Inuit, which has a negative impact on students, teachers and administrators. The turnover rate is much lower with Inuit staff and teachers, as they tend to come from the same community and have stronger relationships with the schools and the students. High schools in the case studies conducted for the ArcticNet grant have relative success, with the average staff retention at Attagoyuk High School in Pangnirtung at 68% and Inuit staff levels increasing from 21% to 42% (2002-2010); Quluaq High School in Clyde River has an average staff retention of 76% with Inuit staff levels increasing from 37.5% to 52% (2002-2010). Maani Ulujuk High School in Rankin Inlet has an average retention of 71%, though Inuit staff only average 15% of the total staff (McGregor 2012).

Research findings indicate that Inuit students and youth feel more connected to and comfortable with Inuit staff and teachers, which fosters engagement in school. Inuit staff, teachers, and administrators understand the culture and language, know the parents of students, and know the community:

[H]aving Inuk teachers...was really good because they could also understand and relate to the social problems that other students may be going through, and you know, they know your parents, they know your family...it feels a lot more comfortable (Kilabuk 2012a).

When there is a high turnover of staff and teachers, youth indicate that they are less engaged and less motivated to work:

[T]here's a point in high school where...there's a lot of coming and going of teachers, and when you're a teenager you meet maybe 15 teachers every year, and your just kind of, 'well, you know what, I don't care anymore so we're going to just not listen to you.' It was like that a lot (Johnston 2012).

Addressing the high turnover rate, through increasing the numbers of Inuit staff, teachers, and administrators, is an important step to improving student success.



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9.4.3 Incorporation of Inuit Qaujimaqatugangit in education

The *Education Act* legislates that education in Nunavut be built on the foundation of IQ. Our research confirms that Inuit educators, DEA members, administrators, parents, youth, and community members understand the value of implementing this foundation for Inuit education, in particular as a way to promote the centrality of Inuit culture in the education system and to engage Inuit students in learning. Culturally-based learning experiences not only teach practical survival and life skills, but also transmit Inuit values and principles founded in IQ. In some schools, principals and teachers are working to ground their daily activities in IQ by welcoming parents and community members, working collaboratively, treating students with respect, offering encouragement, and addressing conflict in a direct and respectful way. As long-time co-principal of Attagoyuk High School and MEd graduate, Lena Metuq states,

[W]e have been incorporating and using IQ for the last three years and this last year seems the easiest so far! IQ values, principles and foundations are now taught in

school and we try to incorporate them into whatever they are learning in school. We are reminded again when the new enrollees start school what we are trying to achieve, and we try to incorporate IQ into everything they learn throughout the day, everyday. We discuss what they think IQ foundations are and that one of the most important values we have is getting along and (being) tolerant of others, help other people, be able to work together and have a welcoming school environment (Metuq 2011).

IQ in schools helps in reclaiming Inuit identity and giving youth and educators the strength to manage some challenges. Reclaiming Inuit identity contributes to improved confidence and self-esteem in students. Going to camp, improving Inuktitut/Inuinnaqtun language skills, participating in sewing classes, and learning from Elders all allow Inuit students to develop a deeper sense of who they are, while maintaining language, culture, and traditions (Walton et al. 2013, Walton et al. 2011).

Not only that, you gain a sense of confidence for who you are and you are no longer in a state of confusion or being so sensitive towards what people say to you. You grow over

that. You empower yourself a little, with just knowing and feeling who you are and learning those cultural things and to be proud of it, as it gives kind of a light in the heart, kind of thing (Kilabuk 2012b).

Through these IQ programs, students are provided with advice and strategies that help them manage challenges they will face and need to overcome as Inuit flourish in the future.

Inuit educators, parents, and youth recognize that in order for students to be prepared for higher education and future employment, they need to function academically at a level that is comparable to Canadian standards. Providing consistent academic standards across the territory, while also consistently implementing IQ in order to build an education system that reflects the Inuit-majority within the school system remains a significant and complex challenge.

9.4.4 Student attendance

While data on attendance is not consistently recorded, it is clear that rates are relatively low among students in Nunavut. Using Statistics Canada averaging methods and Nunavut Department of Education data, analysis finds an average 37% decrease in enrolment between grades 9 and 12 in the period of 2001-2009 (McGregor 2011). Data also indicate that special attention must be given to students in grades 9 and 10 when drop-out rates increase. Our analysis shows that “grade 10 is a critical turning point in the academic careers of our students, when as many as 50% of students tend to become disengaged from school” (McGregor 2011).

Inuit youth indicate in interviews that the support and encouragement of family, teachers, and peers are key factors in keeping them in school and achieving academic success. Parents play a crucial role in Nunavut education, by encouraging their children to go to school and do their best, and also working with teachers and administrators to identify students’ learning needs. Due to the residential school legacy, Inuit parents have mixed feelings about formal education for their children. While many recognize the

importance of their children going to school, there is still some mistrust of formal education. Administrators, DEA members and teachers have to work hard to communicate with parents and help them feel welcome in the schools. This is much easier when teachers and administrators are Inuit. Bilingual Inuit administrators and teachers, who understand the importance of IQ principles, are making some headway in building trust with parents and nurturing supportive relationships for students. Jukeepa Hainnu, principal of Quluuq High School and MEd graduate, states,

[W]e have graduated students whose parents could not help with schoolwork, and who are unilingual Inuit. All they had to do was understand the importance of education. That shows good support. Their vision is (that) children need education (Hainnu 2011).

9.5 Post-secondary education in Nunavut

Hundreds of adult education and post-secondary courses and programs have been offered to Inuit across Nunavut (and formerly across the Northwest Territories) since the 1960s. At first glance, it looks as though students who have completed high school have had many opportunities to pursue vocational training or post-secondary education inside and outside of their territory but this does not reveal the full story.

Despite these initiatives, access to relevant and sustainable post-secondary education in Nunavut has remained extremely limited for most Nunavummiut and long term accessibility to a high quality diversified post-secondary education has been problematic. Although they have made noticeable gains at high school, college and trade program levels since 1981 (Inuit Tapiriit Kanatami and Research and Analysis Directorate 2006), the percentage of Inuit who have completed a university degree has remained quite low (from 1.6% in 1981 to 2.7% in 2006). More significantly, the gap between non-Inuit and Inuit has increased since the percentage of non-Inuit who have completed a university degree during the same period has increased from 6.4% in 1981 to 16.5% in 2006 (Penney 2009).

The lack of progress at the post-secondary level can be explained by many interrelated factors:

- The absence of a university in the North (Poelzer 2009) forces most students wanting to pursue post-secondary education to move away from Nunavut, a step many are not ready to take or cannot take.
- High school education in Nunavut does not fully prepare all Inuit students for the academic requirements of post-secondary education in a southern university (Hicks 2005).
- Post-secondary programs, especially vocational and training programs, have also been designed to mirror the political and economic events and priorities of their time as a means of building a workforce in a wage-economy. They have tended to focus on skills development and improving the employability of Inuit in the wage economy labour force (in both the private and public sectors). For this reason, their scope, numbers and long-term relevance can be limited.
- Few of the initiatives developed by southern universities have proven to be sustainable over a long period of time. Most have suffered from not being synchronized with programs in Nunavut and for only offering opportunities in specific fields of study (mostly in education and health; one program in public policy and one in law), and for only being available in limited locations (primarily in Iqaluit). These initiatives have also proven costly and have required a strong commitment from the various partners over a long period of time.
- Online courses were developed to overcome some of these shortcomings, but most are not well adapted to the needs of Nunavut students who often require extensive support to succeed (Inuit Tapiriit Kanatami 2008). Their curricula is not always adapted to Nunavut realities (Silta Associates 2007).
- Inuit are still lacking confidence as a result of the loss of control their communities have been experiencing since the 1950s (Brody 1975). This loss of control affects community wellness, which in turn has a negative impact

on post-secondary educational success as defined in the South (Rodon 2008).

- Both the educational path and perspectives from a socio-logical and cultural standpoint of Inuit students differ from normative models found in southern Canada. For example, Inuit post-secondary students are generally part of one of two distinctive groups: 1) mature adults who are returning to school after being away for an extended period of time, and 2) young adults who have recently completed high school.

In order to succeed, Inuit adults need access programs and educational programs that reflect their needs as parents and family members, their cultural specificities (Berger 2001, Hicks 2005) and that offer transition and access programs (Inuit Tapiriit Kanatami 2008).

There are no easy remedies to the limited access of Inuit students to post-secondary and university education. This is why the Government of Nunavut is currently trying to develop a strategy to ensure Nunavummiut have access to “consistent, accessible, quality post-secondary education opportunities for all northerners” (Government of Nunavut 2011). There is, however, a need for more evidence-based research on university and post-secondary programs delivered in Inuit regions to identify knowledge gaps that will help improve access to post-secondary education, program design and delivery, program funding, culturally unique student supports, partnership between southern and northern educational institutions, study to work transition, as well as program accountability (Silta Associates 2007). As important as these factors are, they have been overlooked since little is known about Nunavut students’ participation in post-secondary programs, in large part because, until recently, the capacity to collect this kind of data and provide monitoring tools was non-existent (Inuit Tapiriit Kanatami 2008). The ArcticNet project “Improving Access to University Education in the Canadian Arctic” was designed to address these issues (see Chapter 23).



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9.6 Preparation for higher education

High numbers of youth in Nunavut are not completing high school. While young people may drop out in grades 9 or 10, some return to complete their high school education, realizing that this is important for their future opportunities in life. Some students who graduate high school and wish to go on to post-secondary education find they require upgrading to reach the standard required for entry into certain programs. This is discouraging for graduates and their families who feel that their hard work has not been good enough and that the schools have let them down. Some complain that the courses they need for specific programs may not be offered in schools.

[S]o, I'm stuck. I know I could do a lot, and get into a lot of good [programs], but it really hit me when I graduated that I couldn't get into any of these programs because I didn't have [the courses] from my high school...I've been graduated for two years now, but I'm stuck here...that's stopping a lot of people from doing...college and university work (Kilabuk 2012b).

Programs like those offered through Nunavut Sivuniksavut (NS) in Ottawa offer important transition from high school to post-secondary education for Inuit youth. But even young high school graduates accepted to go to NS find the transition difficult.

[W]hen I went to NS, I really found out that I had to do my work for myself because in high school it feels like you are doing it for the teacher. So you are doing your work for the teacher, but at NS I learned that you have to do it for yourself, and on time. It was really hard to adjust that into our heads (Ishulutak 2012).

It is essential that Nunavut high schools provide the course options and career counselling and preparation that students need for academic and career development after high school. To also achieve this in a bilingual and bicultural context is a significant challenge.

9.7 Improving support mechanisms for undergraduate students

Nunavut students who want to pursue undergraduate post-secondary education have very few options. They can choose to study at Nunavut Arctic College, which means they access a limited number of programs, or they can follow one of the few opportunities offered by southern universities in the North (for example, the Akitisiraq Law Program), or undertake a program in a southern institution. Whatever choice they make will have a tremendous impact on their daily lives. Indeed, undergraduate students often need to move away from their home communities to Iqaluit or to a southern city. This means leaving family behind, adapting to a new environment, managing high academic standards and coping with limited financial resources.

To improve academic and personal success and make sure they achieve their goals, undergraduate students need reliable support mechanisms offering students personal and academic assistance. For example, findings show (see Chapters 22 and 23) that students benefit from receiving support from fellow students, whether they study in the same program or not. Students would also benefit from access to improved housing facilities, in both the North and the South. More often than not, students struggle to find accommodation and must work to make ends meet, which in turn affects their capacity to succeed. Students also require differentiated funding. Currently, all students receive the same amount of financial help from the Government of Nunavut, whether they study in the North or in the South, have access to subsidized housing, or have children. Adapting funding to specific needs would be helpful.

Another example from the findings to adapt curricula to reflect the context in Nunavut. Although this is often difficult for southern institutions, programs offered by the Nunavut Arctic College or those designed specifically for Inuit and delivered in the South (for example, Nunavut Sivuniksavut) have designed curricula around the needs of the students. Furthermore, it helps when instructors demonstrate a deep interest in Arctic and Inuit issues.

9.8 Inuit graduate education—fostering leadership and providing support

The UPEI MEd in Leadership and Learning program was a graduate program offered by the Faculty of Education at UPEI in partnership with the Nunavut Department of Education from 2006 to 2013. It was designed specifically for Inuit educators, using decolonizing methodologies and incorporating Inuit culture and approaches. Nunavut MEd graduates have identified the importance of their graduate education in analyzing their social and cultural realities as Inuit, along with developing their critical perspectives, voices, and identities within a broader educational context (Walton et al. 2010, Wheatley et al. 2015). The Nunavut MEd used a decolonizing approach to encourage social critique, and provided opportunities for the students to share their experiences and develop a vision for Inuit education and Inuit society in Canada.

[The MEd] definitely taught me how to think deeper, how to think wider, and not be tunnel vision, but to think of the impact it is going to have on the wider audience where you often think of your own classroom or your own school. So you are thinking students and school, but also... their parents and the community. So you are expanding your vision and how you are creating futures. And building community, and I think that is what schools are and should know (Kuliktana 2012).

In this process, the graduates strengthened their sense of confidence, their voices, and their identities as Inuit educational leaders, Inuit scholars and researchers.

[The MEd] had helped a lot with...the confidence and also ability to really voice what I think...whereas before, as classroom teachers we kind of went along with what was expected, or what was...told, or asked to be followed (Qanatsiaq 2012).

Inuit graduate students who completed the two iterations of the UPEI MEd program (2006 – 2009) and (2010 – 2013) identified areas of support they need or find lacking in the process of accessing graduate studies. Ranging in age from late-20s to 60s, the graduates had significant family

responsibilities and established careers when they started their graduate degrees. They were motivated to continue their higher education for varying reasons that include a personal and professional interest in further education, a desire to give back to the community through educational leadership, and a need to be role models for younger generations of Inuit. UPEI MEd graduate, Nancy Uluadluak, states,

[What I value as a learner is] giving back to my community and learning from other educators. Meaning I took the [MEd] program not to be top of everybody, but being part of my community, being part of Inuit (Uluadluak 2010).

However, barriers do present challenges for Inuit who wish to pursue graduate degrees. At present many degree-holding Inuit are graduates of the Nunavut Teacher Education Program (NTEP) and hold Bachelor of Education degrees. Teachers represent one group of Inuit qualified to apply for graduate programs. The main barrier for Inuit working and living in Nunavut communities with their families is that most graduate programs are not available in the territory, and certainly not in smaller communities. For mature students with extended families and careers, it is very difficult to move to the South to complete a graduate degree. Difficulties also face graduate and undergraduate Inuit students when they choose to leave their homes and communities to pursue opportunities in higher education. They often experience feelings of isolation as they are far away from the supports of family and friends and the Inuit culture. Unfortunately, there are few supports available for Inuit in many university communities, and in large city centres, Inuit students can be overwhelmed by the pace and activity of urban life. As current MEd student, Adriana Kusugak states,

[W]hen students come from a safe community where they know everyone, and go to a completely different place, it is overwhelming. Even going to the cafeteria, where there are too many people, it is unfamiliar and overwhelming. Also, things like public transit in big cities are intimidating. Class sizes are huge, and students don't know the expectations of teachers. The homesickness is overwhelming (Kusugak 2011).

Funding is also a common concern, with the need for income supplements for those taking leave from their careers during graduate programs. In addition, depending on where the program is located, the availability of housing can become a barrier.

The UPEI MEd was a hybrid, cohort model that provided a combination of distance learning, on-site courses in Nunavut as well as at UPEI. Online supports were available, and a close community developed between participants in both cohorts that helped to provide support between participants over the period of three years required to complete the MEd degree on a part-time basis. The part-time design of the program meant that students did not have to leave their communities for long periods of time. The participants greatly appreciate the opportunity to work and learn with instructors, colleagues and Elders who spoke an Inuit language.

[Y]es...the best part about the program was we, over 20 women, we all spoke Inuktitut, so my best part about the program was discussing and talking about the things we have learned or what we did, and the second one is listening to educators, with their achievements and failures that happen in their fields, like in their workplace, in schools (Uluadluak 2010).

9.9 Building capacity for a university in the Arctic region

Graduate education in Nunavut needs to be based on a vision for Inuit educational self-determination. The purpose of programs like the MEd is to build capacity in Inuit graduate scholarship and educational leadership so that these graduates are able to teach and mentor the next generation of Inuit university students in Nunavut. These steps are taking place gradually, with increased Inuit participation in research and efforts to publish Inuit academic work (Walton and O'Leary 2015). Providing supports to enable Inuit to start PhD programs in education and other disciplines is also important. Naullaq Arnaquq, a graduate of the MEd program at UPEI and author of *Uqaujjuusiat: Gifts of Words of Advice: Schooling, Education and Leadership in*



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Baffin Island (2008), started a PhD in Educational Studies at UPEI in September 2012. Inuit need to be able to access the space and time to pursue graduate degrees so their scholarly voices can be heard within research and higher educational contexts in Canada and elsewhere. Inuit voices can shape education in Inuit Nunangat, but also in the rest of the country. The knowledge, perspectives and experiences of Inuit need to be shared in the academic literature.

9.9.1 National strategy on Inuit education

Prime Minister Stephen Harper's June 2008 formal apology to First Nations, Inuit and Métis survivors of Canada's residential schools marks a significant shift by the Government of Canada towards repairing the impact of the residential school experience and opens the door to a 'post-Apology' era in Inuit education. This era requires strategic, policy-based, Inuit-led actions to foster parental engagement and build a school system based on IQ. As Mary Simon, recently retired National President of the Inuit Tapiriit Kanatami (ITK) argues,

[W]e need to get Inuit children into the classroom, and we need them to be successful, and to do this we must focus on innovative strategies that will fundamentally transform our education system" (Simon 2009).

Under Simon's leadership, an Inuit Education Accord was signed in April 2009, creating for the first time a National Committee on Inuit Education (NCIE) representing the four Inuit regions and developing a National Strategy on Inuit Education (National Committee on Inuit Education 2011), focusing on strategic priorities for change. The National Strategy identifies its three broad goals as:

1. Providing supports for children to stay in school and graduate.
2. Offering bilingual curriculum and culturally relevant resources.
3. Increasing the number of Inuit educational leaders and bilingual educators in schools, through such key investments as improved "success in post-secondary education" and "establishing a university in Inuit Nunangat" (p. 9) (National Committee on Inuit Education 2011).

The ten recommendations of the strategy highlight the need for ongoing support for parents, students, and educators; focused development of Inuit educational leadership; improved academic standards; increased access to higher education for Inuit; and support for Inuit educational research conducted by Inuit scholars (National Committee on Inuit Education 2011). While steps are being taken in these directions, there is a great deal of work required at the federal and territorial government levels, as well as in local communities and schools, for these goals to be met in the future.

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PART III

**RESPONDING TO CHANGE:
EFFECTS, OUTLOOK,
ADAPTATION**



Chapter 10 Distribution and Patterns of Persistent Organic Pollutants and Mercury in the Region

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Key implications for decision makers

- The highest levels of mercury and the legacy pesticide HCH in ringed seals and polar bears are found in the Western Canadian Arctic relative to other locations.
- The highest levels of most legacy contaminants, including PCBs, DDT, Σ CHLs, ClBz in ringed seals and polar bears are found in the east (i.e., Ungava Bay and Labrador) and in the Beaufort Sea relative to other locations.
- Mercury concentrations are also elevated in Lancaster Sound and the Gulf of Boothia, possibly due to high productivity in these areas.
- The highest levels of emerging contaminants (e.g., PBDEs and PFOS) are observed in seals and polar bears at southernmost sites (i.e., lower latitudes).
- While long-range transport from divergent southern sources delivers contaminants to Arctic environments, food web structure also appears to play an important role in shaping the spatial trends of mercury and some legacy contaminants.
- Upstream reservoirs in the Arctic and Atlantic Oceans (loaded in previous decades), together with recent atmospheric deposition or riverine input, appear to be the dominant driver of trends and variability in the water. Water is currently important for legacy contaminants whereas atmospheric deposition appears to be more important for emerging POPs such as PBDEs and PFOS.
- Contaminant burdens of legacy POPs and mercury in upper trophic level marine mammals appear to be increasing with increasing temperatures, decreased summer sea-ice extent and earlier sea-ice breakup. These are projected to increase further in the near future.

Abstract

The marine ecosystem plays an important role in Inuit health and well-being. Arctic contaminant research in the marine environment has focused on organohalogen compounds and mercury mainly because they are bioaccumulative, persistent and toxic. Ringed seals (*Pusa hispida*) and polar bears (*Ursus maritimus*) have been key indicator species for the evaluation of spatial and temporal trends of these contaminants in the Canadian Arctic. Presently, the highest levels of total mercury (THg) and the legacy pesticide HCH in ringed seals and polar bears are found in the Western Canadian Arctic relative to other locations. Whereas, highest levels of some legacy contaminants, including Σ PCBs, PCB 153, Σ DDTs, p,p'-DDE, Σ CHLs, ClBz in ringed seals and polar bears are found in the east (i.e., Ungava Bay and Labrador) and in the Beaufort Sea relative to other locations. The highest levels of emerging contaminants, including PBDEs and PFOS in seals and polar bears are found at lower latitudes. Feeding ecology plays an important role in shaping the spatial trends of THg and some legacy contaminants. Spatial and temporal trends for persistent organic pollutants (POPs) and THg are underpinned by historical loadings of surface ocean reservoirs including the western Arctic Ocean, which supplies seawater to the western Canadian Arctic Archipelago (CAA), and the North Atlantic Ocean, which supplies water to Baffin Bay and the eastern CAA. Trends set up by the distribution of water masses across the CAA are then acted upon locally by on-going atmospheric deposition, which is an especially important contributor for emerging contaminants. Warming and continued decline in sea-ice habitat are likely to result in further shifts in food web structure and feeding ecology, which are likely to produce increases in contaminant burdens in upper trophic level marine mammals. The lack of pelagic (open water) and benthic (seafloor) invertebrate and fish contaminant data for the Arctic weakens our ability to evaluate both current and future spatial and temporal trends. Monitoring of seawater and a range of trophic levels would provide a better basis to inform communities about contaminants in traditionally harvested foods, to understand the causes of contaminant trends in marine ecosystems, and to track environmental response to source controls instituted under international conventions.



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10.1 Regional contaminant overview

Contaminants have entered the Arctic predominantly by atmospheric and oceanic long-range transport (Figure 1) and secondarily from local sources. Long-range contaminants having the potential to produce consequential exposures in arctic biota exhibit a set of key characteristics. To transport long distances in the atmosphere or oceans, they must be volatile or semi-volatile, or partition favourably into water, but they must also be sufficiently involatile and chemically stable to deposit from the atmosphere within the Arctic once arriving there (Wania 2003). Furthermore, to produce substantial risk at distant locations like the Arctic these contaminants must have been released in large quantities (e.g., 100s of kt to > Mt (see, e.g., Macdonald et al. 2000, Li and Macdonald 2005, Streets et al. 2011)), and persist in air or water for the time periods required to arrive in the Arctic or move within the Arctic (> 5 days for winds, > 1-10 years for ocean currents). Finally, these contaminants must readily enter biological food webs and be concentrated there to concentrations that exceed thresholds of known or potential adverse effects. Persistent, biologically accumulative, toxic (PBT) characteristics apply particularly to a wide range of organohalogen compounds (OHCs) released either intentionally (e.g., pesticides) or collaterally with industrial activities (e.g., polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) and perfluorooctanesulphonate (PFOS)), and mercury (Hg), which has volatile and toxic forms (elemental and methyl mercury). The OHCs are variously prone to chemical breakdown through metabolism, hydrolysis or photolysis which, in addition to burial in sediments, provide the means for the biosphere eventually to rid itself of such contaminants (taking decades to centuries). Hg can be buried in soils and sediments, which removes it from the biosphere, but it cannot be destroyed. Transfer of Hg to long-term sequestration (sediments, permafrost and the deep oceans) takes centuries or longer during which the contaminant Hg has sufficient time to redistribute widely within air and ocean through volatilization, deposition and transport (e.g., see Driscoll et al. 2013). As a result of the historical loadings, the ocean today is estimated to hold $\sim 56 \pm 16$ kt of contaminant Hg in part

manifested as an approximate tripling of the total Hg (THg) concentration in surface water from the background values of pre-industrial times (Lamborg et al. 2014).

Unlike the OHCs, Hg occurs naturally and is released by human activities and thus has loaded onto this natural background (Lamborg et al. 2014, Streets et al. 2011, Driscoll et al. 2013). Furthermore, Hg exhibits several forms in the environment including inorganic (elemental (Hg⁰), dicationic Hg (Hg²⁺)) and organic (monomethylmercury (MMHg), dimethylmercury (DMHg)) forms (AMAP 2011). Of these forms, MMHg presents by far the greatest concern for environmental toxicity, which implies that the inorganic forms of Hg, which dominate emissions and transport, must undergo methylation within the environment to convert them to the PBT form (Macdonald and Loseto 2010). The potential for Hg to transfer between chemical forms presents a challenge to predicting Hg trends and toxicity within ecosystems because processes of oxidation, reduction and methylation are strongly controlled by environmental conditions like solar radiation and intensity of organic carbon processing.

10.2 Contaminants in the Arctic

The risks to the Arctic from OHCs and Hg, which have long been recognized (AMAP 1998, Barrie et al. 1992), provided much of the motivation to reduce or eliminate industrial and agricultural sources in temperate regions through international conventions (e.g., Minimata 2013, Stockholm 2004). Accordingly, these contaminants all exhibit transient emission histories with globally significant quantities of the OHCs released predominantly after WWII. Mercury has been released for a much longer period dating back even to Roman times (Martínez-Cortizas et al. 1999) but, more pertinent to the present, Hg has been released in large quantities from multiple sources during the past 60 years with coal burning presently contributing a major fraction (Streets et al. 2011, AMAP 2011). Streets et al. (2011) estimated that human activities all told have released 350 kt of Hg to the environment, 61% of that after 1850.

The primary historical loadings of OHCs and Hg to the environment have led to the present situation: persistent

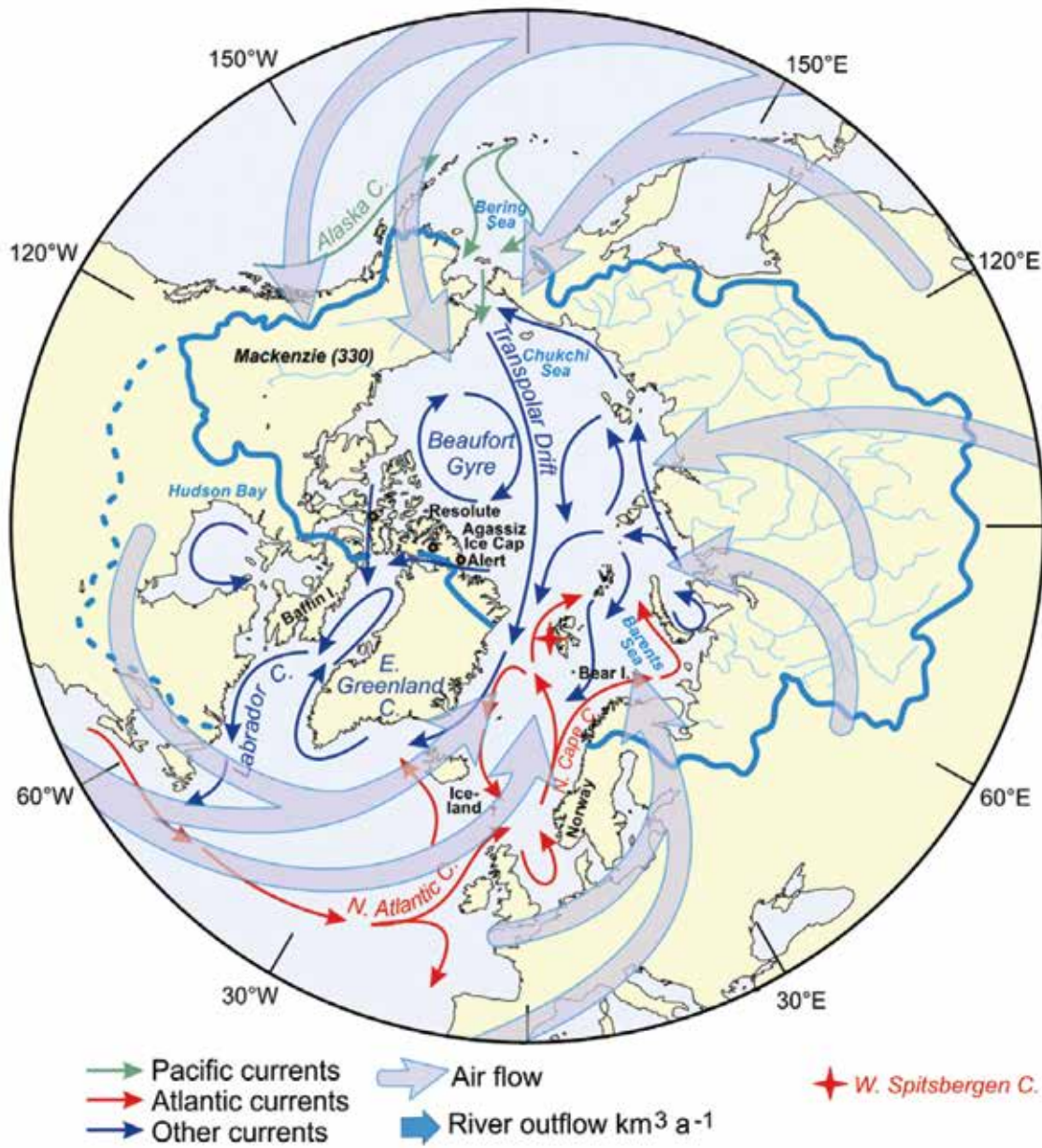


FIGURE 1. A schematic diagram showing the major surface currents in the Arctic Ocean and the predominant atmospheric transport pathways.

contaminants are distributed globally in air, soil, sediment, vegetation, other biota, water and ice. These environmental reservoirs may, in some cases, sequester contaminants for long periods (e.g., burial in marine and lake sediments, entry into abyssal ocean water), sequester them reversibly depending on climate and other conditions (e.g., glacial ice and snow, vegetation, surface water, food webs), or maintain them in active exchange cycles between reservoirs (e.g., air, surface water, vegetation, soil, and food webs). With the passage of time the contaminants tend to redistribute themselves away from locations of high concentration (technically, high fugacity) toward locations of low concentration. International controls during the past few decades have reduced primary emissions of classical contaminants. As a result, these environmental reservoirs (i.e., secondary sources) now play a greater proportional role within the Arctic. Secondary sources are strongly driven by climate conditions like temperature, precipitation, ice cover, and vegetation (Macdonald et al. 2005, Wang et al. 2010).

The western Arctic Ocean, which includes the Chukchi Sea and Beaufort Sea, lies upstream of the Canadian Arctic Archipelago (CAA) and supplies almost all of the ocean water transiting its passages (Figures 1 and 2). Therefore, concentrations of Hg and the OHCs in surface water of the western Arctic Ocean provide the starting point for water passing through the CAA and eventually into Baffin Bay. Surface seawater concentrations in the Arctic Ocean, which are available for HCH, PCB, and other organics like the perfluoroalkyl acids (PFOA) (e.g., Li et al. 2002, Sobek and Gustafsson 2014, Jantunen et al. 2015; Benskin et al. 2012 a,b) and THg (Wang et al. 2012), imply that a reservoir has built up over time in the Arctic Ocean. Li et al. (2004) estimated that at its peak accumulation in 1982 6670 t of α -HCH was held by the Arctic Ocean, and by 2000 the total amount that had entered into the Arctic Ocean exceeded 27 000 t, accounting for about 0.6% of the global emission from land to atmosphere. Sobek and Gustafsson (2014) estimated the total inventory of Σ^7 PCB to be 182 ± 40 t, the major contributors being river discharge (115 ± 11 t), ocean currents (52 ± 17 t) and atmospheric deposition (30 ± 28 t). Outridge et al. (2008) estimated that the Arctic Ocean contains 7920 t of THg, with 945 t of that in the upper ocean,

where it would be most accessible to biota. Atmospheric deposition is thought to be an important ongoing source of inorganic Hg to the Arctic Ocean (~ 100 t yr⁻¹), partly because of atmospheric mercury depletion events (AMDEs) that occur with polar sunrise, but ocean currents from the Pacific and Atlantic also supply considerable amounts of dissolved Hg (48 t yr⁻¹). It is likely that rivers and coastal erosion (60 t yr⁻¹) also play important roles, possibly dominant regionally, although much of this Hg may enter on particulates and end up being buried on the shelves (see, e.g., Dastoor et al. 2014, Fisher et al. 2012, Shang et al. 2015) rather than entering surface water passing through the Arctic Ocean.

10.3 The IRIS 2 region as a contaminant receptor

The CAA is an important pathway for Arctic Ocean surface water to pass into Baffin Bay and the North Atlantic Ocean (Figure 2a). The mechanisms by which the CAA receives sea water and the manner in which sea water becomes processed as it passes through the CAA is discussed in detail in Chapter 5 of this report. The passage of water through the CAA takes but a few years or less. Shallow sill depths, 125 m at Barrow Strait and 220 m in Nares Strait, together with strong density stratification, constrain withdrawal of water from the Arctic Ocean to shallow depths (Figure 2b). As a result, waters within the CAA are relatively rapidly replenished by Arctic Ocean surface seawater, and it is from this source that they inherit legacy contaminants. The Arctic Ocean surface water has a residence time of about 10 years, which means that the past few decades are the most important in terms of contaminant accumulations. Within the CAA, water properties and contaminant burdens are further modified by atmospheric exchange (deposition and evasion), the addition of river water (~ 220 km³ yr⁻¹), and processes like sea-ice formation and melting, primary production and degradation. Runoff within the CAA includes glacial melt, which under the present circumstances of warming in the Arctic provides a means to release legacy OHCs and Hg deposited during decades like the 1950s and '60s when usage was much higher (Macdonald et al. 2005, Blais et al. 2001).

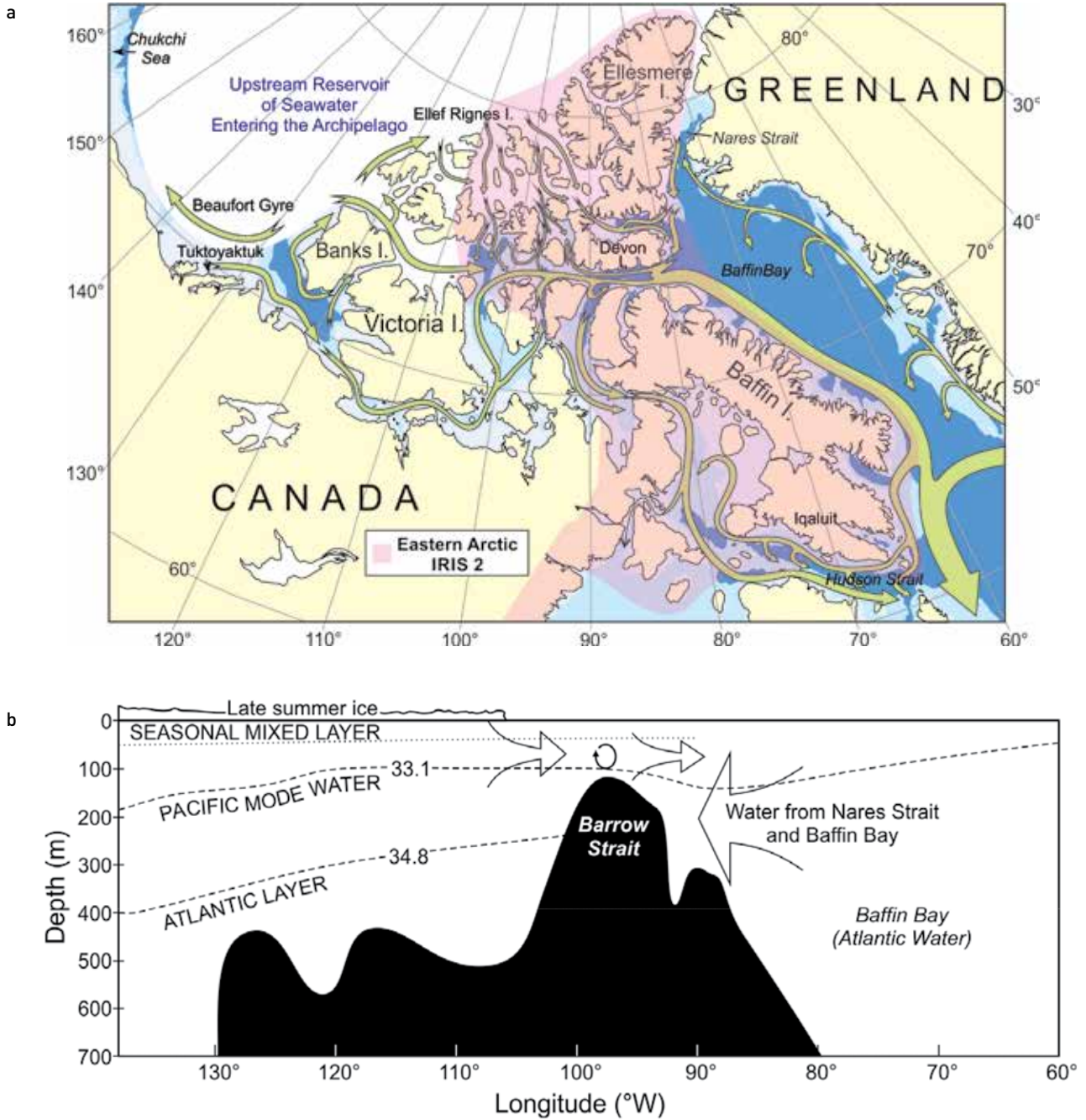


FIGURE 2. A schematic diagram showing (a) the major currents associated with the Canadian Arctic Archipelago, and (b) the water structure and bathymetry within the Archipelago (after Bidleman et al. 2007).

The HCHs provide a clear example of how up-stream ocean reservoirs may affect OHC burdens in the CAA. The emission histories for HCHs are relatively well known, and there are adequate water and air data to infer trends with time in surface waters of the Arctic Ocean (e.g., Li et al. 2004, Macdonald et al. 2000, Wania and Mackay 1999, Harner et al. 1999, Li et al. 2002, Shen et al. 2004, Bidleman et al. 2007, Jantunen et al. 2015). Because the HCHs have a strong affinity for water, especially cold water, a large portion of the HCH transported by air ended up in northern surface waters producing concentrations of α -HCH that exceeded 6 ng L^{-1} in some places during the 1980s. β -HCH also loaded into Arctic Ocean surface waters, but because it had an even higher affinity for cold water the Asian source was rained out or exchanged into surface water in the Bering Sea, before it could get to the Arctic thence to enter the Chukchi and Beaufort seas about 10 years later via water currents through Bering Strait (sill depth of $\sim 50 \text{ m}$) (Li et al. 2002). This large-scale regional separation of HCH compounds due to differing physical properties is more than of casual interest: it has biological significance as elegantly exemplified by bowhead whales, whose tissues exhibited a seasonal variation in HCH α/β ratio due to altered contaminant exposure along their annual foraging migration between the Bering Sea and Beaufort Sea (Hoekstra et al. 2002).

Degradation rates for both α - and β -HCH are slow enough to permit buildup of the inventories in Arctic Ocean surface water over time, with a major removal pathway being outflow into the CAA channels. The western CAA, therefore, reflects the upstream loading of surface waters in the Canada Basin (Figure 2b). Once past the sill at Barrow Strait, the eastern CAA surface waters reflect a mixture of water from the Beaufort Sea (historically higher concentrations) with water of lower HCH concentration from the Atlantic Ocean (Figure 2b), which sets up a longitudinal gradient across the CAA (Bidleman et al. 2007). Presently, CAA waters are shedding some of this HCH by evasion to the atmosphere either within the CAA itself (Jantunen and Bidleman 1995) or into the Labrador Sea (Shen et al. 2004), which would further augment concentration declines from west to east. Microbial degradation and export of HCH from the Canada Basin has, subsequently, led to the

decline in HCH in the Arctic Ocean's surface waters such that HCH will become undetectable by ~ 2020 (Pućko et al. 2013). At that point the Beaufort Sea reservoir will play little role in supplying HCH to the CAA. Although we have fewer data for β -HCH, it seems clear that this compound will follow a similar temporal pattern to α -HCH but with a delay of ~ 10 yrs (Li et al. 2002).

Perfluoroalkyl acids (PFAAs) are highly chemically stable and "terminal" degradation products resulting from the transformation of precursor perfluorinated alkyl substances (PFASs). Chemicals categorized as PFASs have been manufactured in large quantities for over 60 years and used in a wide range of applications including aqueous firefighting foams, grease-proofing paper, textile stain and soil repellents, processing aids in fluoropolymer manufacturing. The use of PFASs in various commercial products has ultimately led to a release of large quantities to municipal waste waters and directly to the atmosphere, leading to the degradation of these precursors and with the formation of PFAAs which are essentially non-degradable in the environment (Li et al. 2017). In particular, PFOS would be widely recognized as a degradation product of the side-chain fluorinated polymers found in the pre-2002 fabric stain protector product called Scotchgard™ (Chu and Letcher 2014). Because PFAAs are strong acids that highly favour aqueous media in their conjugate base anion form (e.g., Gouin and Wania 2007), they provide an interesting comparison with the HCHs. Based on surface water samples collected between 2005 and 2009, Benskin et al. (2012b) constructed a transect showing the spatial distributions of two dominant compounds, PFOA (perfluorooctanoic acid) and PFOS, in surface water across the CAA (Figure 3). Like the HCHs, these PFAAs and PFASs have accumulated in Canada Basin surface waters, entering in part through Bering Strait. Although it is likely that the CAA inherits these upstream concentrations as a starting point, the higher concentrations observed in the central and eastern CAA suggest further atmospheric deposition of PFAAs and PFOS and/or their PFAS precursors. For waters east of Barrow Strait we would expect that transport within Atlantic surface currents has played a dominating role.

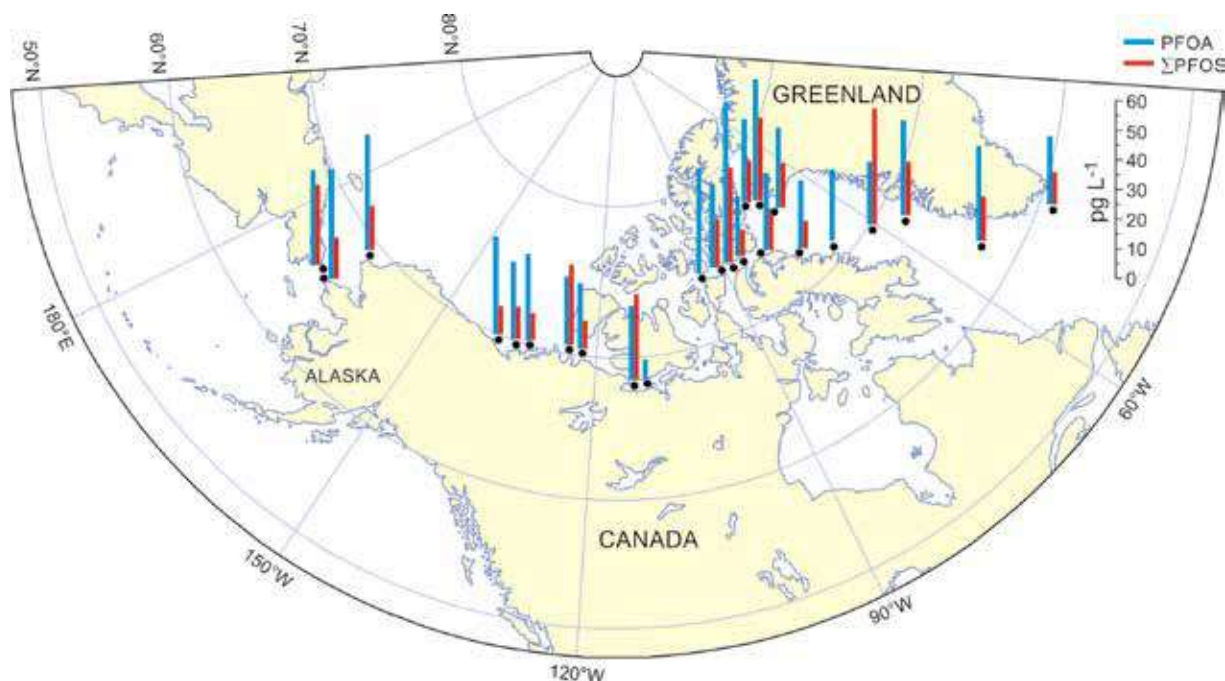


FIGURE 3. The distribution of perfluorooctanoic acid (PFOA) and perfluorooctanesulfonate (PFOS) in surface waters of the CAA (2007 and 2009 data; adapted from Benskin et al. 2012a).

PFAA chemical compositions provide direct insight into manufacturing sources and timescales for these PFASs. Historical production using electrochemical fluorination, which produces a mixture of branched and linear compounds, was supplanted in the 2000s by telomerization, which produces only linear compounds. Examination of spatial data (Benskin et al., 2012a) indicates that surface water in the North Atlantic Ocean is strongly tagged by historical electrochemical production products, whereas the North Pacific and Western Canadian Arctic contains more recent telomerization products likely from Asian sources. These authors inferred from these data that the PFAAs endure for long periods within seawater, and that important sources to the CAA include Atlantic and Pacific oceanic pathways plus atmospheric deposition within the CAA.

The detailed case for HCH demonstrates the importance of contrasts in contaminant concentrations in Arctic Ocean and Baffin Bay surface waters in determining background spatial trends in CAA waters. Unfortunately, we have insufficient data or time series for other legacy

OHCs, but we can infer that gradients between east and west Archipelago waters have likely been set in the same manner as for the HCHs. This broad background pattern is then altered within the CAA by air-sea exchange, degradation, sedimentation and river input of OHCs. For contaminants that have been introduced more recently into global cycles (e.g., PBDEs and PFOS), we can infer that atmospheric deposition within the CAA may presently be more important because surface ocean reservoirs have not had sufficient time to accumulate contaminants to their maximal concentrations. In the case of PFOS, where ocean transport is relatively important (e.g., see Armitage et al. 2009), the ocean pathways may already rival atmospheric pathways to the CAA.

Surface water in the Beaufort Sea also provides baseline concentration of THg entering the CAA. THg concentration is then modified by losses and gains within the CAA. Due to the technical difficulty of measuring Hg in sea water at pM (pico molar = 10^{-12} moles L^{-1}) concentrations, there are relatively few reliable ocean-section data. Recently,

TABLE 1. A summary of dissolved total Hg and monomethyl Hg concentrations in the North Pacific, Arctic and North Atlantic Oceans.

Location	Reference	THg (pM)	MMHg (pM)	n
North Pacific	Sunderland et al. 2009	0.99 ± 0.32	0.095 ± 0.052	48
Beaufort Sea	Wang et al. 2012	1.1 ± 0.45	0.20 ± 0.15	90, 57
CAA	Kirk et al. 2008	2.3 ± 2.4	0.31 ± 0.22	15
Baffin Bay (North Water)	Kirk et al. 2008	1.5 ± 1.3	0.30 ± 0.17	15
Hudson Bay	Hare et al. 2008	3.8 ± 1.7		25
Hudson Bay	Kirk et al. 2008	2.1 ± 2.6	0.19 ± 0.12	29
North Pole	Heimbuerger et al. 2015	0.54 ± 0.09	0.053 ± 0.033	12
Makarov Basin (85°N)	Heimbuerger et al. 2015	1.0 ± 0.25	0.21 ± 0.08	27
Amundsen Basin (81°N)	Heimbuerger et al. 2015	1.3 ± 0.23	0.16 ± 0.10	22
North Atlantic	Bowman et al. 2015	0.89 ± 0.30	0.095 ± 0.098	605, 432

several studies have produced high-quality data that provide a broad view of THg and MMHg in the North Pacific, Arctic and North Atlantic Oceans (Table 1). These data show no significant THg gradient between the N Pacific and the N Atlantic Oceans, with concentrations usually found to be about 1.1 ± 0.6 pM. The most interesting feature of the data in Table 1 is the relatively high concentrations seen in some surface samples in the CAA and Hudson Bay. There is mounting evidence that rivers may play an important role in supplying Hg to surface seawater in the Arctic (Heimbuerger et al. 2015, Andersson et al. 2008, Fisher et al. 2012, Zhang et al. 2015). Accordingly, it seems likely that the Mackenzie River may be an important modulator of THg in surface water entering the CAA (e.g., see Leitch et al. 2007, Wang et al. 2010). Within the CAA the ~ 220 km³ yr⁻¹ of runoff (Alkire et al., 2015) could produce high THg concentrations locally, if not regionally, in surface water, but there are no measurements of Hg in these small rivers. Hudson Bay receives ~ 700 km³ yr⁻¹ of runoff from many rivers distributed around the Bay (Dery et al. 2005). These rivers reportedly carry 0.7 – 3.5 pM THg concentration (Kirk and St. Louis 2009, Hare et al. 2008) and could, therefore, contribute to high THg concentrations observed in surface waters of Hudson Bay.

Using stable Hg isotopes, Lehnher et al. (2011) showed that reactions producing or destroying MMHg were rapid,

which implies that MMHg cannot be transported long distances in the water (Wang et al. 2012). Given that the residence time of water in the CAA is about three years, one would not expect MMHg entering the Archipelago from the Arctic Ocean to persist very far into the passages; instead, MMHg concentrations would reflect methylation processes occurring locally within the CAA (< a few 100 km). However, the lifetime of MMHg in natural seawater at ambient concentration remains unconfirmed. Further work is warranted given the potential importance of MMHg production over the Chukchi/Beaufort shelves, the region where nutrient-rich waters entering the western CAA are produced. The data in Table 1 suggest that production of MMHg is slow relative to destruction in the interior waters of the North Pacific, North Atlantic and at the North Pole, whereas the CAA and Baffin Bay (North Water), both of which have areas of higher primary production/regeneration, may produce more MMHg.

10.4 POPs in the marine ecosystem

10.4.1 Fish and invertebrates

Persistent organic pollutants (POPs), and more specifically organohalogen contaminants (OHCs), bioaccumulate in organisms and increase with each trophic level in the marine food web, biomagnifying to levels that can affect arctic

wildlife and human health (Letcher et al. 2010; McKinney et al. 2012). Invertebrates and fish are excellent indicators of environmental contamination since these organisms can bioaccumulate POPs from the water, sediments, and their diet. Invertebrates and fish, especially Arctic cod (*Boreogadus saida*), are also major diet items of marine mammals in the Arctic. Measuring levels of contaminants in these organisms enables us to interpret and predict the levels and trends of contaminants in marine mammals. Further, a number of fish species are important traditional food items for Inuit.

Very few studies have reported OHC concentrations in Arctic marine invertebrates and fish in the Eastern Canadian Arctic. Further, variations in POP concentrations and patterns can vary with trophic position (indicated by $\delta^{15}\text{N}$), body size, partition coefficients and bioaccumulation of individual compounds. Borgå et al. (2005) measured PCBs and organochlorine pesticide (OCP) concentrations in invertebrates and Arctic cod collected in 1998 from the North Water Polynya in northern Baffin Bay. In the copepod *Calanus* spp. ΣHCH (4.0 ± 3.2 ng/g wet weight (ww)) was found in greatest concentration followed by ΣPCBs , $\Sigma\text{chloro-danes}$ (CHL), $\Sigma\text{dichlorodiphenyltrichloroethane}$ (DDT) and hexachlorobenzene (HCB). The concentration profile differed in the pelagic amphipod, *Themisto libellula*, with ΣPCBs (2.9 ± 1.3 ng/g ww) being found in greatest concentration, followed by ΣCHL , ΣDDT , ΣHCH and HCB. For Arctic cod, ΣCHL (2.7 ± 0.7 ng/g ww) was found in greatest concentration, followed by ΣDDT , ΣPCB , ΣHCH and HCB. Fisk et al. (2003a) measured PCBs and OCP concentrations in seven species of zooplankton collected in 1998 in northern Baffin Bay. These included *C. hyperboreus* (herbaceous copepod), *Euchaeta glacialis* (omnivorous copepod), *Metridia longa* (omnivorous copepod), *Mysis oculata* (detritus feeding and predatory mysid), *Themisto libellula* (predatory amphipod), *Sagitta* sp. (predatory arrowworm), and *Pandalus* sp. (predatory shrimp). The ΣPCB and OCP concentrations varied between species, but in general ΣPCBs ($5.1 - 33.7$ ng/g ww) had the greatest concentrations and $\Sigma\text{chlorobenzenes}$ (CBz) ($0.29 - 0.78$ ng/g ww) had the lowest concentrations (Fisk et al. 2003a). HCB and HCH isomers in zooplankton are generally greater in



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the Western Canadian Arctic than the Eastern Canadian Arctic (Fisk et al. 2003a), which likely reflects the gradient set up by atmospheric and oceanic transport of these chemicals from Asian sources to the Western Canadian Arctic.

Benthic invertebrates tend to have a larger range in POP concentrations across species, with filter- and detritus-feeding invertebrates having some of the lowest concentrations among all biota (Fisk et al. 2003b). ΣPCBs are generally the contaminant found in highest concentration among most benthic invertebrates in the Canadian Arctic, with the greatest concentrations having been measured in the scavenging amphipod *Anonyx nugax* (Fisk et al. 2003b).

Studies in the Eastern Canadian Arctic have found that ΣPBDEs concentrations are greater in zooplankton (e.g., 72.9 ± 10.1 ng/g) than upper trophic level organisms (e.g., 0.4 ± 0.2 ng/g in walrus) (Morris et al. 2015, Morris et al. 2007, Tomy et al. 2008). These results, however, are not consistent with low concentrations found in invertebrates (range: 0.16-0.53 ng/g) from Svalbard (Sormo et al. 2006), which suggests large geographical variability in ΣPBDE concentrations in lower trophic level organisms across the circumpolar Arctic. This variability may be due to the later release of PBDEs into the environment than the classical OHCs with the result that spatial distributions in the ocean have had less time to even out through mixing, transport and exchange. Mean ΣPBDEs concentrations from the Hudson Bay region were 5.4 ng/g lw in the bivalve (*Mytilus edulis*), 9.8 ng/g lipid weight (lw) in Arctic cod (*Boreogadus saida*)

and 72.8 ng/g lw in sculpin (*Myoxocephalus scorpioides*) (Kelly et al. 2008). Hydroxylated (OH-) PBDEs were not detected in these three species, however methoxylated (MeO-) PBDEs were detected with OHBDE-47 representing 30-40% of Σ PBDEs (Kelly et al. 2008). Arctic cod mean Σ PBDE concentrations collected from Davis Strait (23 ng/g lw, Tomy et al. 2008) were similar to Arctic cod PBDE concentrations collected from Barrow Strait (23 ng/g lw, Morris et al. 2007) and Hudson Bay (9.8 ng/g lw, Kelly et al. 2008), but much lower than concentrations measured in cod from the Beaufort Sea (205 ng/g lw) (Tomy et al. 2009). This east to west variability could be due to differences in feeding ecology or due to the later release of PBDEs into the environment resulting in less time to even out through mixing, transport and exchange. Further research and longer time series are needed to understand these geographical patterns.

10.4.2 Ringed seals and polar bears

The ringed seal (*Pusa hispida*) and the polar bear (*Ursus maritimus*) are ideal species for assessing the spatiotemporal trends of OHCs within arctic marine ecosystems. Both species have circumpolar distributions, but individuals of regional subpopulations have a relatively modest home range. Further, ongoing studies have secured samples from both species at various locations across the Canadian Arctic enabling a strong spatial OHCs dataset for comparing average levels between regions. OHCs including PCBs, PBDEs, PFOS, PFCAs, and pesticides (e.g., DDT, CHL, and HCH) can biomagnify to high levels in top predators (Muir et al. 2013). As the top trophic feeding predator of Arctic and subarctic marine food webs, polar bears accumulate high levels of OHCs from their primary prey species, the ringed seal.



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The ringed seal, which is the most abundant Arctic pinniped species, is also considered a top predator in nearshore pelagic food webs. This seal species has a diet that consists of a wide variety of pelagic and benthic invertebrates and fish (e.g., Arctic cod, capelin (*Mallotus villosus*), sand lance (*Ammodytes* sp.), and sculpin (*Cottidae*)) (McLaren 1958, Gjertz and Lydersen 1986, Labansen et al. 2007). At higher latitudes in the Arctic, adult ringed seal have been reported to consume more forage fish (e.g., Arctic cod), than sub-adults which consume more pelagic zooplankton. In contrast, sub-adult and adult seals at lower latitudes both consume more sub-Arctic fish species and pelagic zooplankton (Yurkowski et al. 2015). As mentioned above, ringed seals generally forage within limited areas (Thiemann et al. 2007), however, some regional movements, e.g., from the Western Canadian Arctic to the Bering Sea and East Cape of Siberia (Smith 1987, Harwood et al. 2012, Harwood et al. 2015), from the Labrador coast to Ungava Bay and western Baffin Island (Brown et al. 2014), and between Greenland and Canadian waters have been documented (Teilmann et al. 1999). Adult female ringed seals and polar bears typically have lower levels of OHCs than adult males, due to loss by reproductive females of contaminant load to offspring.

10.4.2.1 Spatial trends of organohalogen contaminants (OHCs) in ringed seals

Despite being banned for numerous decades, Σ PCBs remain the dominant legacy organochlorine (OC) contaminant in ringed seals across the Arctic, followed by Σ DDTs and Σ CHLs (Table 2). This trend is consistent with previous findings which show PCBs remaining the major POP in ringed seal blubber (Muir et al. 2013, Addison et al. 2014). One previous study, however, found Σ DDTs to be the major OC in the Western Canadian Arctic (Gaden et al. 2012). Legacy OC concentrations, which include PCBs and some OCPs, are generally greater in the east compared with the west, with the exception of toxaphene, Σ HCHs, α -HCH, and β -HCH (Table 2; Figure 4). This is consistent with previous Canadian Arctic studies which have shown higher levels of most of the legacy OCs, except for toxaphene, and β -HCH, in ringed seals from the Eastern Canadian Arctic than in

seals from the Western and central Canadian Arctic (Fisk et al. 2003b). Elevated levels in the west likely reflect the greater use of β -HCH in Asia, the strong partitioning of HCHs and toxaphene into cold water, and efficient atmospheric/oceanic transport pathways to the Western Arctic (Figure 1, Li et al. 2002). The reason for generally greater concentrations of PCBs and OCPs in the east is not clear. However, these greater concentrations may reflect global usage patterns: many of these chemicals were used earlier and in greater amounts in North America and Europe than in Asia (Breivik et al. 2002). Furthermore, these compounds do not partition as strongly into cold water as the HCHs and, therefore, the pathway involving atmospheric transport directly to the Arctic followed by air-sea exchange may have been less important than deposition in the ocean close to sources and subsequent transport northward in ocean surface currents (see, e.g., Stemmler and Lammel 2009). The greater Eastern Arctic concentrations could also reflect, partially, the release of archived chemicals deposited onto permanent snowfields and small glaciers within the CAA, which are now receding. Some of the legacy OCs (e.g., Σ PCBs, PCB 153, Σ CHLs, Σ DDTs, p,p'-DDE, and ClBzs) are relatively elevated in ringed seals from Sachs Harbour (Table 2; Figure 4). The greater relative OC concentrations from the Beaufort Sea region may be due to these seals feeding at a higher trophic position relative to seals from other regions (see Table 3 in Brown et al. 2016) or that there have been some continuing inputs of some of these compounds (e.g., Σ DDTs, p,p'-DDE) to the Western Canadian Arctic, despite restrictions on their use in North America during the 1970s (Addison et al. 2014).

PBDEs have been used since the 1980s, mainly as flame retardants in fabrics and other materials, and continue to be used in in-use products despite increasing restrictions and bans on use which were implemented in the early 2000s. Like other POPs, PBDEs accumulate to high levels in upper trophic level marine mammals. BDE-47 is the dominant congener in ringed seals and represents approximately 55 – 80% of Σ PBDEs (Ikonomidou and Addison 2008, Kelly et al. 2008). The most recent data show greater concentrations in the south, which decline northward in the Canadian Arctic; greatest average Σ PBDEs concentrations are found

TABLE 2. Geometric means and 95% confidence intervals (ng/g lipid weight) of chlorinated, brominated and fluorinated contaminants in ringed seals collected from 2003-2010.

	Sachs Harbour	Ulukhaktok	Arctic Bay	Gjoa Haven	Grise Fiord	Resolute	Qikiqtarjuaq	Pangnirtung	Arviat	Inukjuak	Ungava	Nain
<i>n</i>	33	16	19	22	17	52	7	22	62	10	3	8
ΣPCBs ^b	488.7	328.1	334.2	415.0	509.3	358.1	248.9	275.4	338.1	247.2	539.5	912.0
	399.9-597.0	267.3-402.7	274.8-406.4	349.1-492.0	379.3-685.5	310.5-414.0	201.4-307.6	208.4-364.8	287.7-397.2	167.5-363.9	92.0-3169.6	653.1-1270.6
PCB153 ^b	69.3	15.8	45.1	72.1	67.5	40.3	33.0	45.6	43.0	42.3	71.1	201.8
	49.2-97.7	9.1-27.2	34.3-59.2	59.0-88.1	47.6-95.5	33.5-48.4	20.8-52.2	33.5-61.9	33.4-55.3	26.7-66.8	11.5-439.5	142.6-285.8
ΣCHL ^b	225.4	121.3	125.3	120.8	183.7	193.6	152.1	179.1	121.3	101.2	131.5	283.1
	185.8-273.5	97.7-150.7	104.2-151.0	101.2-143.9	128.5-263.0	166.0-225.9	122.2-189.2	143.5-222.8	97.5-150.7	66.2-154.5	10.5-1648.2	196.8-407.4
ΣCIBz ^b	51.2	38.2	29.4	41.4	35.2	41.8	41.0	37.5	18.0	12.6	51.5	32.6
	42.3-61.8	33.1-44.1	24.2-35.6	36.4-47.1	30.3-40.9	37.8-46.2	32.9-51.3	32.4-43.5	15.9-20.4	10.5-15.2	25.1-105.7	23.5-45.1
ΣDDTs ^b	248.3	113.0	181.1	106.9	276.7	186.2	177.0	228.0	145.5	132.4	323.6	599.8
	189.2-325.8	84.3-151.4	137.1-239.3	88.7-128.5	203.7-376.7	155.6-222.3	127.1-246.6	180.7-287.7	119.9-177.0	84.7-206.5	39.5-2654.6	376.7-957.2
<i>p,p'</i> -DDT ^b	36.5	21.2	26.2	18.1	48.8	27.0	22.9	22.8	10.4	n.a.	n.a.	n.a.
	26.6-50.0	16.8-26.7	20.6-33.2	15.0-21.9	37.8-63.0	22.2-33.0	18.1-28.8	17.3-29.9	8.2-13.2	n.a.	n.a.	n.a.
<i>p,p'</i> -DDE ^b	196.8	91.6	140.0	78.2	205.1	141.6	134.3	194.5	128.8	116.7	298.5	540.8
	150.0-258.2	65.9-127.1	102.1-191.4	64.1-95.5	146.2-287.1	117.2-171.0	91.0-198.2	153.5-246.6	105.9-157.0	73.8-184.5	36.6-2426.6	351.6-829.9
Dieldrin ^b	42.1	34.5	36.7	37.8	46.2	50.9	45.0	41.0	25.1	27.1	48.4	61.5
	33.3-53.2	26.2-45.6	29.0-46.7	32.1-44.6	37.4-57.3	44.2-58.7	33.0-61.4	32.7-51.5	20.8-30.2	20.3-36.2	13.4-175.4	38.4-98.6
Toxaphene ^b	95.3	150.3	104.2	45.1	118.3	134.6	n.a.	101.6	52.6	84.5	73.1	n.a.
	70.8-128.2	94.2-239.9	78.5-138.0	36.3-56.0	76.0-184.1	106.7-169.4	n.a.	71.3-144.9	43.3-64.0	54.1-131.8	9.4-564.9	n.a.
ΣHCHs ^b	147.9	99.1	78.2	61.0	61.7	100.5	85.7	91.8	50.9	53.8	75.5	102.1
	121.1-181.1	71.8-136.8	67.1-90.8	49.5-75.0	48.8-77.8	88.5-114.3	73.8-	77.4-108.6	41.9-62.1	42.4-68.5	11.2-509.3	80.2-130.3
α-HCHs ^b	100.0	72.9	49.4	42.5	35.6	64.9	56.5	51.5	40.0	42.8	27.2	67.8
	78.9-126.8	49.5-107.2	41.3-59.3	34.4-52.2	27.4-46.2	56.5-74.5	47.5-67.0	44.5-59.6	33.0-48.5	33.9-53.8	0.7-1013.9	53.7-85.3
β-HCH ^b	40.4	27.9	24.4	15.6	22.5	30.3	26.6	35.8	7.9	9.0	40.1	30.9
	34.3-47.5	23.7-32.8	20.5-29.0	12.1-20.0	18.2-28.0	26.2-34.8	22.3-31.7	28.2-45.4	6.1-10.3	6.4-12.5	15.2-105.7	21.4-44.7
ΣPBDES ^b	5.1	4.9	2.8	11.1	5.0	5.1	5.7	8.1	10.0	16.1	13.5	28.8
	3.7-6.9	3.3-7.4	1.4-5.6	8.9-13.9	3.3-7.6	4.0-6.5	3.2-10.0	6.9-9.5	8.4-11.9	9.6-26.9	1.8-101.9	19.1-43.6
ΣPFCA ^c	14.5	15.8	15.9	71.3	20.2	11.7	27.8	8.2	28.1	43.9	5.9	20.0
	11.0-19.1	10.8-23.3	10.9-23.2	52.1-97.7	13.8-29.7	10.0-13.7	23.7-32.7	5.6-12.1	24.5-32.2	35.0-55.1	1.3-26.7	14.5-27.7
PFOS ^c	8.3	8.3	10.4	32.4	21.5	5.6	22.1	5.6	17.5	36.5	5.1	21.9
	6.3-10.9	5.5-12.5	7.7-13.9	20.7-50.7	13.7-33.9	4.9-6.5	17.2-28.5	3.7-8.5	15.0-20.3	28.3-47.0	2.6-10.0	15.3-31.2

^a Data from Muir et al. (2013); ^b Blubber tissue; ^c Liver tissue.

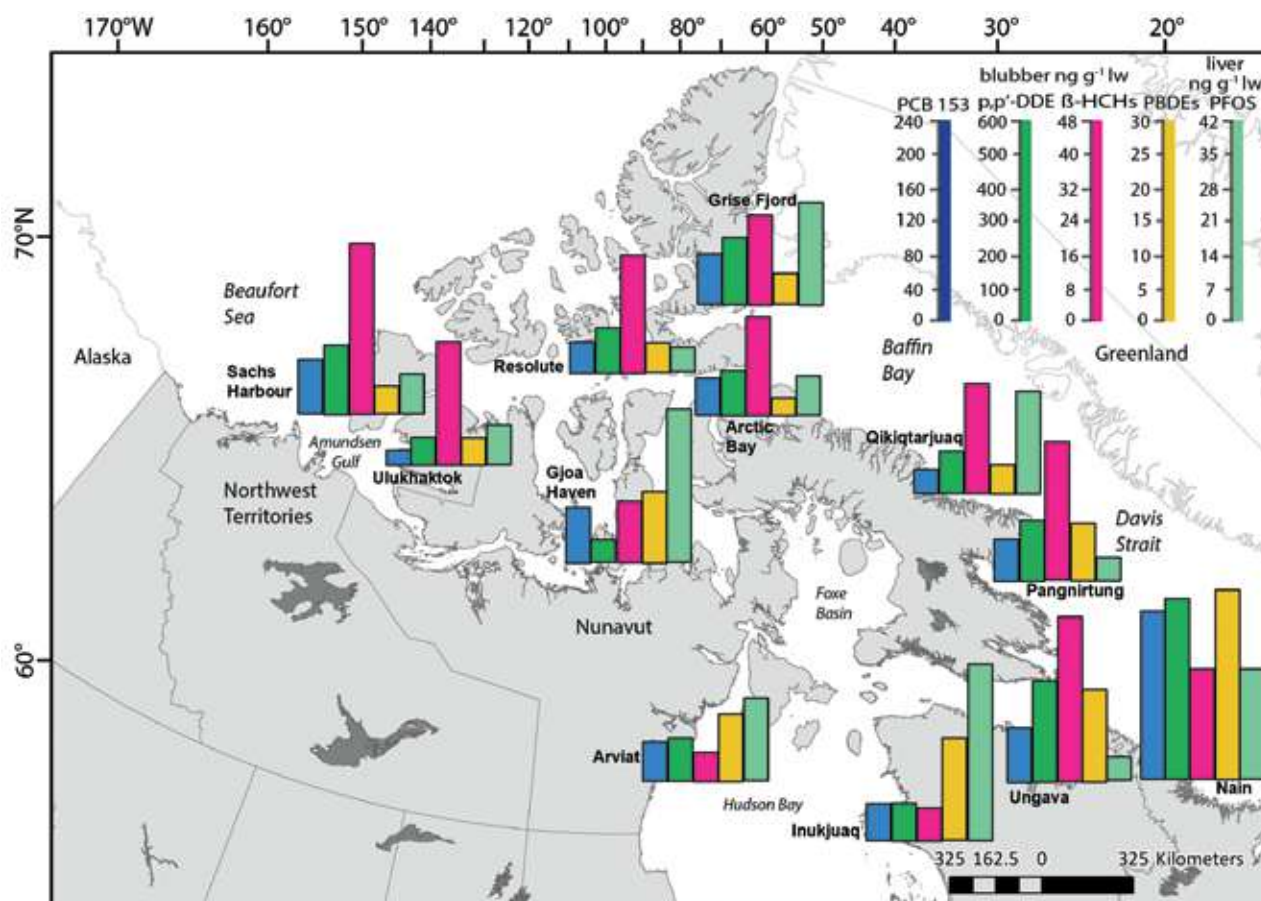


FIGURE 4. Geometric means (ng/g lipid weight) of PCB 153, *p,p'*-DDE, β -HCHs, Σ PBDEs, and PFOS of ringed seals collected from 2003-2010. Data adapted from Muir et al. (2013).

in ringed seals from southern locations in the Eastern Canadian Arctic, e.g., Nain, Inukjuak, and Ungava (Table 2; Figure 4). This is consistent with a recent Canadian Arctic study which showed higher levels of PBDEs in ringed seals from the south than in seals from the northern Canadian Arctic (Houde et al. 2017). This broad south to north distribution likely reflects the relatively early stage of environmental loading of the PBDEs compared to the legacy contaminants. At this stage highly contaminated reservoirs (soils, vegetation, etc.) in temperate industrial regions supply atmospheric transport through seasonal volatilization, which spreads the contaminants northward (see, e.g., Gouin et al. 2004). Average Σ PBDE concentrations in Gjoa Haven were also relatively great, which may be due more to seals

from this area feeding at the highest level of the food web ($\delta^{15}\text{N}$ mean value of 5.6) and having a depleted relative carbon source (RCS) (mean value of 0.8) relative to seals from other areas (Brown et al. 2016), than it has to do with major sources or Σ PBDE transport routes.

PFASs were produced via two major synthesis processes: electrochemical fluorination (ECF) and telomerisation (Buck et al. 2011). The ECF process was used primarily by the 3M Company from the 1950s to 2001 in the production of perfluorooctane sulfonyl fluoride (PFOSF) chemicals which include PFOS. In 2001, the 3M Company announced the phase out of its PFOSF-based chemicals in favour of shorter chain-length compounds (Butt et al. 2010). However, PFOS has continued to be produced in

China since 2003. In contrast, the telomerisation process has been used by various companies since the 1970s for the production of fluorotelomer alcohols (FTOHs), fluorotelomer olefins, fluorotelomer acrylates, fluorotelomer iodides, and PFCAs. FTOHs degrade to PFCAs (Hurley et al. 2004) and research suggests that the fluorotelomer olefins (Nakayama et al. 2007), fluorotelomer acrylates (Butt et al. 2009), and fluorotelomer iodides (Young et al. 2008) may form PFCAs via atmospheric oxidation. In contrast to legacy POPs which accumulate in lipid rich tissues, PFCAs and PFOS are associated with proteins and accumulate mainly in the liver, kidneys, and bile secretions (Butt et al. 2010). The sources and transport routes of PFASs to the Arctic are not well understood. However, two pathways have been suggested: atmospheric transport and oxidation of volatile precursors and direct transport of PFASs and PFASs via ocean currents (Butt et al. 2010). Local inputs are likely minimal, however a few studies indicate that both atmosphere and ocean provide transport pathways to the CAA (Benskin et al. 2012a,b).

Similar to the spatial Σ PBDEs trends in ringed seals, Σ PFCAs and PFOS were greater in more southern locations in the Eastern Canadian Arctic, Hudson Bay and Labrador (e.g., Inukjuak, Arviat, Qikiqtarjuaq, and Nain) than in ringed seals from other locations further north (Table 2; Figure 4). These observations are consistent with previous findings which also showed higher levels of PFCs in ringed seals from these locations (Butt et al. 2008). Consistent with Σ PBDE trends, ringed seals from Gjoa Haven had relatively greater average Σ PFCAs and PFOS concentrations. Similarly, these observations may be a result of these seals feeding at a high trophic level and having a depleted RCS than due to predominant transport routes of PFASs to the Arctic.

10.4.2.2 Spatial trends of OHCs in polar bears

PCBs are among the dominant OHCs in arctic marine mammals and levels in polar bears are among the highest reported in any species (Norstrom et al. 1998, Letcher et al. 2010, 2018, McKinney et al. 2011a). Σ PCBs are the major legacy OC in polar bears from all locations

across the Canadian Arctic, followed by Σ CHLs, Σ CIBz and Σ DDTs (Table 3). Σ PCBs, PCB153, Σ DDTs, and p,p'-DDE concentrations were generally greater in polar bears from the Eastern Canadian Arctic compared with the west, except for Σ PCBs and PCB153 concentrations in bears from the Beaufort Sea which also showed relatively high levels (Table 3; Figure 5). These observations are consistent with previous studies on polar bears from Alaska to East Greenland and Svalbard which showed Σ PCBs and Σ DDTs to be negatively correlated with longitude and that levels in Beaufort Sea populations were also elevated (Verreault et al. 2005, McKinney et al. 2011a). Previous studies have hypothesized that the elevated levels in the Beaufort Sea polar bears could be due to a greater reliance on ice-associated food webs than pelagic food webs or that the higher levels of these particle-associated OCs are related to the large input of suspended particulate matter from the Mackenzie River (Norstrom et al. 1998, McKinney et al. 2011a). Perhaps the higher levels of these OCs in the Beaufort Sea polar bears are due to the consumption of ringed seals from the Beaufort Sea region, which also have elevated levels of these contaminants relative to other locations in the Canadian Arctic. Average Σ PCBs and Σ DDTs in polar bears sampled across the Canadian Arctic are lowest in bears from the Gulf of Boothia and Lancaster/Jones Sound area (Table 3; Figure 5). Average Σ CHLs concentrations in polar bears showed a similar spatial trend to PCBs and DDTs and were greater in the east than the west (Table 3). These results however are inconsistent with previous studies which found Σ CHLs in polar bears to be spatially uniform across the Arctic (McKinney et al. 2011b). Unlike Σ PCBs and Σ DDTs, mean β -HCH was positively correlated with longitude due to higher levels in the west compared with the east (Table 3). As was the case for invertebrates, fish, and ringed seal, elevated concentrations of β -HCH in the west likely reflect the greater use of β -HCH in Asia and atmospheric/oceanic transport to the Western Canadian Arctic. OCS, Dieldrin and Mirex levels were relatively low in polar bears (< 250 ng/g lw) and were spatially uniform across the Arctic. The lack of spatial trend observed in these legacy OCPs may result from a lower historical loading of the Beaufort Sea through gas

TABLE 3. Geometric means and 95% confidence intervals (ng/g lipid weight) of chlorinated, brominated and fluorinated contaminants of adult and sub-adult male and female polar bears collected from 2005-2008.^a

	South Beaufort Sea	North Beaufort Sea	Gulf of Boothia	Lancaster/ Jones Sound	Baffin Bay	Davis Strait	West Hudson Bay	South Hudson Bay
<i>n</i>	17	29	7	13	14	9	12	21
Σ PCBs ^b	3688 2600-5232	5541 4518-6797	2445 1599-3739	2598 2005-3366	3211 2305-4472	4674 2693-8114	4634 3072-6992	5523 4617-6608
PCB153 ^b	1168 1158-1179	1934 1923-1945	864 853-874	970 963-977	1113 1002-1125	1176 1158-1195	1660 1639-1681	1937 1927-1948
Σ CHL ^b	1268 926-1736	1982 1555-2525	1824 1135-2930	1130 788-1619	2167 1523-3083	2135 1383-3298	3477 2386-5068	2166 1604-2924
Σ CIBz ^b	145 106-197	237 199-282	304 231-400	234 194-283	266 205-344	255 149-435	221 174-279	171 150-194
Σ DDTs ^b	81.8 60.5-110	93.7 79.9-110	31.5 19.8-49.7	64.0 44.1-92.7	179 125-257	104 60.0-181	88.1 54.8-141	152 127-182
p,p' -DDT ^b	18.1 17.9-18.3	12.5 12.4-12.7	1.3 1.3-1.3	5.4 5.3-5.5	8.2 8.0-8.3	2.7 2.6-2.7	6.3 6.2-6.4	5.1 5.0-5.2
p,p' -DDE ^b	29.9 29.5-30.4	53.0 52.6-53.3	21.1 20.7-21.4	44.0 43.0-45.0	124 123-126	46.4 44.6-48.2	56.1 55.1-57.2	113 112-114
Dieldrin ^b	69.0 47.5-100	126 104-153	150 111-202	115 90.8-146	197 161-241	183 103-323	244 185-322	143 111-185
Σ Mirex ^b	32.9 24.0-44.8	50.0 42.4-59.0	22.6 14.7-34.6	22.5 18.3-27.6	33.1 25.5-42.9	33.3 17.9-61.1	50.4 34.5-73.5	51.7 41.7-64.0
α -HCHs ^b	38.9 28.4-53.1	63.5 56.7-71.1	91.3 70.3-119	46.7 34.3-63.4	32.7 27.8-38.3	34.9 23.4-51.9	48.9 38.1-62.8	65.7 53.7-80.3
β -HCH ^b	249 190-326	307 250-379	542 361-815	238 174-324	137 101-186	202 139-294	141 102-196	113 87-147
Σ PBDEs ^b	5.8 4.3-7.9	8.8 7.7-10.0	7.0 4.5-10.7	6.8 5.1-9.0	14.0 11.4-17.0	27.1 16.7-43.4	38.6 27.5-54.0	78.4 65.6-93.6
Σ PFCA ^c	420 418-422	445 443-447	387 384-391	321 320-323	433 429-437	243 242-244	362 359-364	657 653-661
PFOS ^c	723 717-729	639 634-643	515 512-518	638 633-643	1007 1000-1014	494 489-498	793 788-798	1551 1543-1559

^aData from McKinney et al. (2011a) and Letcher et al. (2010); ^bBlubber tissue; ^cLiver tissue.

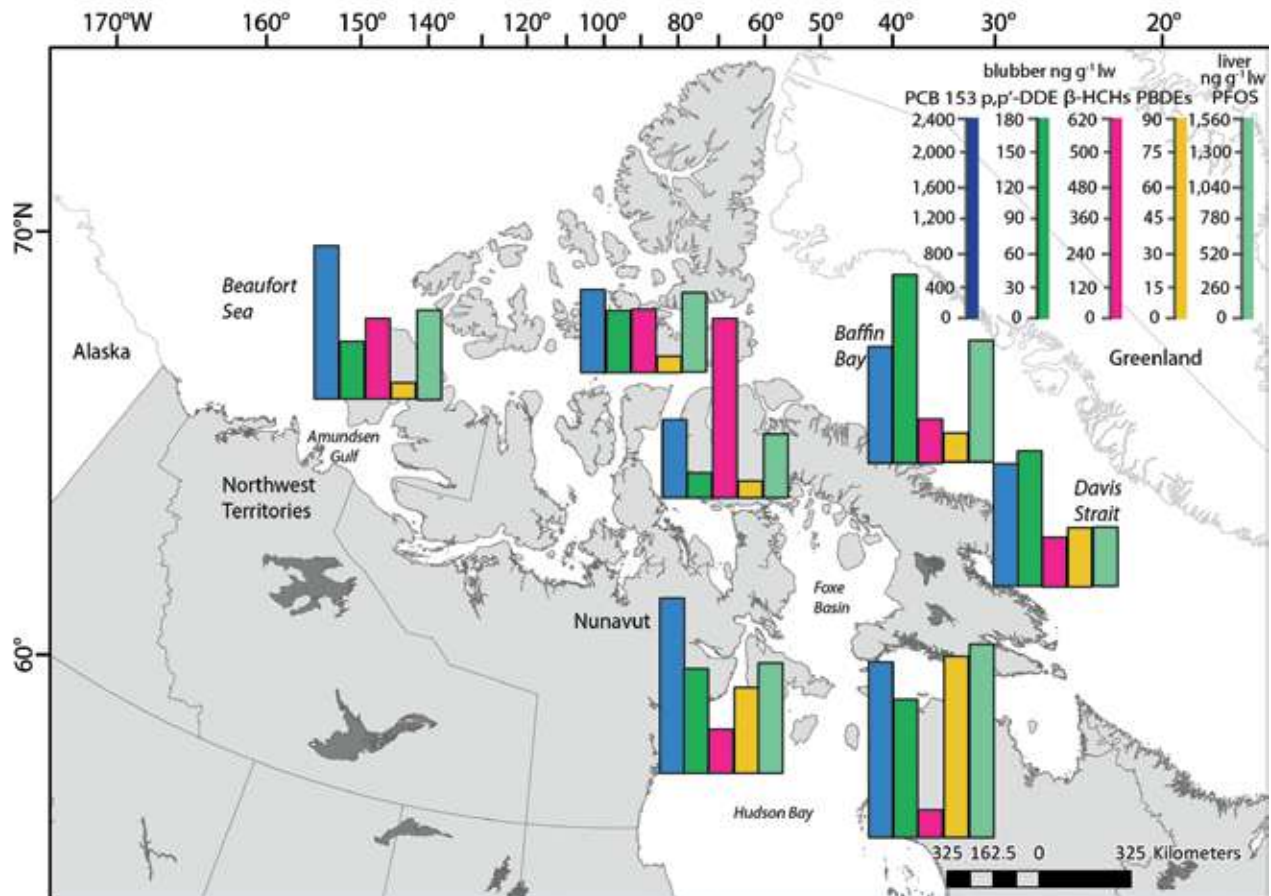


FIGURE 5. Geometric means (ng/g lipid weight) of PCB 153, *p,p'*-DDE, β -HCHs, Σ PBDEs, and PFOS of polar bears collected from 2005-2008. Data adapted from McKinney et al. (2011a) and Letcher et al. (2010).

exchange, resulting in a more even distribution produced by historical atmospheric transport and deposition.

Σ PBDEs, Σ PFCAs, and PFOS concentrations in polar bears vary across the Arctic, with the highest levels found in Hudson Bay, intermediate levels in the Eastern Canadian Arctic (Baffin Bay and David Strait) and low levels in the Gulf of Boothia, Lancaster/Jones Sound, and the Western Canadian Arctic (Table 3; Figure 5). Similar to ringed seals, the higher levels of these compounds observed in polar bears from southern latitudes (e.g., Hudson Bay) relative to higher latitude locations may reflect that these are newer POPs which have had a shorter time period to be

transported to the Arctic and to work their way up through the Arctic food web.

10.4.2.3 Temporal trends of OHCs in ringed seals and polar bears

Most of the legacy OCs appear to be declining with time in ringed seals and polar bears, however there is strong evidence over the last decade of stalling declines in PCB and CHL levels (Letcher et al. 2017, Letcher et al. 2018), which may be related either to continued emissions from in-use materials and stored wastes despite the banning of these product in the 1970s (McKinney et al. 2011a) or the release



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of these compounds archived earlier in global environmental reservoirs (soils, vegetation, snow, ice) due to climate change (e.g., warming, permafrost melting, forest fires) and subsequent redistribution northward (Macdonald et al. 2005, Ma et al. 2016). Σ DDTs have declined significantly in ringed seals since 1998. Toxaphene concentrations in ringed seals have increased in Lancaster Sound and east Baffin over the period of 2008 to 2010. α -HCH has declined significantly in ringed seals in the east, whereas β -HCH increased in Resolute but not in east Baffin (Muir et al. 2013). Earlier studies reported that although global emissions of α - and β -HCH have declined since the early 1980s, there appears to be a lag in response time in ringed seal tissue concentrations (Addison et al. 2009), which is not surprising given the time required to load these compounds into polar seas and then release them through, for

example, outflow through the CAA (Li et al. 2000, Pućko et al. 2013) .

Σ CHL and *p,p'*-DDE concentrations in polar bears have decreased from 1989 to 1996 and 1996 to 2002 and from 2005 to 2008 in most Canadian bear subpopulations (Muir et al. 2013). Higher PCB concentrations were reported in the period of 2005-2008 compared to 2001-2002 for all locations across the Arctic, except for Hudson Bay. Dieldrin levels show no overall declines. Overall PCB levels appear to have levelled off in the 2000s in most subpopulations, subsequent to the declines observed in the 1990s (Norstrom et al. 1998). Unfortunately, temporal comparisons of α -HCH and CBzs were confounded by erroneously low adipose levels in some of the bears and therefore were not reliable (McKinney et al. 2010). Longer-term trends (17-year period) in Hudson Bay show that Σ DDT decreased (11% per year),

α -HCH decreased (12% per year), β -HCH increased (8.3% per year), and Σ PCBs and Σ CHL showed no distinct trends dating back to 1968.

Σ PBDEs have generally increased from 1990s until early 2000s in ringed seals and/or polar bears and are now declining (2005-present). Ringed seals and polar bears achieved maximum Σ PBDEs concentrations during the period of 2000–2004, which were then followed by a decline from 2005 onwards which likely reflects the 2004 pentaBDE and octaBDE phase-outs (de Wit et al. 2010). This rapid response likely indicates that the upstream reservoir in the Beaufort Sea was not strongly loaded and therefore provided a source of low-concentration water to hasten the removal of chemicals deposited atmospherically into the CAA. Maximum levels of PFCs in ringed seal and polar bear livers were reached in the early 2000s in Hudson Bay and the Eastern Canadian Arctic and have continued to decline. As reported in Letcher et al. (2018), in the liver and in samples from 2010 and including up to 2016, PFOS concentrations were consistently greater than for PFCAs, and there were no obvious increasing or decreasing trends for Σ PFCAs and PFOS for both subpopulations of bears over the 2007–2014 period. In contrast, PFAA levels in the Beaufort Sea seals have continued to increase slowly to 2011 (Muir et al. 2013). The maximum concentrations for PFOS in seals and polar bears achieved during the late 1990s and early 2000s were similar to PFOSF-based products during the 1990s.

Modelling results suggest that the redistribution of more water-soluble contaminants (e.g. PFOS and PFOA) from lower latitudes to the Arctic is ongoing and concentrations of these contaminants in the marine environment are expected to increase for the next 10 to 15 years (Stemmler and Lammel 2010, Wania 2007). As a result the distribution of more water-soluble POPs in the Arctic will likely result in a more varied distribution due to oceanic transport into the Arctic. This pattern may therefore be distinct from long range atmospheric transport (LRAT) of these contaminants as well as others, e.g., PBDEs, which tend to result in more uniform deposition fluxes.

10.5 Hg in the marine environment

Atmospheric, terrestrial, and oceanic pathways deliver Hg to Arctic marine waters, where they are taken up by algae and bacteria and transferred through the Arctic marine food web (Atwell et al. 1998, Campbell et al. 2005). Hg, mainly in the form of MMHg, can bioaccumulate and biomagnify in marine food webs (Atwell et al. 1998). The biomagnification of Hg in marine food webs in the Canadian Arctic has been studied in the North Water Polynya (Campbell et al. 2005), Cumberland Sound (McMeans et al. 2015), Hudson Bay (Young et al. 2010), Queens Channel (Clayden et al. 2015) and in the Eastern Beaufort Sea and Amundsen Gulf (Lockhart et al. 2005; Loseto et al. 2008a; 2008b). In the Eastern Canadian Arctic the biomagnification factor (0.256) of MeHg in Queens Channel, located east of Bathurst Island, was higher than in the North Water Polynya (0.223). Further research is needed to determine whether the physical, chemical, or biological characteristics of these ecosystems are influencing Hg bioaccumulation or biomagnification.

10.5.1 Marine fish

Very few studies have measured Hg concentrations in marine fish species in the Eastern Canadian Arctic. Arctic char (*Salvelinus alpinus*) and Dolly Varden char (*S. malmo*) are members of the subfamily Salmonidae. Both char species inhabit freshwater throughout most of their lives with the anadromous (sea-run) forms migrating to sea in the summer for a few weeks of feeding before returning inland to spawn. Anadromous char typically have low Hg concentrations ($< 0.05 \mu\text{g/g ww}$) in contrast to greater concentrations measured in freshwater fish species and marine mammals. Hg concentrations in anadromous char from the Eastern Canadian Arctic range from $0.04 \pm 0.01 \mu\text{g/g ww}$ in Igloodik and Cape Dorset to $0.07 \pm 0.03 \mu\text{g/g ww}$ in Pangnirtung, southern Baffin Island (Evans et al. 2015). Hg concentrations across the Arctic increased as a function of char size, decreasing condition factor and cooler springs (Evans et al. 2015). Temporal trends have shown that Hg concentrations in Cambridge Bay char have increased from 1977 to 2012. Trends of increasing Hg were also found at



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Pangnirtung (1990 – 2009) and Hall Beach west of Fox Basin (1978 – 2007). In contrast, Pond Inlet char have shown no trend over the time period of 2005 to 2012 and a decreasing trend was found at Iqaluit on southern Baffin Island (1992 – 2009) (Evans et al. 2015). Overall, temporal trends for Hg concentrations in sea-run char suggest a recent increase in levels across the Eastern Arctic.

Relatively high THg concentrations have been found in Cumberland Sound Arctic skate muscle ($0.42 \pm 0.18 \mu\text{g/g ww}$) compared to Greenland halibut (*Reinhardtius hippoglossoides*) (0.17 ± 0.16), shorthorn sculpin (*Myoxocephalus scorpius*) (0.16 ± 0.07), Arctic char (0.04 ± 0.02), and capelin (*Mallotus villosus*) (0.02 ± 0.01) (McMeans et al. 2015). The reasons for the elevated levels in the Arctic skate remain unclear (McMeans et al. 2015). Greenland shark (*Somniosus microcephalus*) are the largest predatory fish in the Arctic and had the highest THg concentrations

in muscle ($1.62 \pm 0.52 \mu\text{g/g ww}$) (McMeans et al. 2015). These levels were within the range reported for beluga whale muscle and were consistent with their upper trophic level position in the marine food web.

10.5.2 Marine mammals

Elevated THg was first reported in marine mammals in the Canadian Arctic in the 1970s (Smith and Armstrong 1975, Wagemann and Muir 1984, Muir et al. 1992). Previous studies have observed that THg concentrations were greater in marine mammals from the Western Canadian Arctic compared with the Eastern Canadian Arctic (Muir et al. 1992, Rig  t et al. 2005). These observations are likely due to a combination of local geological influences, atmospheric and riverine sources, dietary preferences, and methylation and biomagnification processes (Leitch et al. 2007, Loseto

et al. 2008a, Loseto et al. 2008b, Cardona-Marek et al. 2009, Gaden et al. 2009, Horton et al. 2009, St. Louis et al. 2011).

10.5.2.1 Ringed seals

Studies have found that THg concentrations in ringed seals from the Eastern Canadian Arctic are two- to three-fold lower than ringed seals from the southern Beaufort Sea (Sachs Harbour and Ulukhaktok) (Wagemann and Muir 1984, Muir et al. 1992). Braune et al. (2015) also reported greater THg concentrations in liver of adult ringed seals (≥ 5 years) in the

Western Canadian Arctic (Sachs Harbour and Ulukhaktok) compared with other locations across the Canadian Arctic. Similar to liver, THg concentrations in muscle of adult seals were greater in the Western Canadian Arctic and in two sites in the Eastern Canadian Arctic (Resolute and Arviat). A recent investigation of THg in sub-adult and adult ringed seals from across the Canadian Arctic confirmed previous reports of greater concentrations in muscle and liver tissue of seals from the Western Canadian Arctic and from Resolute and Arviat (Brown et al. 2016) (Table 4; Figure 6).

TABLE 4. Geometric means and 95% confidence intervals ($\mu\text{g/g}$ wet weight) of total Hg in muscle and liver of sub-adult and adult male and female ringed seals collected from 2007-2011. Data from Brown et al. 2016.

	THg muscle $\mu\text{g/g}$ ww				THg liver $\mu\text{g/g}$ ww	
	<i>n</i>	Sub adult	<i>n</i>	Adult	Sub adult	Adult
Sachs Harbour	31	0.411 0.409-0.414	9	0.890 0.878-0.902	2.26 2.22-2.29	34.6 33.2-36.1
Ulukhaktok	4	0.387 0.385-0.389	16	0.543 0.541-0.545	11.7 11.6-11.9	20.1 19.9-20.3
Arctic Bay	9	0.190 0.188-0.191	9	0.377 0.373-0.381	1.08 1.05-1.10	6.39 6.27-6.50
Gjoa Haven	12	0.171 0.135-0.206	9	0.325 0.317-0.332	1.52 1.48-1.56	5.40 5.23-5.56
Grise Fiord	13	0.102 0.100-0.104	7	0.093 0.092-0.094	1.35 1.32-1.38	16.7 16.5-16.9
Resolute	61	0.380 0.378-0.382	33	0.543 0.541-0.544	4.43 4.40-4.45	11.3 11.2-11.5
Pond Inlet	12	0.180 0.179-0.182	4	0.487 0.480-0.494	2.13 2.06-2.20	8.07 7.89-8.26
Pangnirtung	14	0.235 0.234-0.237	0	n.a.	4.23 4.17-4.29	n.a.
Arviat	58	0.245 0.243-0.246	66	0.270 0.261-0.273	4.76 4.71-4.81	16.2 16.1-16.3
Inukjuaq	13	0.102 0.098-0.107	5	0.139 0.137-0.141	0.99 0.98-1.01	4.05 3.92-4.17
Nachvak Fiord	6	0.141 0.136-0.146	19	0.150 0.146-0.153	n.a.	n.a.
Saglek Fiord	16	0.136 0.127-0.145	12	0.187 0.186-0.188	n.a.	n.a.
Okak Bay	14	0.125 0.124-0.126	14	0.262 0.260-0.264	n.a.	n.a.
Anaktalak Bay	7	0.096 0.095-0.097	4	0.210 0.208-0.212	n.a.	n.a.

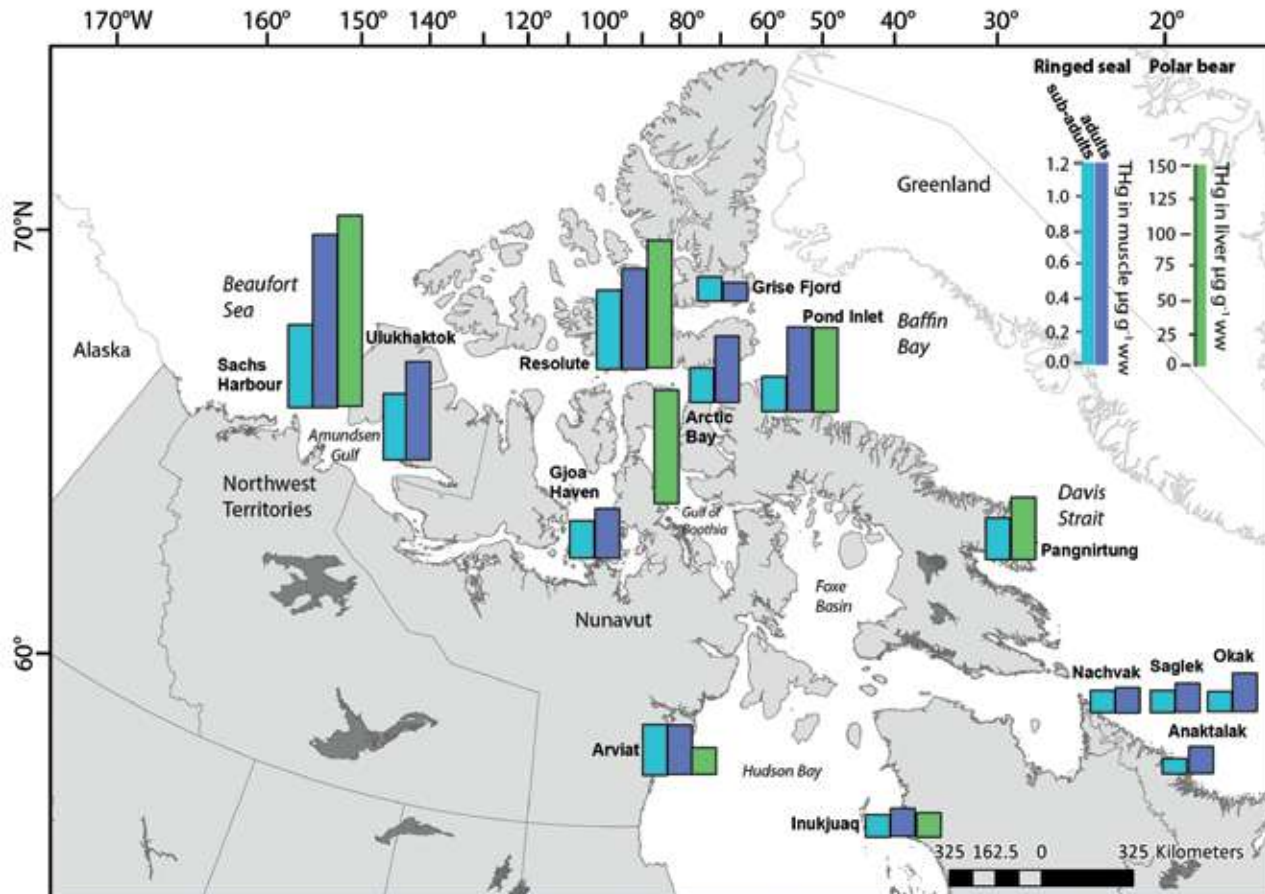


FIGURE 6. Geometric means ($\mu\text{g/g}$ wet weight) of THg in sub-adult and adult male and female ringed seals collected from 2007 and 2011 and polar bears collected from 2005–2008. Data from Brown et al. 2016 and Routti et al. 2011.

The higher levels observed at these locations in the east were attributed to seals feeding at a higher trophic level, whereas the higher levels in the west were attributed to both natural geological differences and to seals feeding higher in the food chain (Brown et al. 2016). The higher levels of THg in the Beaufort Sea seals may be due to active conversion of THg to MMHg in the Western Arctic Halocline where oxygen concentrations are low and organic matter is decomposing (Wang et al. 2012), or to the regional addition of Hg to Beaufort Sea surface waters from the Mackenzie River (e.g., Stern and Macdonald 2005, Andersson et al. 2008).

Samples collected over time suggest that THg concentrations in ringed seals increased from the early-1970s

to mid-1980s, and continued to increase to the mid- and late-1990s (Wagemann et al. 1996, AMAP 2005). While present day THg levels in ringed seals exceed historical concentrations, no significant changes have been reported from 1999 to 2009 (Braune et al. 2015).

10.5.2.2 Polar bears

The polar bear has some of the highest THg concentrations in the Canadian Arctic (Rigét et al. 2011). Concentrations of THg in polar bear liver from the Western Canadian Arctic (northern and southern Beaufort Sea) were significantly greater than other areas across the Arctic, except for bears from the Gulf of Boothia and Lancaster Jones Sound

which also had relatively higher levels compared with the rest of the Arctic (Routti et al. 2011) (Table 5; Figure 6). These results are consistent with the spatial THg trends reported for ringed seal, which are the dominant prey of polar bears. A number of polynyas are within and/or adjacent to these two areas and have higher primary productivity relative to other areas in the Arctic (Hannah et al. 2009). Lancaster Sound in particular is one of the Arctic's most biologically productive marine areas and is characterised by two polynyas, one is along the northern coast of Lancaster Sound and the other at the eastern outflow (Barber and Massom 2007). A consequence of increased productivity could be enhanced methylation of inorganic Hg during regeneration of the labile organic matter as it sinks below the surface. Western and southern Hudson Bay bears had some of the lowest average Hg levels in the Canadian Arctic, followed by bears from Davis Strait (Table 5; Figure 6).

THg concentrations measured in 2007-2008 in polar bears from the Eastern Canadian Arctic were similar to the concentrations reported in the 1980s (Routti et al. 2011). Similar temporal observations have also been observed in ringed seals from several locations in the Canadian Arctic (Gaden et al. 2009). In a very recent report, THg concentrations in the liver collected in 2016 from bears from Western and southern Hudson Bay were retrospectively

TABLE 5. Geometric means and 95% confidence intervals ($\mu\text{g/g}$ wet weight) of total Hg in liver of sub-adult and adult male and female polar bears collected from 2005-2008. Data from Routti et al. 2011.

	<i>n</i>	THg liver $\mu\text{g/g}$ ww
South Beaufort Sea	11	137 (135-138)
North Beaufort Sea	26	153 (152-155)
Gulf of Boothia	6	85.7 (85.1-86.3)
Lancaster/ Jones Sound	13	94.1 (93.4-94.9)
Baffin Bay	14	59.2 (58.3-60.2)
Davis Strait	6	46.1 (45.4-46.7)
West Hudson Bay	11	19.5 (19.2-19.7)
South Hudson Bay	14	18.2 (18.1-18.4)

comparable to concentrations in samples from years going back before 2000, i.e., 5 to 25 $\mu\text{g/g}$ (ww) (Letcher et al. 2018). Similar to previous years, in 2016 liver samples THg concentrations in western Hudson Bay bears were slightly greater than for the southern Hudson Bay bears. However, the THg concentrations were variable from year to year, and so there is a need to continue annual monitoring of THg in Hudson Bay bears.

10.6 Summary and outlook

There appear to be two dominant factors that contribute to spatial trends in Hg and legacy OHCs observed in the CAA. First, the contaminant concentrations in the water column are strongly affected by deposition and transport of contaminants by air and water, and by the historical loading of upstream oceanic reservoirs in the western Arctic Ocean. Second, the concentrations of contaminants in higher trophic levels (e.g., bears, seals) are strongly mediated by local or regional food web structure.

For the first factor, the clearest example is the effect of HCHs loading into the upstream ocean reservoir in the Beaufort Sea leading to a significant west to east decreasing concentration across the CAA. However, direct atmospheric deposition and river input are also important in the CAA, especially for contaminants more recently released like the PBDEs and PFOS. These compounds presently exhibit higher concentrations in the south indicating that northward spread from more highly contaminated locations in temperate regions of the Northern Hemisphere is important. The spatial and temporal patterns of historical usage are also important, with Europe and North America having released PCBs and other compounds in greater amounts and earlier than Asia, and Asian sources favoring compounds like HCHs or telomeric (linear) PFOS. Hg is also strongly affected by sources, with coal burning being presently among the most important. During the past two decades, controls have reduced Hg emissions in Europe and North America whereas continued dependency on coal has resulted in Asia becoming the most important source (AMAP 2011). As was the case for the HCHs, the western Arctic Ocean

reservoir is likely to become more heavily loaded with Hg from the Asian sources whereas the Atlantic Ocean contaminant Hg burden will decline. Although contaminant inorganic Hg is important, toxic risk and biological accumulation depend crucially on methylation within aquatic systems. This step, which accompanies organic decomposition, is controlled by regional factors including dissolved oxygen concentration.

Food web structure plays an important role in shaping spatial trends of MMHg and some legacy contaminants, including Σ PCBs, PCB 153, Σ DDTs, p,p'-DDE. Concentrations of these contaminants in ringed seals and polar bears from the Beaufort Sea are elevated relative to other locations across the Canadian Arctic, which is consistent with the high trophic position occupied by ringed seals from the Beaufort Sea relative to seals from other areas in the central and Eastern Canadian Arctic (Brown et al. 2016). For emerging contaminants like PBDEs and PFOS, atmospheric delivery favouring southern locations is clearly important presently, but will become less so over time once primary sources are controlled.

Like the rest of the Arctic, the CAA is undergoing climate change associated with increasing temperatures. Increased warming of 4 to 8°C by 2050 has been forecasted in fall and winter seasons for the Eastern Canadian Arctic (Chapter 2). The current trend of decreased summer sea-ice extent and earlier sea-ice breakup in the Arctic Ocean is projected to continue (Chapter 2). Within the CAA itself, summer sea-ice extent has been declining, temperatures have been rising, and precipitation has been increasing (Figure 7). These changes will likely enhance air-sea exchange, wet deposition, and transfers from land to rivers. Additionally, change in sea-ice cover strongly affects food web structure, and seasonal timing of primary production is expected to change (Chapter 5), ultimately resulting in an early spring in the CAA. Although continued warming, further loss of sea ice and greater precipitation have been projected by a number of authors, only a few studies have shown the effects of such changes on exposure to pollutants within arctic ecosystems. For example, McKinney et al. (2009) found that changes

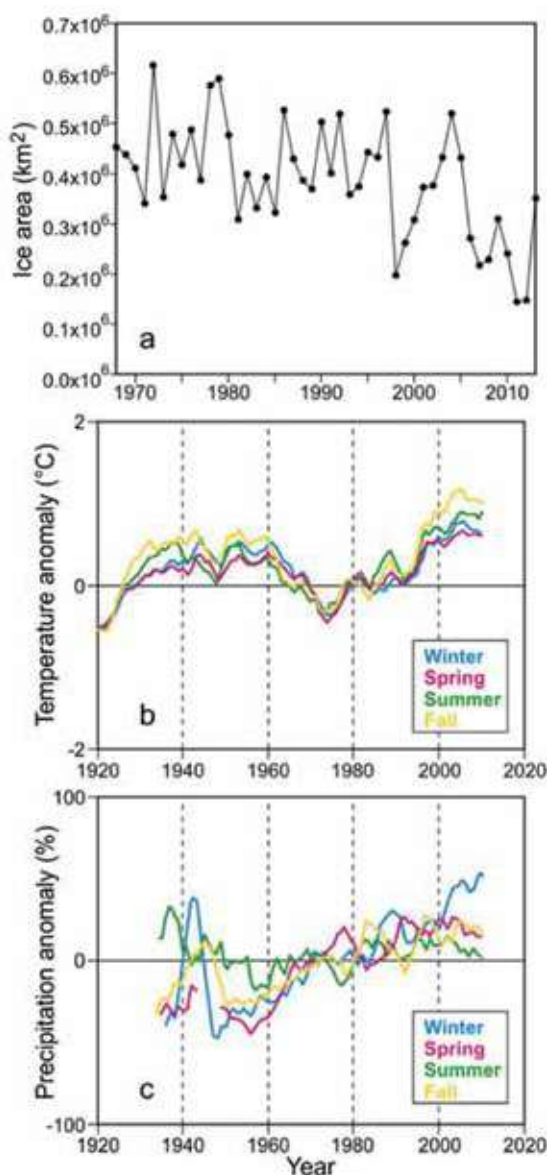


FIGURE 7. Recent trends in (a) summer sea-ice extent, (b) temperature anomaly and (c) precipitation anomaly for the CAA (modified from Howell et al. 2015, Steiner et al. 2015).

in feeding ecology of polar bears from western Hudson Bay, which was largely caused by earlier sea-ice break-up, resulted in increased tissue concentrations of several chlorinated and brominated contaminants. Using food web tracer patterns (e.g., quantitative fatty acid signature analysis and fatty acid carbon isotope) McKinney et al. (2013) reported a shift in diet structure for East Greenland polar bears over 28-years which showed a decrease in ringed seal consumption and an increase in hooded seal consumption. The authors concluded that such a shift could result in slower temporal declines of legacy POP contaminants since subarctic seals have higher contaminant burdens of these pollutants than arctic seals. Gaden et al. (2009) found that both long and short ice-free seasons resulted in increased THg concentrations in ringed seals from the Beaufort Sea. The increased THg levels were attributed to changes in cohort composition of the Arctic cod population, which is the dominant prey of ringed seals. In shorter ice-free seasons a large percentage of young, less contaminated Arctic cod may not survive, leaving older more highly contaminated Arctic cod as the dominant prey available for predators (Gaden et al. 2009). Brown et al. (2014) reported a shift to feeding at a higher trophic level in Labrador ringed seals sampled in 2010, which corresponded to a poor ice year along the coast (Colbourne et al. 2011). This shift in diet appears to have resulted in increased THg concentrations in these seals (Brown unpublished data).

Recent studies suggest that onshore habitat use for some subpopulations of polar bears (e.g., southern Beaufort Sea) is increasing with annual reduced sea-ice duration (Atwood et al. 2016) and that bears annual dietary proportions are shifting (McKinney et al. 2017). For example, during poor ice years the diet of polar bears from the southern Beaufort Sea shows a reduced consumption of the omnivorous ringed seal and beluga whale and an increased consumption of the planktivorous-feeding bowhead whale. The bowhead whale occupies a lower trophic feeding position and thus is generally less contaminated compared with ringed seal and beluga whale, which feed at higher trophic levels (Hoekstra et al. 2003). The increased consumption of harvested and beach-cast

bowhead whales on land over free-ranging ringed seal or beluga whale has the potential to therefore alter contaminant exposure in polar bears.

Yurkowski et al. (2015) reported interannual variation in ringed seal diet and an increased adult isotopic niche size over time, which suggests these seals have adaptability with respect to their diet and to a changing climate. The results also suggested that high-Arctic ringed seals may be at increased risk, due to their more restricted diet, than lower-Arctic populations from ecosystem perturbations, such as climate change. How these changes will affect contaminant concentrations and trends in ringed seals across the Arctic is yet to be determined.

Another possible change for individual ringed seals and polar bears is a variation in body condition which could alter contaminant burdens in both species. For example, reduced body condition may result in increased lipid and/or protein catabolism, which may subsequently mobilize and release contaminants into circulation (Polischuk et al. 2002), which can increase health risks to the affected individuals. Fasting periods and/or decreased body mass have been found to result in increased circulating concentrations of lipophilic POPs (Polischuk et al. 2002, Christensen et al. 2007, Helgason et al. 2013) and THg (Seewagen et al. 2016). Circulating POPs can induce xenobiotic metabolizing enzymes in the liver (Wolkers et al. 2008), which lead to the toxic form of hydroxyl (OH) metabolites of POPs (Letcher et al. 2000). For example, OH-PCBs and OH-PBDE metabolites/contaminants have been reported mainly in the liver and/or plasma of East Greenland ringed seals and/or polar bears, but not in the adipose tissue (Gebbinck et al. 2008; Letcher et al. 2009). Therefore the health risks to individual animals or populations with reduced body condition and/or periods of fasting may be increased due to the mobilization of hydroxylated POPs.

The loss of summer sea ice is likely to favour pelagic primary production assuming adequate nutrients (see Chapter 5), which would extend deeper into the water column due to greater penetration by light. Regeneration

of this organic matter may enhance Hg methylation below the euphotic zone, but this may be offset by photodecomposition of MMHg in surface water (e.g., see Point et al. 2011). However, greater amounts of freshwater and sea-ice melt will lead to greater summer stratification, which may oppose the increase in productivity that should occur under reduced-ice conditions (Chapter 5). This poorly-buffered freshwater is more vulnerable to ocean acidification, which may dramatically affect lower trophic food-web structure (AMAP 2013). The concentration of MMHg in the water column is maintained as a balance between dynamic (i.e., rapid) processes of production and degradation. While it seems clear that projected changes in climate will lead to increases in the rates of both of these processes, it is exceptionally difficult to project how the balance point will be affected, regionally or locally.

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Chapter 11 Access to the Land and Ice: Travel and Hunting in a Changing Environment

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Key implications for decision makers

- Traditional knowledge plays an important role in managing risks associated with access to the land. As Inuit youth spend less time on the land and ice, the loss of traditional modes of *Inuit Qaujimagatuqangit* (IQ) generation and transmission underscores the need to support teaching of traditional skills across generations. Adequate traditional, navigational, language, and survival skills are still needed.
- Hunters and Elders are having difficulty forecasting weather conditions, are more hesitant to provide weather predictions and very few weather stations exist along the coast, this has led to an increased risk of travel during both winter and summer seasons.
- Changes in ice and snow conditions have been observed in several Nunavut communities and climate scenarios suggests these changes will continue into the future. These changes have increased travel risks on trails that were traditionally safe during the shoulder seasons (i.e., the beginning and end of winter), have limited land access and have reduced time spent doing outside activities.
- The degree of vulnerability to climate change differs from one individual to another, from one community to another and the vulnerability of individuals or populations is continuously changing with changing environmental and socio-economic factors. Research that assesses individual and community vulnerability and adaptive capacity to future climate change is limited. There is a need to identify tools and best practices.
- Community-based ice monitoring projects and the introduction of new technologies for adaptation have been implemented for observing future sea ice changes. There is a need for long term program support to ensure continuity of work, technological transfer to the community, availability of local resources (human and financial) and imagery and resolution quality.
- Technology can be used to document environmental changes. An integrated water proof computer, GPS and weather meter technology has been used to document the use of trails by hunters and monitor the environmental changes in Clyde River. This type of project supports long-term data sets and mapping capability and relies on annual funding availability.
- Remote sensing has been recently used as a tool to evaluate the ice conditions in a context of access to land and traditional resources. The challenges include: ensuring continuity of this work, technological transfer to the community, availability of local resources (human and financial) and imagery and resolution quality. Adequate traditional, navigational, language, and survival skills are still needed.

Abstract

Changing environmental conditions are impacting the ability of Nunavummiut to travel on the land and ice. Climate change has altered environmental indicators beyond normal conditions that were observed in the past and the level of risk associated with the access to land has increased, directly impacting travel safety. Traditional knowledge plays an important role in managing risks associated with access to the land. However, Inuit are spending less time on the land and ice due to socio-economic-cultural changes, which have subsequently contributed to the loss of some traditional knowledge and land skills and the incomplete transmission of knowledge to younger generations. Moreover, experienced hunters and Elders are having more difficulty forecasting weather conditions and are more hesitant to provide weather predictions, increasing the risk of travel during both winter and summer seasons. Changes in ice and snow conditions have been observed in several Nunavut communities. Trails that were traditionally safe during the shoulder seasons (i.e., the beginning and end of winter) may no longer be safe. Not all communities, groups of people or individuals share the same degree of vulnerability to climate change. How individuals experience and respond to climate change risks varies between individuals and among communities. Research that assesses individual and community vulnerability and adaptive capacity to a changing climate is critical to developing effective adaptation strategies.



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11.1 Introduction

Access to the land is intrinsically linked with the Inuit way of life. Trails are used to access harvesting grounds, to travel between communities, and for other activities. Trail networks used to access land in many instances have remained the same for several generations (Aporta 2004, 2009), even as contemporary snowmobiles have replaced traditional dog teams.

Changing environmental conditions have impacted access to the land over the last few decades in Nunavut, Nunatsiavut, Nunavik, and the Inuvialuit Settlement Region (Nickels et al. 2005). Several environmental and climatic changes, such as unpredictable weather, wind and ice conditions are directly impacting the ability of Nunavummiut to travel on the land and sea ice. Climate change has altered environmental indicators, such as cloud formations and shifts in wind direction, beyond normal conditions that were observed in the past such that the level of risk associated with access to land has increased and subsequently impacted travel safety (Ford et al. 2006a, 2006b, Pearce et al. 2010).

The livelihoods of Nunavummiut, as well as other Arctic populations, have changed considerably over recent decades (AHDC 2004). For example, the introduction of the wage economy and the southern school system changed the way Nunavummiut access their land and have affected the transmission of traditional knowledge across generations. This has resulted in altering traditional trail route use and has increased the number of travel related incidents. This chapter discusses access to land by Nunavummiut and how they are being impacted by changing environmental conditions. It also identifies challenges associated with travel safety, the methods of adaptive strategies used to cope with such challenges, and the barriers that may limit the adoption of adaptive strategies.

11.2 Access to land (use of ice and water)

11.2.1 Trail networks

Inuit use winter trails over the snow and sea ice to access the land for hunting, fishing and trapping, and to travel between communities which typically extend far beyond a settlement's boundaries and over large areas of the arctic environment (Aporta 2009, Fox Gearheard et al. 2013). Inuit see the Arctic as a network of trails which form communication channels that allow social, economic, and cultural exchanges (social – e.g., weddings, family visits; cultural – e.g., food sharing) among communities (Aporta 2009, 2011). Trails can be considered either one-time use or well-used. On sea ice, trails can form networks that lead from point “A” to point “B” where the trail is considered one-time use. On rivers and land, where landmarks are present, trails are well-used (Figure 1).

The existence of winter trails and their locations have been traditionally passed along through generations through oral history and experiential learning (Aporta 2009). Despite changes in the modes of travel (i.e., dog sled to snowmobile) and means of navigation (i.e., Global Positioning System (GPS)), many trail networks remain the same and *Inuit Qaujimagatuqangit* (IQ - Inuit traditional knowledge) continues to be important for safe and successful travel (Aporta and Higgs 2005, Ford et al. 2006b, Ford et al. 2008, Laidler et al. 2009). IQ embodies understanding and values that have been acquired through experience and observation, either from the land or from spiritual teachings, and have been passed down from one generation to another (Wenzel 1999). IQ is transmitted orally through stories, myths, songs, and lessons, and it is continually being revised and expanded to include new information (Berkes 1999, Aporta 2002, Thorpe et al. 2001, Thorpe et al. 2002, Berkes 2004, Laidler 2006). Moreover, the dynamic and flexible nature of IQ continues to underpin Inuit adaptability to a rapidly changing climate (Laidler et al. 2009, Ford 2009, Ford et al. 2010, Pearce et al. 2015). Marking or following winter trails involves knowledge of snow and ice patterns, and wayfinding skills such as recognizing landmarks and understanding wind patterns and the formation of snow



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FIGURE 1. Winter trail using river ice cover.

drifts (Aporta 2004). Each community has several place names that describe the environment, including topographic characteristics such as rivers, creeks, valleys, hills, bays, and ice that are important for travel navigation (Aporta 2009).

In contrast to winter trails which have been well documented in some communities, summer and autumn boat and All Terrain Vehicle (ATVs) trail networks to harvesting grounds and associated traditional knowledge have not been well documented (Figure 2).

11.2.2 Traditional knowledge

Traditional knowledge of ice dynamics and comprehension of oceanic and weather conditions play an important role

in managing risks associated with travelling on the ice and access to the land (Freeman 1984, Aporta 2002, Ford et al. 2006b, Laidler et al. 2009, Pearce et al. 2015). Hunters assess risks before traveling, take extra precautions (e.g., pack extra food, fuel and supplies; safety equipment – i.e., satellite phone, GPS) and draw on their knowledge of the arctic ecosphere to manage emerging risks (Pearce et al. 2010, Pearce et al. 2015).

Knowledge of ice, especially during times of freeze-up and break-up, may minimize risks faced by hunters who travel on the land and ice (Laidler et al. 2009, 2011). Inuit ice terminology is only partially documented in a few communities (i.e., Igloolik, Clyde River, Pangnirtung, Cape Dorset, and Sanikiluaq) and regions (i.e., Baffin Island,



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FIGURE 2. Summer routes and associated traditional knowledge are not well documented.

Cumberland Sound) in Nunavut (Fox Gearheard et al. 2013, Krupnik 2011, Laidler and Elee 2008, Laidler and Ikummaq 2008, Laidler et al. 2008), despite the more than 950 terms that have been identified (Krupnik 2011). The diversity of terminology tends to be high and variable within and between communities and has mostly been transmitted orally and experientially through generations (Heyes 2011). In a community, the level of competence in using ice terminology is generally determined by the age, gender, or occupation of the person (Krupnik 2011). Only a fraction of the words are often used, and this is especially true for communities affected by linguistic transition (Laidler et al. 2009, Krupnik 2011, Heyes 2011). While it is important to collect Inuit ice terminology, it is particularly urgent to do

so due to the declining number of Elders and hunters who still have the knowledge of such terms (Krupnik 2011).

The erosion of traditional knowledge transmission documented in communities across the Inuit Nunangat is not limited to ice terminology, but also affects other areas of knowledge, such as weather prediction, place names and trails networks (Aporta 2004, Ford et al. 2006b, Laidler et al. 2011, Pearce et al. 2011). For example, Inuit are spending less time on the land and ice due to socio-cultural-economic lifestyle changes, which have contributed to a loss of some traditional knowledge and land skills passed down to younger generations (Pearce et al. 2011). There is a need for future programs to document, maintain, and improve traditional knowledge sharing between generations, specifically

with regards to weather and the environment, including ice dynamics. The Avativut program implemented in Nunavik is an example where the natural environment has been used to expose highschool students to an intergenerational dialogue between different domains of knowledge (Inuit Traditional Knowledge and Western science) (Gérin-Lajoie et al. 2014).

11.3 Impacts of changes

11.3.1 Socio-cultural-economic changes

Socio-cultural-economic changes have altered Inuit access to land, thereby affecting how Inuit interact with and respond to changing environmental conditions. Inuit across the Arctic have been and continue to be affected by the industrialization of the region, the sedentarization of former semi-nomadic hunting groups to permanent settlements, and the integration to the globalized economy (AHDR 2004). Inuit livelihoods have been transformed in a few decades following the introduction of wage economy and compulsory schooling (Ford 2009). Before these socio-cultural-economic changes, customs and traditions related to land access and safety were essentially transmitted from generation to generation during land based activities (Aporta 2004, Dowsley et al. 2010, Laidler 2006, Heyes 2011). Subsistence activities provided opportunities during which experienced hunters were able to teach younger generations how to live off the land. Both Inuit men and women hunted and traveled from an early age, which provided them with ample opportunity to learn environmental nuances and other knowledge that were essential for their survival (Gearheard et al. 2006, Heyes 2011). As mentioned in the previous section, due to these socio-cultural-economic changes, the current generation of youth spends more time inside (i.e., in classrooms or workplaces) which is having a negative impact on the exchange of traditional knowledge on the land and ice between older and younger generations (Pearce et al. 2011, Ford et al. 2006a). The dialogue between older and younger generations has also been altered due to changes in the nature of intergenerational dynamics and in using the English language more. In addition, Elders which hold the traditional knowledge may

not have the physical ability to spend long hours outside to transmit knowledge (Heyes 2011). Several research recommendations have been made to support teaching and transmission of traditional skills between generations (Budreau and McBean 2007, Ford et al. 2010, Ford et al. 2007). For example, there is a need for support the teaching and transmission of environmental knowledge and land skills (Ford et al. 2010) among younger Inuit (Pearce et al. 2011) and institutional support is need to assist in strengthening this transmission of traditional skills (Pearce et al. 2015).

Socio-cultural-economic changes have also affected Inuit transportation modes (e.g., transition from dog sledding to snowmobiles) which could have negative impacts on travel safety. Snowmobiles may be beneficial in that they allow hunters to travel long distances quickly and without the knowledge required to operate a dog team (Ford et al. 2008). However, dogs were effectively used as “navigational tools” during travels, as they could feel and report to hunters the presence of unstable ice. Furthermore, dogs could succeed in pulling a sled out after an unexpected fall in the icy water and could find their way in a blizzard or when the hunter was lost (Tremblay and Furgal 2008).

11.3.2 Climatic and environmental changes

11.3.2.1 Unpredictable weather

Increasing weather variability in Nunavut (Riewe and Oakes 2006, Weatherhead et al. 2010) and the rest of the Arctic is making it more difficult for hunters and Elders to forecast conditions (Riedlinger 2001, Ford et al. 2006a, 2006b, 2008). Traditional weather indicators such as cloud formations, shifts in wind direction, and changes in animal behavior are less reliable and the anticipated weather changes do not always follow traditional indicators (Ford et al. 2006b, Laidler et al. 2009, Gearheard et al. 2009). The unpredictable weather has increased the risk of travel during both winter and summer. For example, strong winds in the summer have reduced boat travel across large lakes and the ocean (Nickels et al. 2005, Ford et al. 2006a, 2006b), thereby limiting access to hunting grounds (Ford et al. 2006a). Autumnal winds have resulted in non-uniform

freezing rates, causing variations in ice thickness (Laidler et al. 2009). Changes in wind patterns during winter can influence ice movement and sudden and unanticipated wind changes during spring can cause sea-ice disintegration (Ford et al. 2006a). Changes in wind can also transform snow drift orientation which are used for snowmobile navigation on land and sea (Ford et al. 2006b). The reduced capacity of Inuit to predict weather conditions has increased reliance on meteorological weather forecasts that are not always accurate. For example, these weather forecasts do not reflect the diversity of micro-environments that travelers can encounter while they access land (Riedlinger 2001, Downing and Cuerrier 2011). This is often due to weather stations being limited in number and located only near airports (Ford et al. 2010).

11.3.2.2 *Changes in ice and snow conditions*

Increasing temperatures and precipitation in Nunavut have resulted in changes in ice and snow conditions in several communities in the region (Nickels et al. 2005). For example, warmer autumn and winter seasons have contributed to delayed ice freeze-up (Nickels et al. 2005, Ford et al. 2006b, 2009, Laidler et al. 2010), whereby travel by ice is often postponed and more hazards are observed (Nickels et al. 2005). Snow accumulation during these warmer periods can often hide thin ice and pose a hazard to hunters (Ford et al. 2006b, 2008). Snow can also insulate underlying ice, thereby promoting increased melt from the heat of the ocean and the movement of currents (Ford et al. 2009, Laidler and Elee 2008, Laidler and Ikummaq 2008, Laidler et al. 2008, Laidler et al. 2010). Later snow accumulation during the fall season has been observed and can impede the use of snowmobiles and limit trips further from communities (Ford et al. 2008). Warmer water temperatures in the spring cause ice break-up and snow melt to happen earlier (Nickels et al. 2005, Laidler et al. 2010) which results in more hazardous travel conditions. In the past, Inuit travelling on the ice were less concerned about the conditions because they were more predictable. Trails that were traditionally safe during the shoulder seasons (i.e., the beginning and end of winter) may no longer be safe, and therefore require alternative routes and transportation modes. Longer

routes and more land-based trails, as opposed to ice trails are being used to access resources in some communities (Laidler et al. 2010). Climate change projections for 2050 show a continuation of observed trends, with major changes projected for snow and ice cover over the region (see Chapter 2). Onset of the snow season is expected to happen between 4 and 24 days later where the largest changes should be over the more northern areas of Nunavut (see Chapter 2). Snowfall should increase between 13 and 35 mm where the largest increase should be over southern Baffin Island and Belcher Islands, and the end of the snow season is predicted to occur between 7 and 14 days earlier over most of the region. Winter temperatures are expected to increase between 1 and 8 °C and thawing degree-days are predicted to increase up to 349 degree-days, where the strongest changes are projected over southern parts of the IRIS 2 region (see Chapter 2).

Socio-cultural-economic changes as well as climatic and environmental changes are not uniform between communities, and depend largely on the physical and cultural geography (e.g., location, size, history, demographics etc.) (Duerden 2004). It is important to document and understand these changes at the community level. There is a need for research and/or programs to develop better indicators of ice conditions with the integration of traditional knowledge (Ford et al. 2013) and a need to improve weather forecasts at the community level. SmartICE is an excellent example of a program that is working with partners and local community sea-ice experts to develop and refine stationary and mobile sensors that measure sea-ice thickness, generate community-scale sea-ice hazard maps from radar imagery, and work with communities on how the knowledge produced will be managed, disseminated and shared to meet the needs of individuals, communities and businesses (Box A). Most importantly, SmartICE is co-designed with and involves Inuit in all its operations (Box A).

BOX A. SmartICE: A working climate change adaptation tool in northern communities

Arctic climate change is causing landfast sea ice to be thinner, form later and break up earlier than before, resulting in increasingly dangerous over-ice travel. This has real potential to affect risk or perceived risk associated with Inuit use of sea ice to access country foods and to maintain cultural and family activities. Ultimately, physical and emotional health will suffer. SmartICE has been developing its sea-ice information service for the past four years, culminating in pilot projects in Nain and Pond Inlet (Bell et al. 2014, Safer 2016). Working with partners and local community sea-ice experts, it has developed and refined stationary and mobile sensors that measure sea-ice thickness (Figure A1), generated community-scale sea-ice hazard maps from radar imagery (Figure A2), and discussed with communities how the knowledge produced will be managed, disseminated, shared, and integrated into a decision-making platform that serves the needs of individuals, communities and businesses. Most importantly, SmartICE is co-designed with and involves Inuit in all its operations with the intention to integrate, not replace, Inuit knowledge about sea-ice environments.

SmartICE community operators are key to both operationalizing SmartICE activities and building sea-ice user confidence in climate adaptation measures. Andrew Arreak, the SmartICE operator in Pond Inlet commented in a recent interview: "...the travel conditions are changing. The safety of people on the ice can be threatened by these



FIGURE A1. SmartICE community operator Andrew Arreak at the flow edge off Pond Inlet in April 2017. The SmartQAMUTIK sensor is secured inside the insulated qamutik box and connected to the handlebar-mounted user interface on the skidoo. Andrew is able to read off in real-time the ice thickness underneath the qamutik as he travels across the ice.

changes. In order to maintain our way of life, travelling on the sea ice is essential, so we need to provide information to travellers to allow them to plan for their safety. As a community member, I have the confidence and trust of the community. I want to use all the knowledge available to do the best job I can for the community” (McMillan 2016).

With the support of the 2016 Arctic Inspiration Prize, SmartICE has created a northern social enterprise to expand from current pilot programs to communities across the North. The choice of a social enterprise business model commits to maximizing social impact and creating positive community change, while applying an entrepreneurial approach to the delivery of sea-ice information services. For example, service expansion will require bulk manufacturing of SmartICE technology. Consistent with a social enterprise approach, SmartICE will train Inuit youth at its technology production hub in Nain (Nunatsiavut) to assemble ice thickness sensors for distribution to northern communities. The operational hub and training centre for SmartICE is in Pond Inlet (Nunavut).

The SmartICE information system, through generation and dissemination of near real-time ice information, directly supports public safety, food security, and health and wellbeing in communities. In addition, its services enable and support local economic activity under a changing climate. Mining, shipping, fisheries, emergency response, national defense and environmental monitoring are all carried out to some degree on or through sea ice along the Arctic coast and therefore more specific information on sea-ice conditions, especially during freeze-up and break-up, reduce risk and improve performance for these commercial and government activities. As part of its sustainability plan, SmartICE intends to pursue both private sector sales and public sector funding to support its social enterprise expansion across the Arctic.

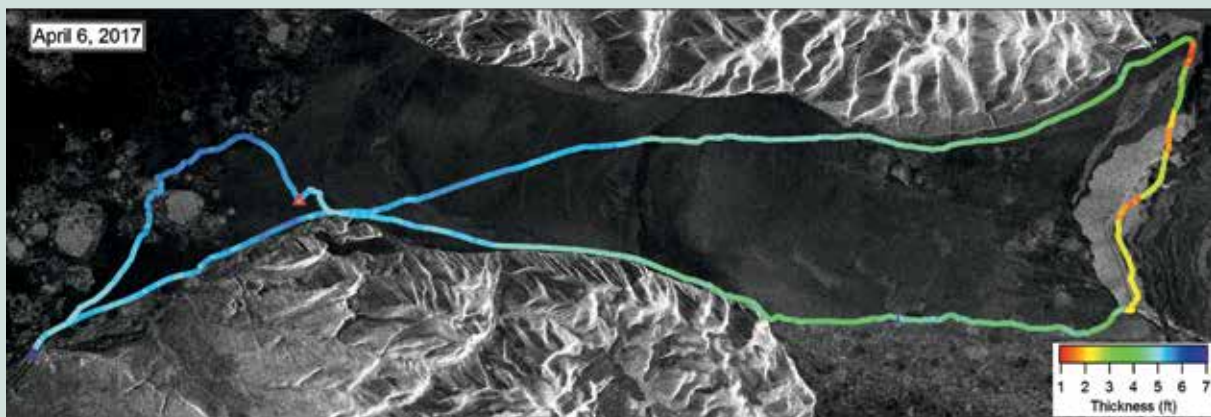


FIGURE A2. Map of sea-ice thickness generated from the SmartQAMUTIK survey between the hamlet of Pond Inlet (left) and the floe edge (right) in Eclipse Sound. Local hunters use this data to inform travel decisions to the floe edge. Upon return to the community, the SmartQAMUTIK data are automatically uploaded through WiFi to the SmartICE database to be processed and disseminated to the community through the SmartICE data portal.

11.4 Vulnerability

Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse impacts. Vulnerability to climate change is a function of the character, magnitude, and rate of change and variation to which a system is exposed, its sensitivity, and its adaptive capacity (Ford and Smit 2004). Not all communities, groups of people or individuals share the same degree of vulnerability to climate change. How people experience and respond to climate change risks will vary between individuals and communities, and will be conditioned by local geography and a range of endogenous factors, including demographic trends, economic complexity, and past experience dealing with change (Duerden 2004). Laidler et al. (2009) examined the complexity of the relationship between sea-ice conditions and the vulnerability of people to cope with these changes. A young hunter or even a part-time hunter (who has a full-time paid employment) has a much lower exposure than an active hunter who spends more time hunting. Therefore, from the perspective of access to land and travel safety, young hunters and part-time hunters are likely to be at greater risk than an active hunter due to their limited knowledge of the environment. Expert hunters will have much less difficulty in identifying changing ice conditions and minimizing potential risks by employing adaptive strategies (Ford et al. 2012a, Ford and Pearce 2012, Ford 2008, Ford et al. 2010). The capacity in identifying and understanding ice freeze-up and break-up and in managing physical hazards is part of the toolbox of expert hunters.

The vulnerability of a system may be influenced by the economic system. For example, wage economy has changed the way Inuit harvest, and has therefore altered the way in which land is accessed (Ford et al. 2013). In a wage economy system, many hunters are restricted to travel on their weekend or holidays due to employment obligations (Ford et al. 2008, Laidler et al. 2009). Hunters that are part/full time employees must book time off for hunting trips far in advance, and weather and safety concerns may be superseded by consideration of time availability when harvesting decisions are made (Ford et al. 2008). At the same time, financial costs can limit access to adaptive strategies (Ford

et al. 2008). Low incomes combined with rising prices in the Arctic reduces the ability for individuals and groups of people to afford new equipment (e.g., snowmobiles, radios, positioning devices) that allow them to cope with environmental changes (Ford et al. 2009, Laidler et al. 2009).

Adaptive capacity is facilitated by traditional knowledge and land-based skills (Pearce et al. 2015). Knowledgeable and experienced hunters act as an ‘institutional memory,’ maintaining and transmitting local knowledge and providing information during periods of change (Ford et al. 2008). Southern educational requirements have resulted in a decrease in time spent participating in harvesting activities and has limited the transmission of skills such as, navigating without instruments, adequate preparation for trips, and identification of hazardous conditions (Ford et al. 2008, Laidler et al. 2009, Pearce et al. 2011). New technology is being used to compensate the erosion of traditional Inuit knowledge and land-based skills. GPS, for instance, means that knowledge of traditional navigational skills is not as essential for safe travel (Figure 3) (Ford et al. 2008). Sensors and satellite images can also provide information on the ice conditions prevailing along the planned route (Laidler et al. 2011, Bell et al. 2014) (see Box A). However, technology cannot always identify locally meaningful



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FIGURE 3. GPS is currently used for navigation.

safety indicators or fully replace the value of land-based skills (Laidler et al. 2011, Pearce et al. 2011).

New technology can help to reduce vulnerability when accessing land if technology is used in combination with traditional knowledge (Laidler et al. 2009, Pearce et al. 2015). Equipment, such as GPS, radios, and other safety equipment, is frequently shared within the extended family and occasionally with friends (Ford et al. 2008). However, it is argued that the access to these new technologies may have also increased the vulnerability associated with the risks of varying sea-ice conditions by resulting in people being over confident and less cautious when out on the ice (Laidler et al. 2009, Aporta and Higgs 2005). Additionally, some hunters are now travelling in conditions that would have been traditionally considered to be too dangerous (Ford et al. 2008).

The vulnerability of individuals or populations is continuously changing along with the environment and socio-economic factors. The current dangers and challenges associated with varying ice, weather and other environmental conditions are expected to persist into the future (see Chapter 2), and there is concern regarding increased exposure, greater sensitivity, and additional barriers to adaptation (Ford et al. 2008.). There is a limited amount of research regarding the future vulnerability to climate change; most studies focus on the past and the present (Ford et al. 2012b). There is a need to focus on research that assesses the human implications of future climate change (Laidler et al. 2009).

11.5 Examples of ongoing adaptations

11.5.1 Contemporary adaptation strategies

Inuit have a strong adaptive capacity and they have historically adapted to changing environmental conditions (Wenzel 2009). Inuit are adapting in numerous ways to experienced changes (Table 1). There are different adaptation strategies that are used to cope with unpredictable weather, wind and ice conditions. For example, avoiding travel during certain times and at certain locations (Furgal and Seguin

2006, Gearheard et al. 2006, Ford et al. 2008b), planning for potential risks – knowledge of what to do in emergency situation (Laidler et al. 2009), communicating trail hazards (i.e., radio), and using search and rescue techniques are all examples of contemporary adaptation strategies (Ford et al. 2010). However, because vulnerability to climate change may differ from one individual to another or from one community to another, different adaptation strategies are used.

Travelers take extra food, gas, and supplies in anticipation of potential dangers of unpredictable weather, wind and ice conditions. New equipment are taken along such as GPS, and satellite phone (Aporta and Higgs 2005, Laidler et al. 2009, Gearheard et al. 2011). Travelers use weather forecasts on television and radio to complement traditional weather predictions (Aporta and Higgs 2005) and to identify safe areas where shelter can be found prior to travel. More powerful outboard boat engines are used to reduce time spent on exposed water and hunters are taking along small row boats to safeguard against the risks of getting stranded on drifting ice (Ford et al. 2006a). Other travelers are being risk averse, avoiding travelling on land or water if they have reason to believe the weather is going to be bad and they wait for adequate weather conditions. While these adaptive strategies can be beneficial, there are several barriers to adopting them. For example, taking extra supplies or utilizing new equipment is not always feasible (Ford et al. 2006a, Ford et al. 2006b).

Several strategies are used to cope with snow and ice hazards. Travelers tend to avoid thin ice, whether it be exposed or covered by snow, during the freeze-up period by using alternative land-based routes (Laidler et al. 2009). Other travelers continue to travel on thin ice but are more vigilant (Laidler et al. 2009). For example, Inuit also travel with others when possible, avoid dangerous areas altogether, or postpone travels during the freeze-up period in order to wait for solid ice (Ford et al. 2009). However, these strategies are not always feasible. Avoiding dangers and using alternative routes may increase the cost of gas due the longer distance that travelers must cover and harvesting resources may not be accessible by way of the land-based route (Laidler et al. 2009).

TABLE 1. Summary of gaps of knowledge concerning travel and hunting on the land and ice in a changing environment.

Trails/use of the ice:
<ul style="list-style-type: none"> • Few studies have documented the routes used and the role of traditional knowledge in understanding features such as sea, rivers and lakes and their associated tides, currents, water levels that are relevant during these seasons; • Little information on the role that TK plays regarding safely accessing land via ATV.
Traditional Knowledge (TK):
<ul style="list-style-type: none"> • Need for future research to document, maintain, and improve TK sharing between generations, specifically with regards to weather and the environment, including ice dynamics.
Socio-cultural-economic changes:
<ul style="list-style-type: none"> • Need for future research to document, maintain, and improve TK sharing between generations, specifically with regards to weather and the environment, including ice dynamics.
Climate and environmental changes:
<ul style="list-style-type: none"> • Information on climate change impacts not systematically available for all Nunavut communities.
Vulnerabilities:
<ul style="list-style-type: none"> • The current dangers and challenges associated with varying ice, weather and other environmental conditions are expected to persist into the future, and there is concern regarding increased exposure, greater sensitivity, and additional barriers to adaptation. • There is a limited amount of research regarding the future vulnerability to climate change; most studies focus on the past and the present. • There is a need to focus on research that assesses the human implications of future climate change.
Ongoing adaptations:
<ul style="list-style-type: none"> • Need to understand better the costs of climate change impacts on people, communities and governments in link with the access to land and travel safety. • Very few studies have focus on the effectiveness, durability, socio-economic and ecological implications, long term variability, and costs of such adaptive strategies. • Most research focuses on hunters and neglects other subpopulations that may be vulnerable.

There is a need to understand better the costs of climate change impacts on people, communities and governments together with the access to land and travel safety. A number of adaptation and coping strategies have been identified in the literature (Ford et al. 2010, Ford et al. 2007). However, very few studies have focused on the effectiveness, durability, socio-economic and ecological implications, long term variability, and costs of such adaptive strategies. Further, most research focuses specifically on hunters and neglects other subpopulations that may also be vulnerable.

11.5.2 Adaptation tools and technology integration

Community-based initiatives have been implemented to increase adaptive capacity. More specifically, community-based ice monitoring projects have been implemented to identify and monitor winter trails (Tremblay et al. 2006, 2008) and to establish a baseline for observing future ice dynamic changes (Mahoney et al. 2009, Clerc et al. 2011, Ford et al. 2013). Community-based monitoring responds to the community needs (Mahoney et al. 2009, Tremblay et al. 2008) and involves hunters and Elders that collaborate with their knowledge to guide the research

(Mahoney et al. 2009). Mahoney and Gearheard (2008) have produced a guide entitled “Handbook for Community-based Sea Ice Monitoring” that explains in-detail the methodology of monitoring ice. This guide has been used in the Eastern Arctic as well as several other Arctic regions (Nunavik, Nunatsiavut and Alaska). This handbook guides the local observer in choosing a site, installing the equipment, measuring ice/snow depth/snow temperature/water depth/air surface temperature, and storing equipment during the summer. The equipment described in the handbook is robust and requires no specialist training to build, operate, or repair. Local researchers can install stations and carry out observations on a weekly basis (Mahoney et al. 2009). Local knowledge is essential to know if sea-ice conditions are stable and identify when to install and remove stations from the ice. As such, traditional and scientific knowledge are used together. This form of community-based ice monitoring as well as programs like SmartICE which was described earlier are enabling communities to develop warning or hazard alert systems and can all be used as tools to assess community vulnerability to ice dynamics and their sensitivity to future changes (Figure 4).

Technology can be used to document environmental changes. An integrated water proof computer, GPS and weather meter technology has been used to document the use of trails by hunters and monitor the environmental changes in Clyde River (Gearheard et al. 2011). The Igliniit Project is a community-based project that combines traditional and scientific knowledge. Collaboration between science and engineering enable expert hunters to capture with their technology observations such as land and ice features, animals and regular activities of local experts across time and space. Data gathered can be used to understand patterns and changes in sea ice, weather conditions, and other aspects of the environment (Gearheard et al. 2011). This technology can also be useful for collecting information on the impacts of changing fuels prices or hunting practices, document travel patterns and land activities (Gearheard et al. 2011). However, there are some challenges related to the use of this technology. The hardware must be adapted to cold conditions and to be more user friendly for the observer. This type of project may need to maintain support for



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FIGURE 4. The Gearheard and Mahoney sea ice thickness station operated by communities. This station is off Pond Inlet established by SmartICE to validate a stationary sea ice thickness sensor, located on the right side of photo.

data management and mapping capability. This initiative also relies on temporal funding availability.

Remote sensing has been used to monitor sea-ice extent and characteristics for decades. The Canadian Ice Service (affiliated with Environment Canada) classifies sea ice mainly for navigation purposes, and describes the concentration of ice, the stage of development, the predominant size of ice, and the thickness of ice. Remote sensing also allows for the monitoring of annual variation in sea ice throughout the Canadian Arctic. Remote sensing has been recently used as a tool to evaluate the ice conditions in a context of access to land and traditional resources (Gauthier et al. 2010, Laidler et al. 2011). Gauthier et al. (2010) identified important steps to follow to build ice maps. These steps involved traditional knowledge information gathering about the environment, including conditions (and observed changes) of ice cover and trail networks, critical dates during the season, and frequency of ice monitoring needed. The ice was classified in a comprehensible and relevant way for users using Inuktitut nomenclature of ice which is essential to interpret the remote sensing images as close as possible to the Inuit perspective of ice. Maps were produced and delivered to the community in a minimal time lag (within 36 hours after remote sensing image acquisition).

Gauthier et al. (2010) identified challenges related to image validation. Even if air survey, ground pictures and field measurement can provide relevant information for map validations, these types of validations are expensive and not always accurate. The accuracy of ice maps is lower during the freeze-up and break-up periods, which are times that are particularly critical from a land access and safety perspective. Laidler et al. (2011) propose that a community-based ice monitoring system (ice conditions, snow conditions, and air and water temperature) could provide important data to help support the image interpretation and map accuracy. Gauthier et al. (2010) also mentions that ice maps were judged useful by the community even with the actual map accuracy. The challenge is to ensure continuity of this work and technological transfer to the community itself. Local resources (human and financial) are not always available to pursue the effort on a regular basis. Moreover, in a land access context, the imagery may not be sufficient to address local concerns about unpredictable ice conditions. Adequate traditional, navigational, language, and survival skills are still needed (Laidler et al. 2011).

11.5.3 Government led-adaptation in Nunavut

According to a recent study on government led-adaptation strategies ($n=700$) in Nunavut, the majority of adaptation initiatives are being implemented at the community level (62%) compared to the territorial (19%) and federal levels (19%) (Labbé et al. 2017). Despite the number of adaptation occurring at the community level, the number of initiatives were found to vary considerably between communities. The study reported that Arviat, Cambridge Bay, Clyde River, Iqaluit, Kugluktuk, and Whale Cove had the highest number of adaptations documented, with the city of Iqaluit having the highest number of initiatives (Labbé et al. 2017). Twelve other communities (Arctic Bay, Baker Lake, Cape Dorset, Gjoa Haven, Hall Beach, Igloolik, Kimmirut, Kugaaruk, Pangnirtung, Pond Inlet, Rankin Inlet, and Repulse Bay) were only found to have between 1 and 3 adaptation initiatives and no adaptation initiatives were reported for the following eight communities (Bathhurst Inlet/Umingmaktok, Chesterfield Inlet,

Coral Harbour, Grise Fiord, Qikiqtarjuaq, Resolute Bay, Sanikiluaq, and Taloyoak) (Labbé et al. 2017). While this study focussed on adaptation initiatives related to a variety of topics (Labbé et al. 2017), these results likely reflect what would be expected for initiatives related directly to land and ice travel. The focus on adaptation in the region has largely been aimed at the ground work level which includes informing and preparing for adaptation, yet the implementation of solutions and adaptive strategies for many of these initiatives is often lacking.

11.6 Conclusion

Access to the land is still part of the way of life in Nunavut and is critical to maintaining healthy communities. Socio-cultural-economic as well as climatic and environmental changes are transforming exposure and sensitivity to risk when Inuit access the land and ice. Adaptations are facilitated by traditional knowledge and new technologies. Several adaptive strategies and coping mechanisms to access land and to reduce risks during travel have been identified and were discussed in this chapter. However, there is a need to identify the effectiveness, durability, socio-economic and ecological implications, long term variability and costs of these adaptations (Ford et al. 2012b). Also, there is a need to assess the potential impacts of future climate change on the more vulnerable cohorts, as much of the previous research has focused specifically on hunters.

Traditional knowledge continues to be an effective tool to cope with climate change and remains essential to manage risks associated with access to land (Pearce et al. 2015). Traditional knowledge is continually expanding to include new information (Laidler 2006). There is a need to document, maintain and improve traditional knowledge sharing between generations to preserve this tool accessibility for new generations. The Young Hunters Program in Arviat is an good example of a program that teaches kids skills that their ancestors used and that they have never learned before. New technology has emerged to compliment traditional knowledge and land-based skills, however use of this newer technology needs to be exercised with caution so that hunters do not become overconfident or travel in

conditions that would have been traditionally too dangerous (Aporta and Higgs 2005, Ford et al. 2008).

Traditional knowledge and science integration is essential to improving our understanding of current and future climate and environmental changes. For example, remote sensing images can be used to document ice dynamics (Gauthier et al. 2010, Laidler et al. 2011) but also needs to take into account Inuit perspective of ice and its characteristics. It is essential that scientific and Inuit ice experts continue to work together to better understand ice dynamics so as to inform Inuit needs in the future.

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Chapter 12 Human Health and Well-being

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Key implications for decision makers

- Food insecurity and mental health are key priorities for policy-makers in the region. They affect significant proportions of the population and have wide-reaching impacts on other aspects of Inuit health and well-being.
- Obesity and diabetes are emerging as significant health challenges with transformation and modernization of Inuit society.
- Smoking is a widespread, preventable health risk for Inuit adults and is associated with both immediate and long-term negative respiratory health outcomes for young children living in homes with smokers.
- Traditional food consumption continues to decline, especially among younger Inuit adults, despite the numerous benefits including increased food security, improved diet quality and reduced risk of cardiovascular disease.
- Childhood obesity is emerging as a significant health issue in Nunavut, in part due to the large amount of food and drink high in sugar and fat consumed by Inuit children.
- Generally, the nutritional benefits of eating country foods outweigh the risks from contaminant exposure.
- Blood contaminant concentrations in Inuit from Nunavut are generally below human health guideline levels, but are higher than average levels reported for the rest of Canadians.
- Cadmium, which is largely attributed to smoking, was the only contaminant that the average population level among participants exceeded guideline levels.
- PCB levels in the blood of Inuit are generally not high enough to cause health problems.

Abstract

The Inuit Health Survey (*Quanipitali* in Nunavut, meaning “How Are We?”) was conducted in 2007 and 2008, covering all Inuit communities in Nunavut, the Inuvialuit Settlement Region, and Nunatsiavut. The Nunavut Inuit Child Health Survey took place in 16 Inuit communities in Nunavut. Together, these studies represent the most recent comprehensive assessment of health and nutrition among Inuit residents of Nunavut. This chapter presents summary findings on the health and well-being of Inuit adults living in the IRIS 2 region and children living in Nunavut. It contains background on survey design and methods, health patterns in adults and children, and major scientific findings that arose from the surveys. Finally, it provides an overview of public health strategies that address the significant health challenges described by the research.



VINCENT L'HÉRAULT/ARCTICNET

12.1 Introduction

Since 1999, the Government of Nunavut has been responsible for providing comprehensive health services to residents of the Eastern Arctic IRIS 2 region. The remoteness of many communities makes health service delivery a considerable challenge in the region, one that can be supported by accurate health assessment data. In 2007 the first-ever large-scale, comprehensive health assessment of people living in Canada's polar regions was launched.

The Inuit Health Survey (hereafter IHS, named *Quanipitali* in Nunavut, meaning “How Are We?”) was conducted across the Canadian Arctic over two summers in 2007 and 2008, including all Nunavut communities (with the exception of Kinglet/Bathurst Inlet and Umingmaktuk, whose small population sizes precluded their participation), the Inuvialuit Settlement Region, and Nunatsiavut. The data collected are compatible with, and will contribute to the International Inuit Health in Transition Study involving Inuit communities in Nunavik, Greenland and Alaska.

The Nunavut Inuit Child Health Survey (hereafter CHS) was conducted across the Canadian Arctic over two summers in 2007 and 2008, covering 16 Inuit communities in Nunavut. The study focused on children aged 3-5 years since this is a critical age where growth and development are proceeding rapidly and children are particularly sensitive to the environment around them. Because the CHS examined a smaller number of participants than the adult survey, we protect the anonymity of the families involved by reporting results for the entire territory. The CHS covers communities from the Kitikmeot, Kivalliq and Baffin regions of Nunavut and therefore ranges slightly beyond the boundaries of IRIS 2. We consulted with health service providers and community members in the IRIS 2 region who felt it was important to include results of the CHS in this chapter.

The overall objective of the IHS and CHS was to provide a broad-based assessment of health among Inuit adults and children, respectively. Inuit in the Canadian North are undergoing rapid social and economic changes, with

important consequences for their health. It is intended that the results from the survey will not only provide a baseline with which future surveys can be compared, but also lead to targeted interventions directed at priorities to be established in collaboration with Inuit communities and organizations.

The IHS and CHS capitalized on the opportunity offered by the International Polar Year (IPY) and the substantial funding made available by the Canadian federal program, without which a survey of such large scale would not have been feasible. Supplementary funding was also provided by the Canadian Institutes of Health Research, Health Canada, ArcticNet, and the territorial governments and regional health authorities.

The IHS and CHS were developed through a participatory process involving extensive consultations with stakeholders and formation of steering committees. Memoranda of understanding were developed and university-community research agreements signed to govern the implementation of the survey and outline roles and responsibilities of different parties.

Twenty communities within the boundaries of IRIS 2, namely those in the Kivalliq and Baffin regions of Nunavut, participated in the IHS (Table 1). Participants were chosen in a two-stage procedure: the household, and individuals within the household. A total of 1067 households (410 in Kivalliq and 657 in Baffin) were selected, from which a final



STEPHANIE MACDONALD/INUIT HEALTH SURVEY

TABLE 1. Communities in the Kivalliq, Baffin and Kitikmeot regions that participated in the Inuit Health Survey and Child Health Survey.

Kivalliq	Baffin	Kitikmeot
Arviat ^{a,b}	Arctic Bay ^a	Kugluktuk ^b
Baker Lake ^{a,b}	Cape Dorset ^a	Kugaaruk ^b
Chesterfield Inlet ^{a,b}	Clyde River ^a	Cambridge Bay ^b
Coral Harbour ^{a,b}	Grise Fiord ^a	
Rankin Inlet ^{a,b}	Hall Beach ^a	
Repulse Bay ^a	Igloolik ^{a,b}	
Sanikiluaq ^{a,b}	Iqaluit ^{a,b}	
Whale Cove ^{a,b}	Kimmirut ^{a,b}	
	Pangnirtung ^a	
	Pond Inlet ^{a,b}	
	Qikitarjuaq ^a	
	Resolute Bay ^a	

^a communities that participated in the Inuit Health Survey

^b communities that participated in the Child Health Survey

sample of 1483 adult participants aged 18+ were selected (585 in Kivalliq and 898 in Baffin). Women predominated, accounting for 59% of the sample. About half (49%) were aged 40 and above.

Sixteen communities, namely those in the Kivalliq, Baffin and Kitikmeot regions of Nunavut, participated in the CHS (Table 1). Participants were chosen in a two-stage procedure: children were recruited through a list of homes with children ages 3-5 that participated in the adult health survey (ship-based) and through a list of children provided by the local health centers. A randomized list of children was created and parents/caregivers were contacted by telephone. A total of 388 children ages 3-5 years, along with their parents/caregivers, participated in the survey. All coastal communities were reached by the Canadian Coast Guard Ship (CCGS) *Amundsen*, while Baker Lake was visited by air by a separate research crew. The CCGS *Amundsen* was equipped with laboratory and research facilities and ensured the safe transport of participants to and from their communities. The survey employed approximately 100 staff representing bilingual Inuit interviewers



STEPHANIE MACDONALD/INUIT HEALTH SURVEY

FIGURE 1. The *Amundsen*'s barge picking up survey participants from Chesterfield Inlet.

and greeters, local community assistants and drivers, who helped coordinate survey activities in communities, interpreters, graduate students, lab technicians, quality control officers, ultrasound and bone density specialists, dietitians, communications officers, a mental health counsellor and nurses, many of whom have worked in the Arctic for years.

Three separate land teams, usually composed of one northern nurse, one bilingual Inuit research assistant, and one additional assistant, travelled to all communities ahead of the *Amundsen*. In each community they were joined by local research assistants and drivers. Community corporation offices, hamlet offices or the health centres provided office space where land team members could meet and interview participants. Prior to the ship's arrival in a community, land team members recruited and interviewed participants and arranged for clinic appointments on board the *Amundsen*. After the ship's arrival in the community, participants were brought on board the ship by a shuttle (barge) or a helicopter (Figure 1).

For the CHS, a caregiver was contacted and asked to participate with their child in the health survey. If the caregiver gave written informed consent, an interview proceeded with six questionnaires: identification chart, home-based questionnaire, 24-hour dietary recall, child food frequency questionnaire, child medicine and supplement use and child

individual questionnaire. When the interview was complete, the child would see the nurse with the caregiver to complete the clinical assessments. The 2007 CHS research team consisted of a bilingual Inuk nurse who conducted all venipuncture and the majority of the clinical assessments, a bilingual Inuk interviewer who conducted the majority of the interviews and two research assistants from The Centre for Indigenous Peoples’ Nutrition and Environment (CINE), McGill University who were responsible for

training, logistical arrangements, recruitment, interviewing, assisting the nurse, file management and blood sample preparation. The 2008 team was similar except that the nurse was a non-Inuk northern nurse who had previous experience working in Nunavut. Questionnaires, clinical measurements and laboratory tests were conducted on board the *Amundsen* (Table 2 and 3) and between 40 and 50 participants were seen daily, with visits lasting up to three hours.

TABLE 2. Questionnaires, clinical measurements and laboratory tests conducted on board the *Amundsen* for the Inuit Health Survey.

Questionnaires	
Household	Language spoken at home; home ownership, number of rooms and occupants; homeless visitors; smoking restriction; hunting practice; use of country food; food insecurity; income support
Individual	Self-rated health; dental health status; past medical conditions; menstrual history and pregnancy; birth control; sun protection; physical activity; smoking; marital status; education; income source; personal income; employment status
Community and personal wellness	Activities out on the land; community activities; violence in community; job satisfaction; sleep pattern; emotional support; depressive symptoms; suicidal ideas and attempts; stress relief; gambling; alcohol and drug use; past history of verbal, physical and sexual abuse; personal qualities; community advantages
Medicine and supplement	Use of selected medication, vitamins, and nutritional supplements
Dietary	Food frequency and quantity of selected country and market foods consumed, using food models; 24-hour recall of food intake
Clinical Measurements	
Holter monitoring	To measure heart rate and detect irregular cardiac rhythms
Ultrasonography	Carotid arteries – to measure thickness and patency; abdominal – to measure intra-abdominal fat deposits
Anthropometry	Height and weight; waist circumference; sitting height; bioelectrical impedance to measure body fat
Laboratory Tests	
Venous blood tests	Fasting and 2-hour post-challenge plasma glucose, insulin; vitamin D, parathyroid hormone and osteocalcin; total cholesterol, HDL, LDL, apolipoprotein B, triglycerides; red blood cell fatty acids; adiponectin, leptin; serology for selected infections; ferritin, transferrin; vitamin B6, folate; magnesium; C-reactive protein; selected contaminants
Capillary blood tests	Hemoglobin
Blood pressure	Diastolic (DBP) and Systolic (SBP)
Bone density	Measured in forearm and heel bone, among women 40+ years only
Toenail samples	To measure selenium level

TABLE 3. Questionnaires, clinical measurements and laboratory tests conducted on board the *Amundsen* for the Child Health Survey.

Questionnaires	
Individual	Child's health history; mother's health practices during pregnancy, birth weight, breastfeeding, respiratory tract infections, ear infections, injuries, languages and speech, dental health and bone health
Home-based	Languages spoken in the home, household crowding, smoking in the home, hunting practices, household expense and income and food security
Dietary	Food frequency questionnaires and 24-hour recall of child's food intake; a subsample of caregivers were asked to return for a 20-minute appointment to complete a repeat 24-hour dietary recall on a nonconsecutive day
Medicine and supplement	Use of selected medication, vitamins, and nutritional supplements
Clinical Measurements	
Anthropometry	Height and weight
Heel ultrasound	Bone density
Laboratory Tests	
Hair sample	Mercury levels
Venous blood tests	Fasting plasma glucose, insulin; vitamin D, parathyroid hormone and osteocalcin; total cholesterol, HDL, LDL, apolipoprotein B, triglycerides; red blood cell fatty acids; adiponectin, leptin; serology for selected infections; ferritin, transferrin; vitamin B6, folate; magnesium; C-reactive protein; selected contaminants
Capillary blood tests	Hemoglobin



FIGURE 2. Survey procedures conducted on the *Amundsen*. (a) nurse collecting blood sample; (b) interviewers reviewing questionnaires; (c) measuring heart rate and rhythm with the Holter monitor; (d) ultrasonography of the carotid arteries.

12.2 A portrait of the adult population's health

12.2.1 Self-rated health

A useful index of overall health is a respondents' self rating of health as "excellent", "very good", "good", "fair" or "poor". Only a small minority (7%) of respondents rated themselves as in poor health. Studies have shown that there is strong correlation between a person's self-rated health and long-term health outcomes such as mortality and hospitalization.

12.2.2 Pre-existing health problems

Respondents were also asked if they had ever been told they have certain health conditions. About 24% of adults were affected by hypertension, while 7% had diabetes (Figure 3). Note that a survey is not useful to estimate the burden of highly fatal diseases (such as cancer). For certain conditions, the survey itself may uncover additional cases – glucose tests for diabetes and actual measurement of blood pressure.

12.2.3 Cultural and socioeconomic determinants

Use of traditional language is a strong indicator of the vibrancy of traditional culture. Fully 84% of respondents said they spoke Inuktitut or another Inuit language in their homes.

About 77% of households occupied public housing. One quarter of the homes were considered to be in need of major repairs. About 5% of homes had a problem with moulds. About 19% of households reported having provided lodging to a homeless person, with a median of 61 days of stay. As a measure of crowding, about one-third (32%) of homes had more than one person per room – the proportion was higher among homes with children (39%). On average there were 2.85 persons per bedroom.

Lower educational attainment has been shown to be associated with the presence of many health problems. About 67% of adults did not complete secondary school – among the younger generation under 40 years of age, the proportion is slightly lower, at 61%, compared to 73% of those older than 40 (Figure 4).

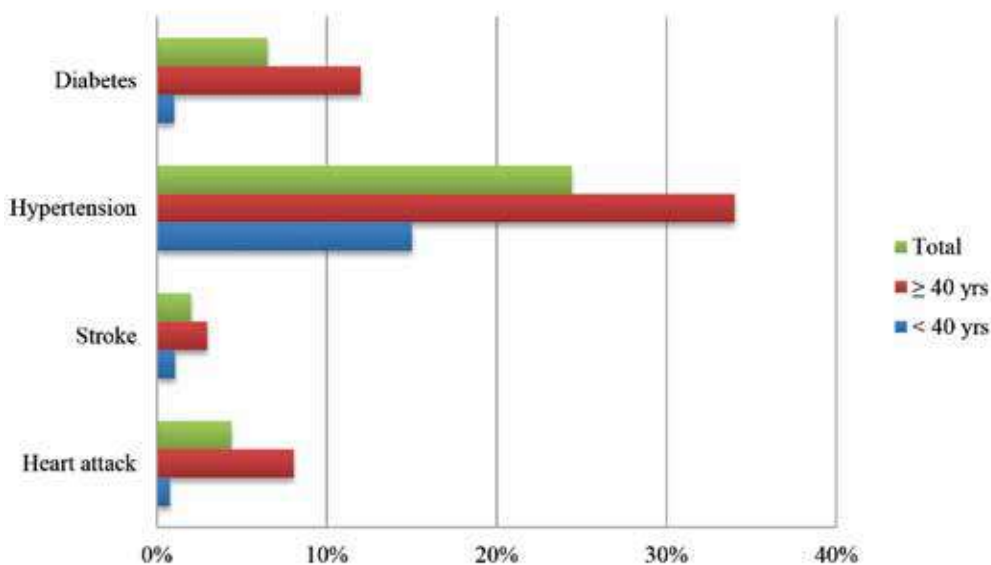


FIGURE 3. Frequency of self-reported health conditions.

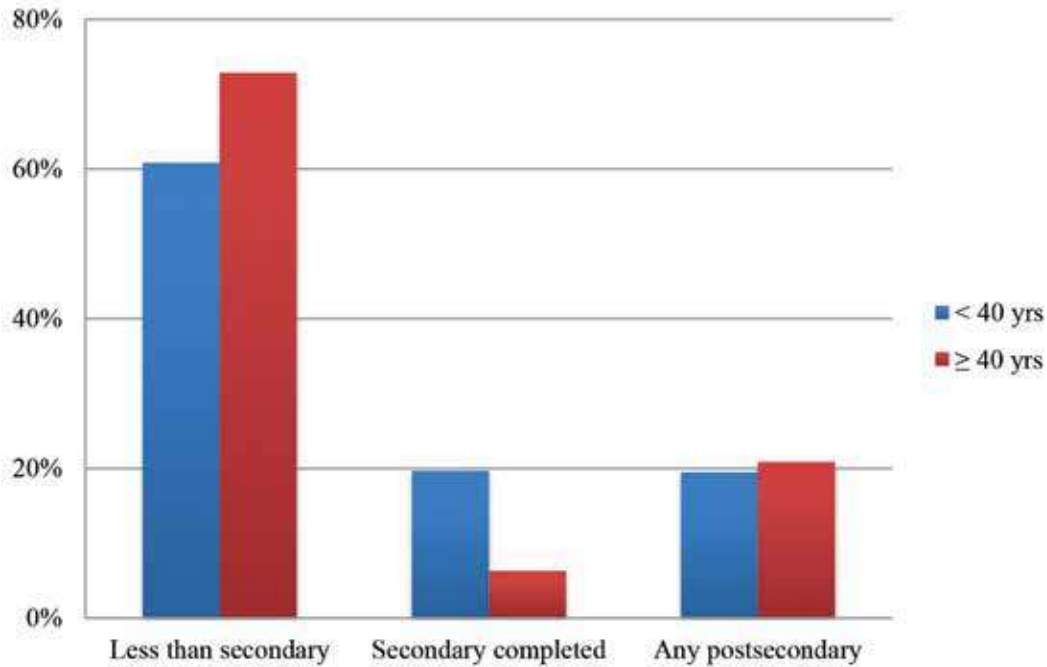


FIGURE 4. Highest level of education among Inuit Health Survey respondents.

About 33% of respondents received income support. Well over half of the individuals (58%) had total personal income less than \$20,000 per year (Figure 5).

12.2.4 Health-related behaviours

Among the most important risk factors for a variety of diseases is smoking. Among adults 73% were current smokers, while 83% had ever smoked. Among smokers, the average number of cigarettes smoked per day was 11.6. The average age when smokers began smoking was 15.1 years. Exposure to environmental smoke was almost universal in homes – 89% of households had at least one smoker, and the proportion was even higher (91%) among households with children.

Physical activity was assessed by asking participants if they walked for at least 20 minutes on three or more days in the past week (86% did so) and if they engaged on vigorous activities for at least 20 minutes on three or more days in the past week (38% did so).

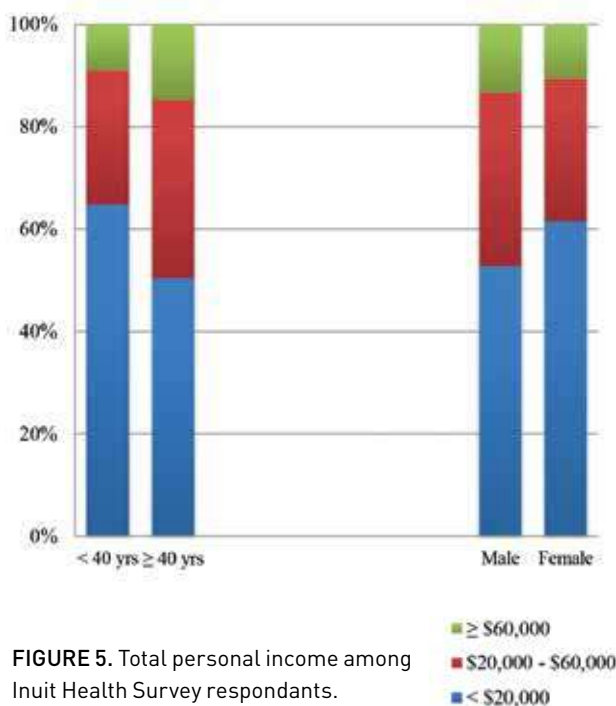


FIGURE 5. Total personal income among Inuit Health Survey respondents.

12.2.5 Nutrition and food security

The role of country foods in the diet continues to be strong. Just over 64% of households had an active hunter, and 74% distributed game meat to other members of the community.

Only a minority of homes (30%) were considered food secure, while 34% had moderate and 36% severe food insecurity. See Chapter 13 for further details on food security in the Eastern Canadian Arctic.

Some key dietary data from the 24-hour recall (on energy intake) and food-frequency questionnaire (consumption of specific foods) are shown in Table 4 below.

Specific dietary deficiency can also be detected by blood tests. For vitamin D, 34% of adults (54% among the <40 and 15% among the 40+ age groups) were found to be deficient. Based on their haemoglobin level, 21% of men and 24% of women were defined as anaemic. Various blood tests for iron status identified 6% of men and 27% of women as suffering from iron deficiency.

12.2.6 Cardiometabolic risk factors

Clinical measurements and laboratory tests conducted as part of the survey enable the estimation of the proportion of the population who are “at risk” for the development of chronic diseases.

Table 5 below summarizes key findings on plasma lipids and blood pressure:

TABLE 5. Plasma lipid levels and blood pressure categories.

“At risk” plasma lipid levels	%
Total cholesterol	37.8
LDL-cholesterol	24.5
HDL-cholesterol	23.8
Triglycerides	20.3
Distribution of BP level:*	
Normotensive	55.0
Pre-hypertension	30.7
Hypertension stage 1	11.6
Hypertension stage 2	2.8

*Note: “normotensive” = SBP <120 and/or DBP <80; “pre-hypertension” = SBP 120-139 and/or DBP 80-89; “hypertension stage 1” = SBP 140-159 and/or DBP 90-99; Hypertension stage 2 = SBP ≥ 160 and/or DBP ≥100

TABLE 4. Daily dietary intake by macronutrient and selected categories of traditional foods.

	Total	Age < 40 yrs	Age ≥ 40 yrs	Male	Female
Total energy (kcal)	2081.7	2254.4	1893.6	2274.8	1955.3
% energy as fat	30.8	29.4	32.3	31.2	30.5
% energy as CHO	47.0	51.7	41.9	44.2	48.9
% energy as proteins	20.8	17.8	24.2	22.8	19.5
Daily intake of traditional foods (g)	252.0	207.1	281.9	335.5	192.4
Marine mammals	42.5	31.1	58.4	85.9	27.4
Land mammals	74.2	67.8	79.1	101.2	54.6
Fish	22.4	15.1	30.2	36.2	15.6
Birds	0.9	0.0	1.8	1.8	0.4
% who drank soft drinks daily	83.5	88.0	78.7	87.1	81.2

12.2.7 Mental health

Studies have shown that the quality of a person's social networks is strongly associated with their overall level of health and well-being. The emotional support provided by close friends and family can help a person deal with stressful events in their lives. The IHS found that many Nunavut residents had strong social networks: 64% of respondents reported getting together with people sometimes, often or very often to play games, sports, or recreational activities. Sixty-one percent of respondents reported participating sometimes, often or very often in activities where people came together to work for the benefit of the community, such as coaching, foster parenting, community board membership or food sharing.

However many residents of Nunavut lack a strong social support networks. Overall, only 46% of respondents reported that they have someone to turn to most or all of the time when they need emotional support.

The IHS did not collect data on whether people suffered from an anxiety disorder; we simply asked respondents how often they felt anxious. Excessive or frequent anxiety

can interfere with a person's ability to cope with everyday life: school, work, social activities and recreation.

In Nunavut, 14% of respondents reported feeling anxious all or most of the time. Thirty-one percent (31%) of respondents reported sometimes feeling anxious. Anxiety disorder is the most common cause of mental illness in Canada. Statistics Canada estimates that one in ten Canadians suffer from some form of anxiety disorder (Public Health Agency of Canada 2002). There are effective treatments for anxiety including counseling and stress management.

The term "depression" can be used to describe both a general feeling and a serious mental illness. The feeling of depression is characterized by a general sadness. In our survey, we asked people to report whether they experienced the feeling of depression. We did not ask respondents whether they had a diagnosed depressive illness. Forty-three percent of respondents reported feeling depressed some or a little of the time while 9% of respondents reported feeling depressed all or most of the time during the past 30 days (Figure 6). More Nunavut women (11%) than men (6%) reported feeling depressed all or most of the time.

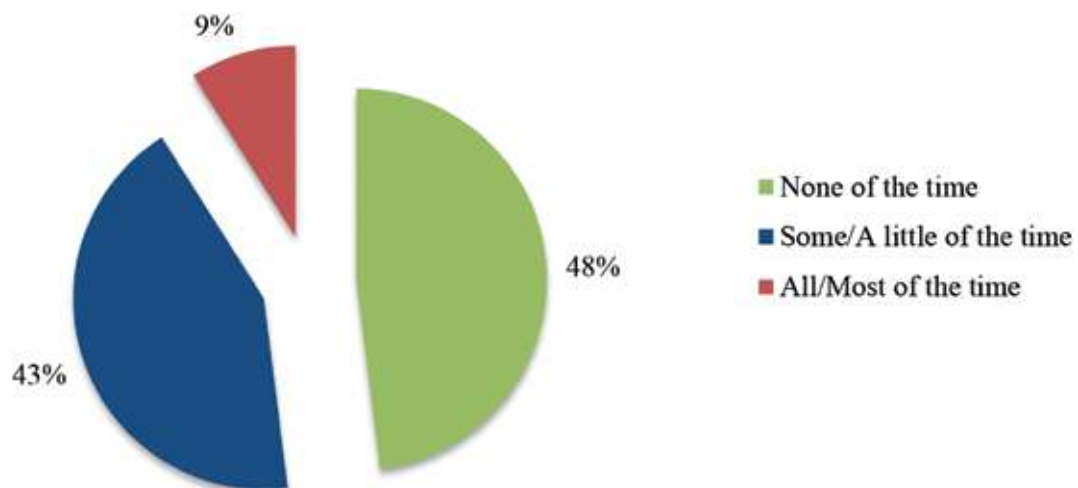


FIGURE 6. Frequency of feeling depressed during the previous 30 days.

The survey also asked respondents a series of questions about whether they had experienced physical or sexual abuse. Fifty percent of survey respondents reported having experienced at least one form of physical violence as an adult. Fifty-two percent (52%) of women and 22% of men reported that they experienced sexual abuse during childhood. Some, 27% of women and 5% of men, reported that they had experienced some form of forced sexual activity as adults, including unwanted sexual touching, sexual coercion, or forced sexual intercourse.

Suicidal ideation, or having thoughts about suicide, is a sign that a person is having severe difficulty coping with life events and needs immediate treatment. The frequency of reported suicidal ideation and reported suicide attempts was extremely high and much higher than for other Canadians (Statistics Canada 2004).

Forty-eight percent (48%) of respondents reported having experienced suicidal ideation, or serious thought about suicide, at some point in their lives. Rates of attempted suicide in Nunavut are extremely high. Twenty-nine percent (29%) of respondents reported a non-fatal suicide attempt at some point in their lives. Five percent (5%) of all Nunavut respondents reported a non-fatal suicide attempt in the last 12 months. Among Nunavut adults, younger adults (18-49 years) reported more recent suicide attempts than older people.

Sixty-five percent (65%) of men and 55% of women reported having consumed alcohol at least once in the 12 months prior to the survey. There were similar rates of men (18%) and women (15%) who reported having lost a close personal relationship because of their drinking. Forty-three percent (43%) of respondents reported using recreational drugs such as marijuana or hashish in the previous 12 months.

12.2.8 Contaminants

The contaminant portion of the Inuit Health Survey evaluated the levels of contaminants in country foods, and in Inuit, and assessed the benefits and risks of consuming

country foods. The findings revealed, that the nutritional benefits of eating country foods generally outweigh the risks from contaminant exposure. Further, the consumption of country foods provides an important source of essential nutrients such as selenium, polyunsaturated fatty acids, omega-3 fatty acids.

Blood contaminant concentrations in Inuit from the region were generally below human health guideline levels, but remain higher than average levels reported for the average Canadian. However, some participants, did have contaminant concentrations that exceeded human health guidelines, ranging from 5% of the population for selenium to 73% for cadmium. Cadmium, which is largely attributed to smoking, was the only contaminant that the average population level among participants exceeded guideline levels.

There were some age and sex differences among the blood contaminant concentrations. For example, Inuit over 61 years of age had higher blood concentrations of mercury, lead (Pb), PCBs, and some organochlorine pesticides (e.g., DDT, DDE, toxaphene, and chlordane) than Inuit between 41 and 60 years of age. Inuit between the ages of 18 and 40 generally had the lowest blood concentrations for these contaminants. Inuit between the ages of 18 and 40 had higher Cd concentrations than participants over 41 years of age. Men generally had higher blood concentrations of mercury, Pb, PCBs, and OCPs than women. Some women of child-bearing age had blood mercury concentrations that exceeded the Health Canada guideline (8 ppb). As a result, women of child-bearing age are advised to avoid eating ringed seal liver and instead consume ringed seal meat or other traditional foods such as char and caribou muscle that have lower mercury levels.

The primary dietary source of mercury for Inuit in the region is ringed seal liver, whereas the primary dietary sources of PCBs and OCPs are beluga and narwhal blubber. Blood PCB levels were generally not high enough to cause health problems.

The primary dietary sources of selenium, which is an essential micronutrient, were caribou meat, beluga blubber (muktaaq), and Arctic char. Arctic char meat is an

excellent source of polyunsaturated fatty acids (PUFA) and omega-3 fatty acids.

12.3 A portrait of child health

12.3.1 The home environment

The home environment is an important determinant of child health. The survey explored various aspects of young children's home environment, including contact with extended family, languages spoken at home, household overcrowding, and the presence of smoking in the home.

Results showed that Nunavut children live in households with strong family and cultural ties. Sixty-two percent (62%) of children were cared for in the home, while 34% attended preschool or daycare programs. A large majority (84%) of children had contact with their extended family (grandparents, aunts, uncles, cousins) every day. In Kivalliq and Baffin, 80% of children spoke some Inuktitut words, and 45% of children used Inuktitut as their primary language at home (Figure 7). Inuktitut was the primary

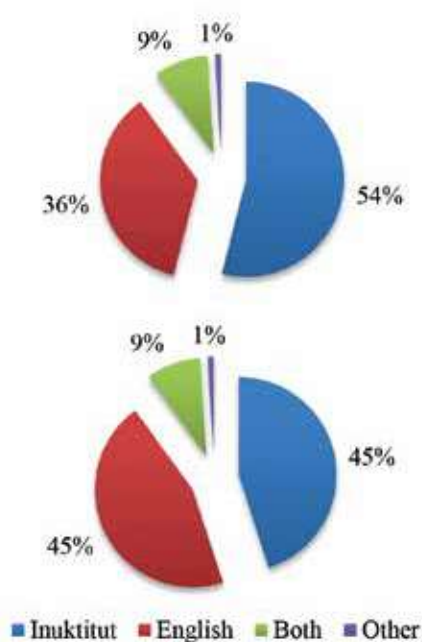


FIGURE 7. (top) Primary language spoken to children 3-5 years of age; (bottom) Primary language pre-school children spoke.

language spoken by adults in 54% of homes in Nunavut (Figure 7).

Housing is a serious issue in Nunavut, and one that has consequences for child health. The survey reported that 53% of children lived in homes that were overcrowded. The average number of people living in children's homes was six, much higher than the Canadian average of 2.5 (Statistics Canada 2006). Thirty-seven percent of children's homes had more than two people per bedroom and 11% of families with 3-5 year old children gave shelter to homeless people in the past year. About 35% of children lived in homes needing major repairs.

Smoking is very common in Nunavut. In homes with young children, there were on average 2 people who smoked. However 93% of parents and caregivers surveyed reported that they had rules about smoking in the home, the most common of which was that smoking was only allowed outside.

12.3.2 Pregnancy and early infant feeding

The survey asked parents some questions about health and feeding practices during pregnancy and early childhood. Sixty-eight percent (68%) of mothers breast fed their children, and the average duration of breastfeeding was 18 months. This is excellent news. The World Health Organization recommends exclusive breastfeeding for 6 months, after which complementary foods may be introduced, and that mothers continue breastfeeding, if possible, for up to two years (Health Canada 2004). The high rate and long duration of breastfeeding among Nunavut women is a success story.

Many Nunavut mothers took vitamin supplements during pregnancy to improve their nutrition. Thirty-one percent of mothers took iron or Vitamin D supplements. The majority of mothers (83%) reported that they smoked during pregnancy.

12.3.3 Child Nutrition and Food Security

The CHS found that, like children in southern Canada, children living in Nunavut consumed a high number of foods and drinks high in sugar and fat. Almost 35% of

children’s total food energy came from high sugar or high fat food and drinks such as chips, candy, soft drinks, powdered sweet drinks, fruit juice, high-sugar cereals and baked goods. On average, 78% of children drank sweet drinks the day before the interview. The average amount of sweet drinks consumed was three per day.

Fibre intake among Inuit children was very low. On the other hand, many Nunavut children are eating country food, which is very healthy for them. Caregivers reported that 46% of children ate some type of country food on the day before the survey, and nearly all children (99%) ate some kind of country food in the month prior to the survey (Figure 8). Children’s favourite country foods were caribou, fish and berries (Figure 8).

The reason that many children have access to country foods on a regular basis is that hunting culture and food sharing networks are strong in Nunavut. Seventy-two percent (72%) of caregivers said they had an active hunter in the household and 73% said they obtained country food from their families.

We compared the 24-hour recalls of children who ate no country food the day before with those of children who ate large amounts of country food the day before survey. Children with high intake of country food had significantly higher intakes of protein, Vitamins A and D, iron, zinc and magnesium. These nutrients are very beneficial for growing children.

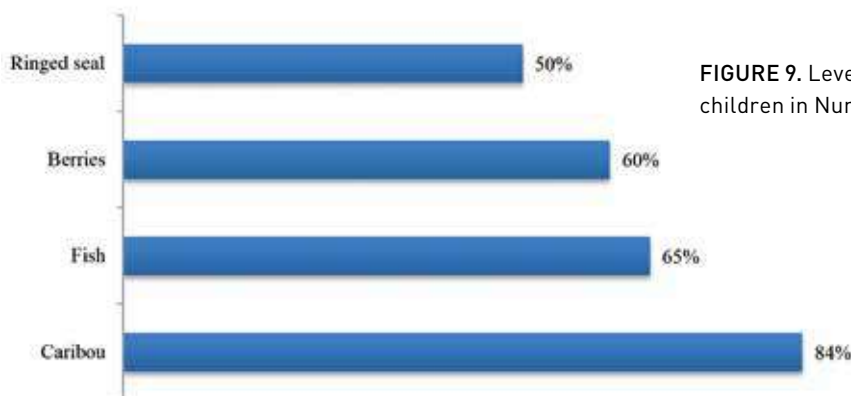


FIGURE 8. Percent of children consuming country foods in the month prior to the survey.

Some families use vitamins and supplements to improve children’s diets. About 21% of children receive a vitamin daily, most commonly multivitamins and vitamin C. Vitamin D supplements are free at local health centres but are not commonly taken.

Food security was a significant problem for families with young children. Thirty-four percent (34%) of parents or caregivers of young children said they did not have enough food to feed their families (Figure 9). Twenty-four percent (24%) of children lived in homes reporting severe food insecurity (Figure 9). Families where adults received income support or lived in public housing were more likely to report food insecurity. These results show in Nunavut that many families with young children experience food insecurity.

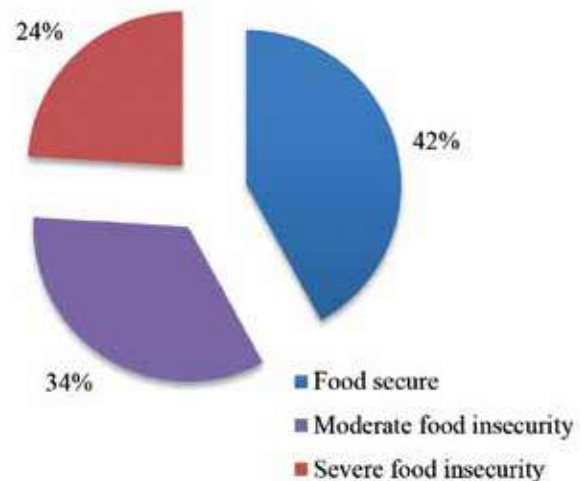


FIGURE 9. Levels of food insecurity in homes with young children in Nunavut.

12.3.4 Clinical findings

The results of clinical examinations indicated that childhood obesity is becoming a significant problem in Nunavut. Only about one-third of 3-5 year olds had body mass index (BMI) below the cutoff for “overweight”. This finding is likely at least partly related to the elevated intake of foods and drinks high in sugar and fats observed in the study.

A related finding was the high frequency of dental decay in survey children. A majority of children (72%) had decayed, extracted or filled baby teeth.

The survey found that 20% of Nunavut children aged 3-5 years had low levels of haemoglobin in their blood, a condition known as “anaemia”. Anaemia can be caused by not eating enough iron, however only 5% of survey children had this form of “iron-deficiency anaemia”. Anaemia may cause children to feel tired or weak, have difficulty paying attention in school, and, if left untreated, experience slower rates of growth. It is important to identify and treat children who have anaemia.

Blood tests also showed that many children in Nunavut were not getting enough Vitamin D. Only 21% of children had healthy, optimal levels of Vitamin D in their blood (Figure 10). The rest suffered from some degree of Vitamin D deficiency, ranging from “suboptimal” to “deficient” (Figure 10).

In the warmer months of the year, our bodies can make Vitamin D when the sun shines on our skin. But in the long and dark winter in Nunavut, vitamin D must come from food sources. Arctic char is an excellent source of Vitamin D, as is fortified milk.

Vision testing showed that 99% of preschool-aged children living in Nunavut had normal vision. Ear infections were common, however, with 34% of children having an ear infection in the year prior to survey and 84% of those requiring medical treatment.

Respiratory illness was common among Nunavut children. Many children had experienced asthma, bronchiolitis, bronchitis or pneumonia. Prior to the age of two years, 32% of children in the survey had a serious lung infection, and about half of these required hospital treatment outside of Nunavut. In the year prior to survey, 42% of children had gone to a health centre or hospital for a respiratory illness.

Tests also revealed that almost half of children (46%) had been exposed to *Helicobacter pylori* infection. While *H. pylori* is usually not a serious infection, in some children over time it can contribute to anaemia or the development of stomach ulcers. There was no relationship between *H. pylori* infection and anaemia in Nunavut children, however health care personnel should be on the look-out for signs or symptoms of chronic or repeated infection from *H. pylori*.

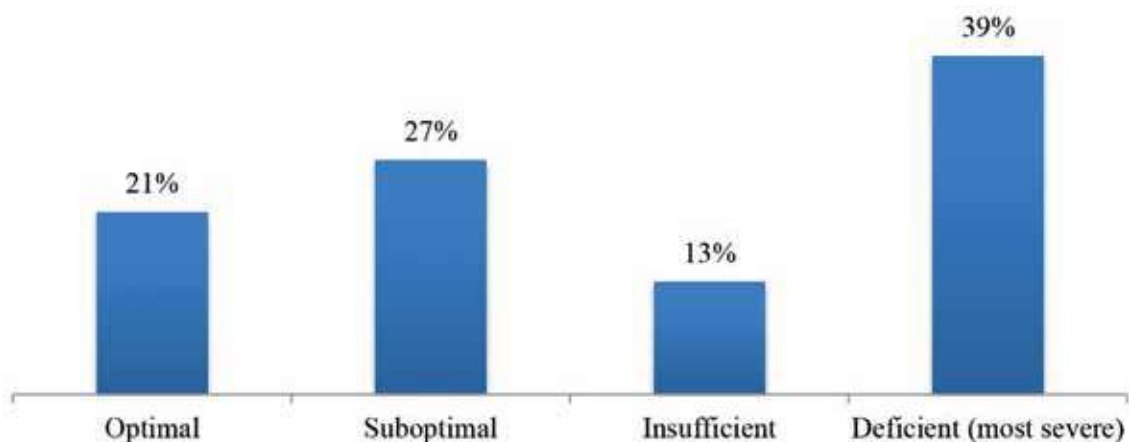


FIGURE 10. Vitamin D status in Nunavut children 3-5 years of age.

Children's hair was tested for methyl-mercury, an environmental contaminant. There has always been a small amount of methyl-mercury in our bodies because it is part of the natural environment, but pollution has increased the levels that are now found in the environment. The survey showed good news with the majority of children having hair mercury levels below the threshold of health risk.

12.4 Major findings

12.4.1 Inuit Health Survey

The Inuit Health Survey has produced and continues to produce a large number of scientific publications. These cluster around two major themes: (1) the emergence of chronic diseases such as obesity and diabetes, and understanding their metabolic pathways; and (2) the changing diet and nutritional status, including food insecurity, and specific deficiencies such as iron and vitamin D.

Results from the Inuit Health Survey can be compared with data collected earlier in other studies. Compared to 1999, the average BMI among Inuit have increased from 26.2 to 27.2 among Inuit younger than 40 years of age, and from 28.5 to 29.3 among those older than 40 (Figure 11). Among men, the average BMI has remained stable, while that of women increased from 27.2 to 29.1 (Sheikh et al. 2011).

In an analysis of sociodemographic variables, it was found that factors related to adoption of a Western lifestyle were strongly associated with obesity (Zienczuk and Egeland 2012). Higher educational attainment, any employment, higher income and private housing were all significantly associated with obesity. Those who spoke an Inuit language at home were less likely to have an at-risk BMI than those who spoke English at home. Walking was associated with lower rates of obesity among adults.

The older anthropological literature indicated that Inuit had a high trunk length relative to their legs, i.e. high sitting height ratio (SHR). In the IHS, SHR was not found to effect BMI or the prevalence of obesity. The obesity problem among Inuit is thus "real", and not an artefact of their body proportions (Galloway et al. 2011).

Is excessive BMI harmful to Inuit's health? The answer appears to be "yes" if a person's weight is distributed about their waistline. It has previously been shown that Inuit appear to be "protected" from heart diseases and diabetes, and that the health impact of obesity appears to be less among the Inuit. However, in the Inuit Health Survey, diabetes was found to affect 7% of adults and 12% of participants aged 50 years and older. A good predictor of who is at risk for diabetes is called "hypertriglyceridemic-waist". A person with a large waistline, who also has high levels of blood triglycerides, is more likely to become diabetic (Figure 12). Among Inuit, such a person is almost 9 times more likely to have diabetes than someone who has a slim waist and normal blood triglycerides (Egeland et al. 2011a).

The IHS provides a detailed description of the diet and food intake of Inuit today, with a special interest in the role of traditional foods obtained from hunting, trapping and fishing. Not surprisingly, compared to a decade ago, there was a significant decrease in the proportion of daily energy intake from traditional foods, and a corresponding rise in "market foods", especially sugar-sweetened beverages, potato chips, and pasta (Figure 13).

While food insecurity is widespread in the North, Nunavut households had higher rates of food insecurity (69%) than households in Inuvialuit (43%) or Nunatsiavut (46%) (Rosol et al. 2011). Some 60% of households in the IRIS 2 area experienced food insecurity. Adults living in severely food insecure homes reported that there were times in the past year when they or other adults in the household skipped meals, went hungry, or did not eat for a whole day. Those living in moderately food insecure homes reported that times when they worried food would run out and there was no money to buy more.

There is evidence that food insecurity is associated with poor diet quality in Inuit families. Diet quality can be measured using the Healthy Eating Index (HEI). When their diets were compared, Inuit living in food-insecure households had lower HEI scores than Inuit living in food-secure homes (Huet et al 2012). Another interesting finding is that

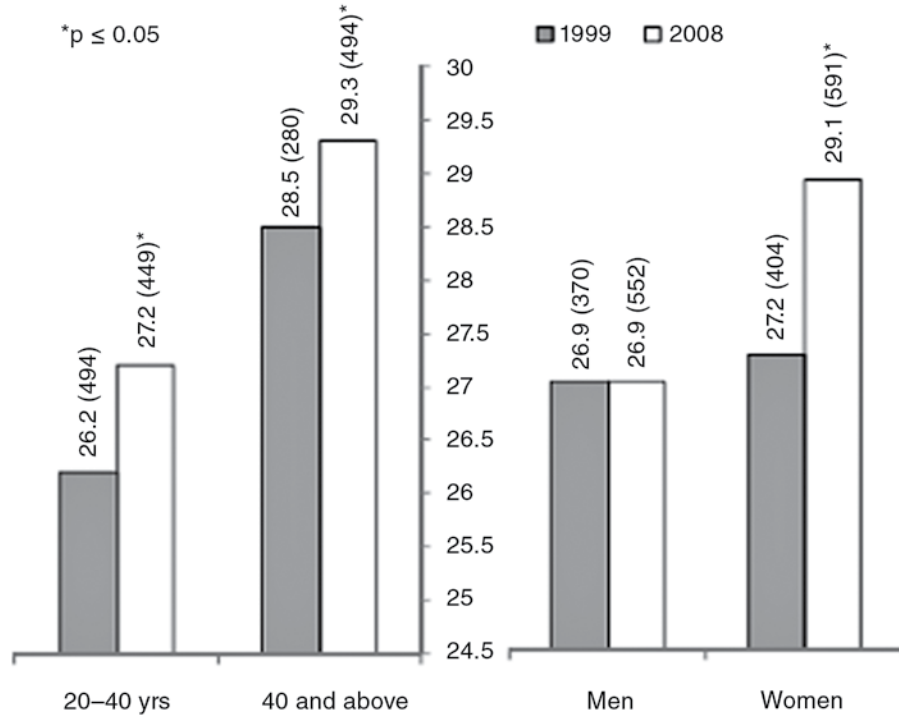


FIGURE 11. Mean body mass index (BMI, kg/m²) in 1999 and 2008 by age group and sex. () Number of respondents with BMI reading.

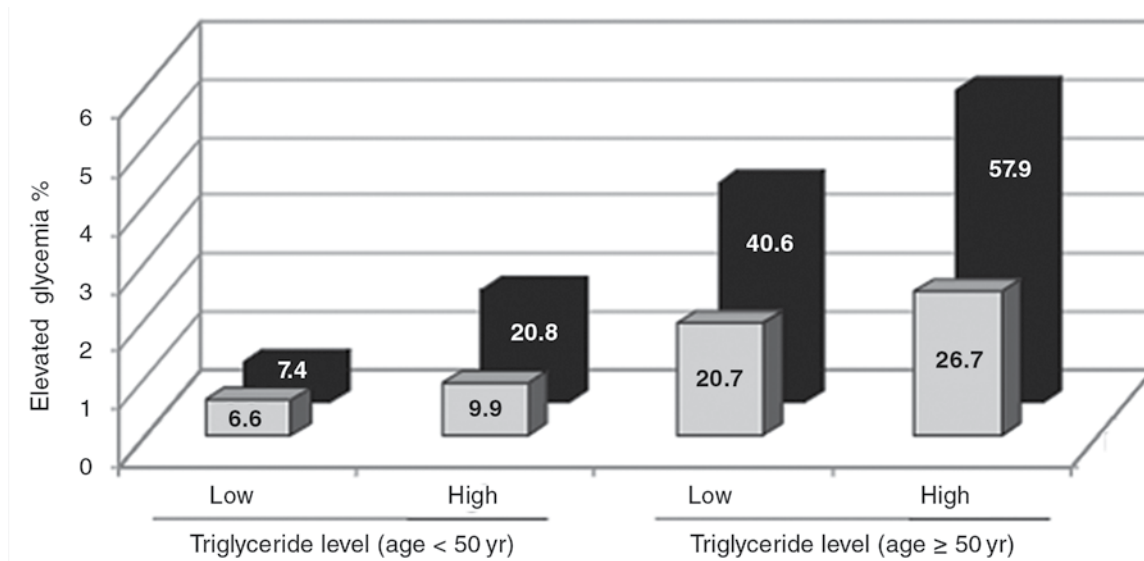


FIGURE 12. Prevalence of glycemic by age group, waist circumference and fasting serum triglyceride level. Glycemic was defined as a fasting glucose level ≥ 5.6 mmol/L or taking medication for diabetes. An at-risk waist was defined as ≥ 102 cm for men or ≥ 88 cm for women. A high triglyceride level was defined as ≥ 1.7 mmol/L. Note: WC = waist circumference

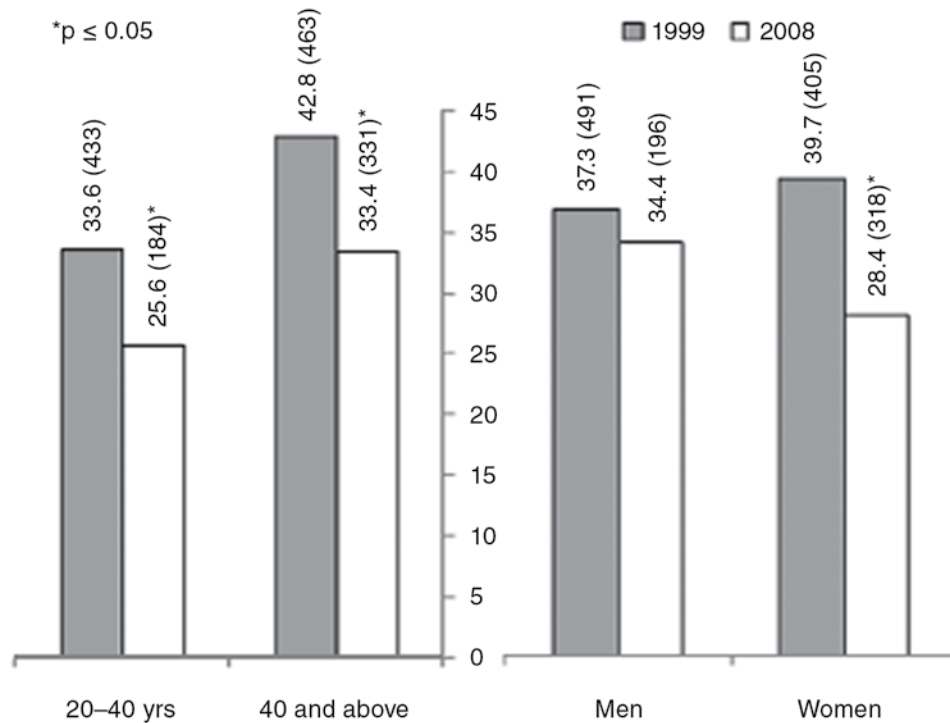


FIGURE 13. Percentage of energy taken from traditional foods among consumers by age group and sex from 24-hour recalls in the 1999 and 2008 food surveys. Number of respondents who consumed traditional foods. % total energy TF in 2008: men=34.38 vs. women=28.35* ($p \leq 0.05$)

Inuit living in food-secure households were more likely to have an active hunter in the home (Huet et al 2012).

In terms of specific nutrients, food insecurity was associated with lower intakes of vitamin C, D, folate, iron, zinc, magnesium, and calcium. However consumption of traditional foods appears to moderate the impact of food insecurity, elevating the blood levels of vitamin D and iron (Egeland et al. 2011b). Men who consumed traditional food had significantly better iron stores than those who did not and thus were protected against iron-deficiency anaemia (Jamieson et al. 2012). Older people, and people living in coastal communities, had significantly higher levels of highly unsaturated n-3 fatty acids, important “good fats” that protect the body from risk of heart disease and stroke (Zhou et al. 2011).

12.4.2 Child Health Survey

Several important studies have been published examining findings from the Nunavut Inuit CHS. An analysis of risk factors for oral health outcomes determined that children who drank pop or ate high-sugar foods such as candy were more likely to have dental caries (Pacey et al. 2010). In a comparison of dietary patterns, it was revealed that the more milk children drank, the less likely they were to experience tooth decay and cavities.

An analysis of the food security data from the CHS revealed that parents and caregivers in households with severe food insecurity reported experiencing times in the previous year where children skipped meals (76%), went hungry (90%) or did not eat for a whole day (60%) (Egeland et al. 2010b). Caregivers in households which were classified as moderately food insecure reported experiencing

times in the previous year where they worried food would run out (85%), when they fed their children less expensive food (95%), and when their children did not eat enough because there was no money for food (64%).

Overall, the majority of children met the minimum daily requirements for many nutrients (Johnson-Down and Egeland 2010). However, the quality of children's diets differed significantly depending on whether the household was food secure (Egeland et al. 2011b). Children living in food-insecure homes had significantly lower healthy eating index scores (77.1) than children living in homes that were food-secure (79.9). Children in food-insecure homes drank more pop and sugary drinks (429 vs. 377 grams per day) and less milk (52% vs. 73%).

The negative effect of food insecurity was buffered somewhat in children with access to traditional foods. Children in food-insecure homes were more likely than others to have consumed traditional food (52% vs. 40%) suggesting these children were benefiting from sharing networks that endeavoured to assist families in need (Egeland et al. 2011c).

Children that consumed traditional food had higher protein and lower carbohydrate intake and showed a tendency toward a lower prevalence of iron deficiency regardless of food security status (Egeland et al. 2011c). The children at the highest degree of nutritional risk were those from food insecure homes who did not consume traditional foods.

Finally, a study of factors contributing to respiratory illness in young children reported the presence of smokers in the home was significantly associated with severe lower respiratory infection in the first two years of life (Kovesi et al. 2011). Having experienced a severe lower respiratory tract infection in the first two years of life was associated with ongoing respiratory illness, such as wheezing, bronchitis or pneumonia, in 3-5 year old Inuit children. While the high prevalence of smoking restrictions in homes with children is evidence of the success of public health messaging, further work is needed to decrease smoking behaviours and thereby lower the risk of respiratory illness in young children (Egeland et al. 2010a).

12.5 Outlook for human health and well-being in Nunavut

12.5.1 Food insecurity

In June 2012, the Nunavut Food Security Coalition formed around the goal of eliminating food insecurity in Nunavut. The meeting included representatives from seven departments of the Government of Nunavut as well as four Inuit organizations. The Coalition has since expanded to include numerous community organizations and developed the Nunavut Food Security and Action Plan, a strategic framework for action that addresses six key areas: country food, store-bought food, local food production, life skills, programs & community initiatives, and policy & legislation (Nunavut Food Security Coalition 2014). This ambitious and innovative approach to food security is causing increased momentum toward addressing this significant challenge to health and well-being. Please see Chapter 13 for more details.

12.5.2 Mental health

In 2010, the Government of Nunavut, Nunavut Tunngavik Incorporated, the Embrace Life Council, and the Royal Canadian Mounted Police developed the Nunavut Suicide Prevention Strategy, an evidence-based approach to suicide prevention (Government of Nunavut et al. 2010). The strategy outlines the partners' vision for a healthier Nunavut and the historical and present-day factors that lead to high prevalence of suicide among Nunavut residents. This information informed the development of a Nunavut Suicide Prevention Action Plan, released in 2011 (Government of Nunavut et al. 2011). Community groups, regional Inuit organizations, and the Nunavut Government are acting on the initiatives proposed in the plan.

In 2015, researchers published results from the Nunavut Suicide Follow-Back Study, a project that examined risk factors among 120 Inuit who died by suicide between 2003 and 2006. This innovative research, the first of its kind in the world, found that Inuit who died by suicide were more likely than their peers to have experienced childhood

abuse, have family histories of depression or suicide, and have a history of alcohol or marijuana dependence (Chachamovich et al. 2015). Results of the study underscore the need for supportive mental health services for Nunavut residents.

12.5.3 Diabetes and obesity

In its report *At the Tipping Point: Diabetes in Nunavut*, the Canadian Diabetes Association and Diabète Québec (2015) describe best practices associated with diabetes prevention and management in Nunavut. For example, the Government of Nunavut's Healthy Living strategy incorporates numerous programs to support healthy eating, active living, and healthy lifestyle choices. Diabetes education programs are offered by community health staff. Coordinated diabetes care is provided through Nunavut's chronic disease framework (Canadian Diabetes Association and Diabète Québec 2015).

12.5.4 Smoking

Smoking remains a major preventable risk factor for Inuit living in Nunavut. In 2011 the Government of Nunavut released its Tobacco Reduction Framework for Action 2011-2016 (Government of Nunavut 2011). Its central pillars are to increase community awareness, target youth and schools, strengthen cessation activities, and adjust tobacco taxation levels. A number of recent grassroots and social media campaigns have been highly effective in building momentum toward a tobacco-free Nunavut, including "Nunavut Quits" and "Tobacco has no place here".

12.5.5 Traditional food consumption

The beneficial effects of traditional Inuit diet on health are widely recognized and have long been incorporated into public health strategies such as *Nutrition in Nunavut: A Framework for Action* (Government of Nunavut 2007). There is also a recognition that, despite the centrality of traditional food to Inuit culture, consumption of traditional food is declining, especially among younger Inuit. In 2012, the Nunavut Food Security Coalition made country food

the number one strategic area in its action plan (Nunavut Food Security Coalition 2014). Widespread efforts are underway to support hunters and harvesters, promote country food sharing networks, and preserve the ecological integrity of Nunavut's food systems through conservation and wildlife management (Chapter 13).

Specific goals have also been realized relevant to traditional food use in the IRIS 2 region. The Arctic Char Distribution Project is a community-based program that provides Arctic char to pregnant Inuit women living in six villages along the Hudson Bay coast (Gautier et al 2016). The Government of Nunavut advises women who were pregnant or thinking of becoming pregnant to avoid consuming ringed seal liver due to the risk of possible mercury exposure, though the highly-nutritious ringed seal meat itself poses no danger (Government of Nunavut 2012, Nunavut Tunngavik Incorporated 2012).

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Chapter 13 Food Security: Accessibility, Availability, Quality

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Key implications for decision makers

- Addressing food security requires an integrated, multiscale, cross-government response.
- Climate change acts as a risk multiplier to food insecurity.
- Climate change can be mainstreamed into existing food programming and policy, but will also need targeted response options.

Abstract

Food insecurity is a major challenge facing communities in the IRIS 2 region. Rates of food insecurity significantly exceed the Canadian average, with food access, availability, and quality affected by a variety of environmental and socio-economic factors. Climate change acts as a risk multiplier to existing food security challenges, compromising access to traditional foods, disrupting transportation networks for store foods, and creating concerns over food safety and foodborne illness. Efforts to strengthen food systems go beyond the mandate of any one organization, necessitating an integrated approach across levels of government and in collaboration with communities and Inuit organizations. There has been significant public mobilization around food security, with the Nunavut Food Security Strategy and Action Plan seeking to catalyze action at a policy level. Climate change has been examined as a driver of food insecurity in the literature, although few studies have developed scenarios of potential future vulnerability in light of projected climate and socio-economic trends, or evaluated how adaptation can be integrated into food programming and policy. Studies that have been conducted indicate the importance of Inuit traditional knowledge, sharing networks, and access to hunting equipment as sources of resilience to the effects of climate change on food systems.

OPPOSITE PAGE: SARA STATHAM



SARA STATHAM

13.1 Defining food security

The World Food Summit of 1996 defined food security as existing “when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life” (FAO 1996). Food insecurity therefore exists when these conditions fail to be met. In acknowledgement of the dual food system in Inuit regions, traditional food security additionally entails “the continued and predictable availability and access to food, derived from northern environments through Indigenous cultural practices” (Paci et al. 2004). This definition stresses the importance of the traditional food system from a social perspective (Wesche and Chan 2010), and recognizes that the traditional diet of country food is not only a vital source of nourishment but also an integral part of emotional, spiritual, and cultural well-being. For Canadian Inuit, the right to food extends far beyond basic physical and economic accessibility, as country food is integral in providing social cohesion and identity (ITK and ICC 2012). Inuit livelihoods have historically been, and continue to be, defined by a deep relationship to the environment and the resources it provides.

There are numerous criteria used to identify food security. Consistent with the research, four main components

of food security are recognized in order to understand the social and environmental factors relevant to the Inuit food system: availability (sufficient quantities available consistently), accessibility (enough resources to obtain food), quality (adequate nutritional and cultural value), and use (required knowledge of how to utilize food) (Ford 2009, Ford and Berrang-Ford 2009, Gregory et al. 2005, WFP 2017). There are various elements that contribute to the presence or absence of these components, summarized in Table 1.

13.2 Importance of food security to health

Food security is a recognized determinant of health for both Indigenous and non-Indigenous populations, both nationally and internationally (Gundersen and Ziliak 2015, McIntyre et al. 2003). Food security and health are closely linked, with those who are food insecure being more likely to suffer from a compromised health status (UNFPA 2007, Chapter 12). Therefore, it is important to identify factors affecting food security to ensure that populations remain healthy. Food inadequacy is often associated with nutrient deficiencies and diets that are inconsistent with healthy eating (Che and Chen 2001). As a result, there are negative psychological, social, and physical consequences. These

TABLE 1. Framework for components of food security in circumpolar countries.

Component	Element	Definition
Availability	Abundance	# of animals/amount of food present
	Diversity	# of species/variety of food present
Accessibility	Physical	Physical ability to get food
	Social	Access via social networks/relations
	Economic	Economic ability to purchase food
	Political	Political rights to access food/hunt and fish
Quality	Nutrient/Chemical	Nutritional adequacy and chemical safety
	Biological	Zoonotic and microbiological safety
	Cultural	Cultural desirability
Use	Skill	Cooking proficiency
	Financial literacy	Purchasing efficiency

may include mental health problems such as anxiety and depression in both children and adults as well as social exclusion (McIntyre and Tarasuk 2002). Those who experience food insecurity are more likely to feel unhealthy, be prone to infection, experience stress, as well as have chronic health problems, mental health challenges, and a lower learning capacity (Hamelin et al. 2002, Hamelin et al. 1999, Health Canada 2005, Lambden et al. 2006, McIntyre et al. 2003, McIntyre and Tarasuk 2002).

Gender difference has to be considered for effects of food security on health. Women's traditional role in society as caregivers and preparers of food for the family, as well as an increasing recognition of their role as heads of households, warrants the consideration of women as a special group to evaluate the effect, consequences, and areas for intervention in terms of food insecurity (Ivers and Cullen 2011). Laraia and colleagues (2006) propose three potential reasons why food insecurity might have particular importance for women during pregnancy: nutrient demands are higher, the effort required for food preparation may be more difficult, and pregnant women may be obliged to leave the workforce, especially in later pregnancy, which leads to financial strain. Food insecurity has been shown to decrease mental health status in pregnant women and mothers (Ke and Ford-Jones 2015, Laraia et al. 2006). Moreover, food insecurity has been associated with poor pregnancy outcomes, including low birth weight, neural tube and other defects, gestational diabetes, maternal depressive disorders, and pregnancy loss (Bhutta et al. 2013, Black et al. 2008, Borders et al. 2007, Ke and Ford-Jones 2015). Maternal health and nutrition have both short and long term health impacts on the mother and child. These include mortality, morbidity, disability, stunting, development capacity, reproductive performance, micronutrient deficiencies, and increases the likelihood of metabolic and cardiovascular disease of the child (Bhutta et al. 2013, Black et al. 2008).

13.3 Food security in Canada in general and the Eastern Arctic in particular

In 2011/2012 1.1 million Canadian households reported being food insecure; 5.8% were moderately food insecure

and 2.5% were severely food insecure (Roshanafshar and Hawkins 2015). Between 2007 and 2012, 8.2% of adults and 4.9% of children lived in food insecure households (Roshanafshar and Hawkins 2015). Households with children experienced higher food insecurity (10.3%) than households without children (7.5%). Rates of food insecurity are differentially experienced, and particularly vulnerable sub-populations are visible: younger generations, women, single mothers, and Indigenous peoples have most commonly reported to be food insecure (ITK and ICC 2012, Ledrou and Gervais 2005, McIntyre et al. 2003, McIntyre and Tarasuk 2002, Willows et al. 2009, Willows et al. 2011). For example, in Nunavut, the Inuit Health Survey (2007-2008) found that 24% of children lived in food-insecure homes (see Chapter 12).

In May 2012, the issue of food insecurity in Canada was internationally brought to light by the visit of the United Nations Special Rapporteur on the Right to Food. This event marked the first United Nations investigation of food security in a developed country. The purpose of the mission was to examine the way in which the right to adequate food is being realized in Canada. After meeting with municipal and provincial authorities, political party officials, communities, and Aboriginal groups, the Special Rapporteur concluded that, "Canada has long been seen as a land of plenty," yet "rates of food insecurity are unacceptable." Consequently, he suggested that "it is time for Canada to adopt a national Right to Food strategy." According to his End of Mission Statement, the Special Rapporteur was particularly concerned by the severe food insecurity faced by Aboriginal peoples, recognizing that a longstanding history of political and economic marginalization has left many with considerably lower levels of access to food compared to the general population. Furthermore, he posited that Canada's system "presents barriers for the poor to access nutritious diets and tolerates increased inequalities between rich and poor, and Aboriginal and non-Aboriginal peoples."

Such inequalities are experienced amongst Inuit inhabiting the Eastern Canadian Arctic, where the rates of food insecurity are among the highest in industrialized nations. In 2011, the Canadian Community Health Survey showed



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that Nunavut had the highest rates of food insecurity in the country – four times the overall Canadian rate with 36.7% of Nunavummiut reporting to experience conditions of severe food insecurity compared to the Canadian average of 8.3%. The Aboriginal Peoples Survey (APS) in 2012 found that 41% of Inuit over the age of 15 had experienced food insecurity in the past year (Wallace 2014). Data from the Inuit Health Survey indicated that these experiences impact children as well; approximately 70% of children aged 3-5 years live in food insecure homes (Egeland et al. 2010). As such, the topic of food security has been identified by communities, decision makers, and ArcticNet scientists as a cross-cutting IRIS 2 regional issue.

13.4 Prevalence of food insecurity in the Eastern Arctic

While food insecurity affects populations worldwide, it is a particularly urgent public health issue for Indigenous populations in Canada due to high rates of poverty, the

effects of climate change on traditional food systems, and high incidence of diet-related diseases (Huet et al. 2012, Power 2008, Tse et al. 2016). Studies have shown that Indigenous populations experience a greater prevalence of food insecurity than their non-Indigenous counterparts (Browne et al. 2009, Willows et al. 2009), and food insecurity has been identified as particularly problematic for Inuit inhabiting the Eastern Canadian Arctic (see Chapter 12).

Using data from the 2012 APS, Arriagada (2017) found that approximately 59% of adults in the Inuit Nunangat “often” or “sometimes” reported that food didn’t last (i.e., running out of food) because there was no money to buy more in the previous year, compared to 6.9% of households in Canada (Tarasuk et al. 2016). Further, 31% of Inuit adults reported that household members cut or skipped meals because there was not enough money for food, far exceeding the 3% documented for Canada as a whole (Tarasuk et al. 2016). Community-based studies indicate food insecurity rates ranging from 45 to 80% (Egeland

2011, Egeland et al. 2010, Ford and Berrang-Ford 2009, Guo et al. 2015, Lawn and Harvey 2003). The 2007-2008 Inuit Health Survey found that almost 69% of adults living in Nunavut had a very high prevalence of food insecurity (Rosol et al. 2011), which is six times higher than the Canadian average and the highest rate for any Aboriginal population in a developed country (Egeland 2011, Rosol et al. 2011). Furthermore, the same survey found that 40% of all Inuit children are reported to have gone hungry at least once in 2006 (Egeland et al. 2010).

Amongst Inuit food security research, studies have identified vulnerable sub-populations within Nunavut, including women (Arriagada 2017, Beaumier and Ford 2010, Ford and Beaumier 2009, Healey and Meadows 2007), children (Egeland et al. 2010, Johnson-Down and Egeland 2010), and the elderly (Smith et al. 2009). At the household level, vulnerability emerges amongst households without an active hunter, and households engaged in the harvesting sector but with limited access to cash resources (Beaumier and Ford 2010, Chabot 2003, Healey et al. 2011, Lardeau et al. 2011). Inuit who are financially marginalized (i.e., those with low household incomes, limited access to resources, and economic problems) have been identified as particularly vulnerable to food insecurity (Bohle et al. 1994, Erber et al. 2010, Sarlio-Lähteenkorva and Lahelma 2001). Indeed, a study assessing food security amongst public housing residents in Iqaluit indicated that 54% of households reported “not hav[ing] enough money to buy store food and/or not [being able to obtain] country food?” during winter 2010/2011 (Statham et al. 2015). These high rates of food insecurity are likely to make Inuit communities susceptible to the impacts of climate change on food systems, with potentially significant health implications (Ford 2009, Power 2008).

13.5 What does the recent research say about food security in the Canadian Arctic?

The last two decades have witnessed a proliferation of food system studies in the Canadian Arctic, providing key insights for food security. Firstly, there is a long history

of food system studies in Arctic communities in anthropology, with research focusing on the role of kinship and food sharing in traditional and contemporary Inuit society (Chabot 2004, Collings 1997, Collings et al. 2016, Collings et al. 1998, Duhaime et al. 2002, Duhaime et al. 2004, Kishigami 2004, Wenzel 1991, 1995). Secondly, the 1990s initiated a suite of biomedical studies recognizing the threat posed by contaminants in traditional foods. This work has documented the prevalence of contaminants in traditional foods, examined associated health implications, and investigated how concerns over contaminants have affected food consumption (Bjerregaard et al. 2001, Bordeleau et al. 2016, Boucher et al. 2009, Dewailly et al. 2001a,b, Oostdam et al. 2005, Fontaine et al. 2008, Furgal et al. 2005, Hu et al. 2017, Jardine et al. 2004, Laird et al. 2013, Sandau et al. 2000). Thirdly, a significant body of research has focused on quantitatively assessing the adequacy of nutrient intakes within and across communities and regions (Egeland et al. 2010, Kuhnlein et al. 2008, Lambden et al. 2007, Lambden et al. 2006, Sharma et al. 2009). Longitudinal studies have highlighted declining consumption of nutrient-rich traditional foods and increasing consumption of nutrient-poor store foods; what has been described as the ‘nutrient transition’ (Egeland et al. 2009, Egeland 2011, Egeland et al. 2010, Kuhnlein et al. 1996, Kuhnlein et al. 2008, Lambden et al. 2007, 2006, Rosol et al. 2016, Sharma et al. 2010a,b, Sharma et al. 2009, Sheehy et al. 2015). Fourthly, an emerging focus in the Arctic literature are studies that seek to quantify the prevalence of food insecurity using questionnaires, examining statistical relationships between food insecurity and respondent characteristics (Arriagada 2017, Egeland et al. 2010, Ford 2009, Ford and Berrang-Ford 2009, Lawn and Harvey 2003, Ledrou and Gervais 2005, Tarasuk et al. 2016). Finally, there is an emerging body of literature examining the implications of climate change for Inuit food systems, mostly involving in-depth case studies to document impacts and examine vulnerabilities in the context of broader socioeconomic conditions (Beaumier and Ford 2010, Beaumier et al. 2015, Chan et al. 2006, Ford et al. 2007, Ford 2009, Ford and Beaumier 2011, Guo et al. 2015, Guyot et al. 2006, Statham et al. 2015).

13.6 The Inuit food system in the Eastern Canadian Arctic

A food system comprises “dynamic interactions between and within biophysical and human environments which result in the production, processing, distribution, preparation and consumption of food” (Ericksen 2008, Gregory et al. 2005). This system both operates within and is influenced by socioeconomic, political, and environmental factors. More specific to the Eastern Canadian Arctic, a traditional food system includes all processes involved in feeding a population from local natural resources that are culturally accepted (Kuhnlein et al. 1996), and includes all aspects of hunting, harvesting, preparing, sharing, and consuming food. Therefore, food systems involve much broader considerations than productivity and production alone - they underpin food security (Gregory et al. 2005).

The Canadian Arctic is characterized by a distinctive dual food system that incorporates both traditional or country foods and store-bought foods (Table 2). Country food includes items that people can access locally from the natural environment and is commonly obtained from terrestrial or (often frozen) aquatic environments (herein collectively termed “the land”) via hunting, fishing, and harvesting. It may include a variety of locally obtained non-domesticated wildlife species such as caribou, seal, fish, and berries (Priest and Usher 2004). Consumption of country food varies seasonally as well as at the individual, household, and community level. In Nunavut, traditional sharing practices are important in accessing traditional foods for many households. Such practices differ across Inuit regions in Canada and between communities due to different societal directives, socio-economic and cultural context and sensitivities to environmental conditions (Damas 2002, Duhaime et al. 2004, Kishigami 2004, Usher et al. 2003, Wenzel 1995). While sharing of traditional foods continues to underpin Inuit food systems, there has been an increase in the commercialization of country food documented in some communities in recent years, with people obtaining traditional food through small retail outlets, informal country food markets, and through social media such as Facebook (Statham et al. 2015, Ford



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et al. 2016). There remains a widespread reluctance to exchange traditional foods directly for money (Gombay 2006), although there is evidence that this is becoming more common in some locations (Beaumier and Ford 2010, Statham et al. 2015).

Store foods, on the other hand, are those that enter communities often through global commercially organized retail outlets and must be purchased (Kuhnlein et al. 2009). Typical store foods include canned goods, cereals, as well as fruits and vegetables. Communities throughout the Eastern Canadian Arctic usually have a number of small retail grocery stores that stock a limited variety of fresh and processed foods that can be found in southern Canada. Perishable items are regularly brought in by scheduled air service, while non-perishables items arrive

TABLE 2. The country food and store food components of the Inuit food system (Ford 2009).

Components/Aspects	Inuit Dual Food System	
	Country food	Store food
Production	Locally obtained from natural sources (i.e., small-scale hunting, harvesting, fishing, foraging); labour-intensive	Distally obtained from industrial sources (i.e., large-scale factories, facilities, cultivating, irrigating); capital-intensive
Processing	Locally by hand (i.e., skinning, cleaning, preparing)	Distally by machine (i.e., slaughtering, grinding, packaging)
Distribution	Small sharing networks (traditionally); cash transactions between individual and hunter/harvester (increasingly common)	Large transportation networks; cash transactions between individual and store
Preparation	Often communally	Often individually
Consumption	Often communally	Often individually
Times of reliance	Economic stress	Environmental stress

once a year via sea-lift during the summer ice-free period. Store foods have played an increasingly important role in the diet of Canadian Inuit over the past 50 years at the expense of traditional foods (Ford 2009, Kuhnlein et al. 1996), yet both country food and store food are important components of the contemporary Inuit food system (Ford 2009). Communities are particularly reliant on country food during times of economic stress, and on store food during times of environmental stress.

13.7 The nutrition transition in the Canadian Arctic and its effects on Inuit diet

Inuit food consumption patterns have undergone rapid changes within the past few decades due to a number of socioeconomic and cultural factors (Myers et al. 2004). As such, the balance between country food and store food is changing, and several dietary studies show that more commercially produced, imported food is being consumed (Erber et al. 2010, Hopping et al. 2010, Kuhnlein and Chan 2000, Myers et al. 2004). This 'nutrition transition' has been documented throughout the Canadian Arctic whereby nutrient-rich country foods are replaced with nutrient-poor store foods (Hopping et al. 2010, Kuhnlein and Receveur 1996, Sharma et al. 2010a,b). The traditional diet of country food on which Inuit have long subsisted offers a rich source

of antioxidants, omega-3 fatty acids, monounsaturated fatty acids, protein, and micronutrients (Egeland et al. 2009, Sheehy et al. 2015). Kuhnlein and Receveur (2007) found that for children and adults, even a single portion of country food resulted in significantly increased levels of energy, protein, vitamin D, vitamin E, riboflavin, vitamin B-6, iron, zinc, copper, magnesium, manganese, phosphorus, and potassium. Traditional foods are therefore extremely important to ensure high dietary quality of both children and adults (ITK and ICC 2012, Kuhnlein and Receveur 2007, Rosol et al. 2016, Sharma et al. 2010a,b). Health status is being threatened by this increase in store food consumption, as preferred store foods are often heavier in saturated fats, sugars, salt and carbohydrates (Hopping et al. 2010, Kuhnlein and Receveur 1996) and has been linked to an increased likelihood of nutrient deficiencies and chronic disease (Bjerregaard et al. 2004, Chan et al. 2006, Kuhnlein et al. 2004, Tse et al. 2016). Furthermore, the nutrition transition has been related to a higher prevalence of lung, breast and colon cancers, diabetes, cardiovascular disease, dental caries and other afflictions that were historically rare in northern communities (Bjerregaard et al. 2004, Friberg and Melbye 2008). In developing countries, the nutrition transition has been associated with both under- and over-nutrition being cited within the same communities and even the same households (Cai 2014, Popkin

2002, Steyn and Mchiza 2014). Likewise, both overweight and obesity and sub-optimal nutrient intakes co-occur in Inuit communities and households (Egeland et al. 2011, Kuhnlein et al. 2004). Despite these dietary changes, country food still constitutes a considerable portion of Inuit diet (Duhaime et al. 2002, 2004, Poppel et al. 2007), albeit in a decreasingly prominent way.

13.8 Determinants of food insecurity in the Eastern Canadian Arctic

Many factors converge in the Eastern Canadian Arctic to undermine food security, and are outlined in Table 3. These determinants operate at various spatial and temporal scales and often interact to exacerbate food insecurity. Climate change is cited in the literature as a key food security determinant across the Inuit Nunangat (Beaumier and Ford 2010, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Guo et al. 2015, Guyot et al. 2006, Lambden et al. 2007, Myers et al. 2004, Nancarrow and Chan 2010, Wesche and Chan 2010), as the components of availability, accessibility, and quality are particularly sensitive to changing environmental conditions. On the other hand, the component of use is greatly impacted by sociocultural factors such as changing livelihoods and intergenerational knowledge transmission that affect the ability to use (i.e., produce, distribute, prepare) traditional and contemporary foods (Wesche and Chan 2010). We focus here on the environmental and socioeconomic determinants of food security and explore how they affect the four pillars of food security: availability, accessibility, quality and use.

13.8.1 Environmental determinants

13.8.1.1 Availability

Climate change is expected to result in shifts in biodiversity as well as in the ranges of animal and plant species important to northern people in the Eastern Canadian Arctic (Darnis et al. 2012, Eberle et al. 2009, Hobson et al. 2009, Laidler and Gough 2003, Larsen et al. 2014, Pearson et al. 2013, Tews et al. 2007a,b, White et al. 2007). With regards

to country food, availability is compromised when animal migration routes are altered, with some impacts already observable in some communities in the region (Beaumier and Ford 2010, Cunsolo Willox et al. 2012, Damman et al. 2008, Ford 2009, Ford and Beaumier 2009, Guyot et al. 2006, Lambden et al. 2007, Myers et al. 2004, Nancarrow and Chan 2010, Wesche and Chan 2010). Studies have examined how climate change might affect caribou in northern Nunavut (Tews et al. 2007a,b), as well as Quebec and Labrador (Payette et al. 2004, Sharma et al. 2009). Indeed caribou herds are already reported to being affected by climate change, whereby direct and indirect consequences, such as alteration in habitat use, foraging behaviour, and demography, have affected migration patterns (Sharma et al. 2009). Some marine mammals species have been identified as vulnerable to the effects of climate change, including polar bear, bearded seal, ringed seal, and narwhal, whose life histories depend on the sea ice, particularly towards the south of their range (Crompton et al. 2008, Durner et al. 2009, Laidre et al. 2008, 2015, Moore and Huntington 2008, Prost et al. 2013, Simmonds and Isaac 2007, Stirling and Parkinson 2009).

It is important to note that changes in plant and animal distribution may also positively influence the availability of food. While the loss of historically abundant native species may harm food security, the replacement of these species with novel non-native species may counter this somewhat (Beaumier and Ford 2010, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Guyot et al. 2006, Lambden et al. 2007, Myers et al. 2004, Nancarrow and Chan 2010, Wesche and Chan 2010). Temperate or seasonally migrant species have the beneficial capability to extend their geographic range into Arctic marine habitats (Larsen et al. 2014, Moore and Huntington 2008). For example, there has been a recent influx of killer whales into Eastern Arctic waters as the sea-ice melts and enlarges their habitat (Darnis et al. 2012, Ferguson et al. 2012). However, ecosystems may be subsequently altered, resulting in a top-down transformation of the food web with unknown consequences (Ferguson et al. 2012, Higdon and Ferguson 2009, Prost et al. 2013).

TABLE 3. Determinants of food (in)security in the Eastern Canadian Arctic.

		Determinants of Food (in)Security	
		Country Food	Store Food
Availability	Environmental	Altered migration patterns of wildlife Varied distribution of wildlife Seasonal disparity in wildlife	Inclement weather causing flight delays Changing sea-ice dynamics causing sea-lift delays
	Socioeconomic	Growing populations putting localized pressure on wildlife Lack of hunter in the household	Stores ordering enough supply to meet demand Lack of worker in the household Presence of community food programs (i.e., food bank, soup kitchen) Presence of government food programs (i.e., Breakfast Program)
Accessibility	Environmental	Shorter sea-ice season preventing hunters from using the ice Longer open water season allowing hunters to boat Unpredictable weather patterns More frequent storms Stronger and more variable winds causing white-out conditions	Isolation of communities Heavy reliance on external transportation networks Extreme weather events preventing people from leaving their homes
	Socioeconomic	Level of traditional knowledge required to hunt/harvest wildlife Time needed to hunt/harvest High cost of hunting (i.e., equipment, gas) Weakening of sharing networks Gambling/substance abuse/addiction	High cost of food Insufficient financial resources required to purchase food Inappropriate and insensitive policies/regulations Weak social networks Gambling/substance abuse/addiction
Quality	Environmental	Contaminants affecting health of wildlife Freeze-thaw cycles preventing animals from adequately foraging	Flight delays causing spoilage
	Socioeconomic	Traditional knowledge required to harvest the healthiest animals	Nutritional knowledge required to make healthy food choices Language barriers (i.e., English food labels hinder unilingual Inuit)
Use	Environmental	Changing environmental conditions leading to spoilage (i.e., caching)	N/A
	Socioeconomic	Traditional knowledge required to prepare wildlife	Cooking skills required to prepare groceries Language barriers (i.e., English recipes hinder unilingual Inuit)



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Store food is also susceptible to climatic conditions. The majority of store food items are imported to communities over long distances via air transportation. Thus, extreme weather hazards, including high winds and blizzards, can delay air access to the community and limit the availability of fresh food stocks in local stores (Beaumier and Ford 2010, Ford and Beaumier 2011, Ford and Berrang-Ford 2009). For example, in 2011 the Nunavut community of Grise Fiord went without a food shipment for over three weeks, leaving empty shelves in the local grocery store (CBC 2011).

13.8.1.2 Access

Country food accessibility is also affected by climate change, as environmental changes such as thinner ice, later ice freeze-up, earlier ice break-up, more variable snowfall, unpredictable weather, warmer temperatures, and more frequent and intense storms can impact access to wildlife

(Beaumier and Ford 2010, Damman et al. 2008, Ford 2009, Ford and Beaumier 2009, Guyot et al. 2006, Lambden et al. 2007, Larsen et al. 2014, Myers et al. 2004, Nancarrow and Chan 2010, Wesche and Chan 2010). Changes in wind patterns have been observed across the Arctic (Overland et al. 2012), and stronger winds have been found to cause white-out conditions that avert hunters from going on the land (Ford and Goldhar 2012). Extremely short sea-ice seasons, such as that experienced in Iqaluit during winter 2010/2011, mean that hunters are increasingly unable to access traditional hunting grounds or use the sea ice as a platform for hunting (Statham et al. 2015). Inclement weather conditions also impact the potential for inter-community trade, as they can delay regularly scheduled air service as well as prevent Inuit from travelling between communities via snowmobile or boat (Larsen et al. 2014, Parkinson 2009). Similar conditions can have similar impacts on store food, whose access is also at the mercy of the environment, albeit in a less direct way.

13.8.1.3 Quality

The quality of country food can also be negatively impacted by environmental conditions. Lambden et al. (2007) explored observed climate-related changes in country food and noted reduced animal size, physical deformities of animals, as well as variations in taste and other sensory changes. Others have noted a general decrease in wildlife health of some species (Beaumier and Ford 2010, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Guyot et al. 2006, Lambden et al. 2007, Loring and Gerlach 2015, Myers et al. 2004, Nancarrow and Chan 2010, Wesche and Chan 2010). Accumulation of contaminants in wildlife consumed by Inuit has also emerged as a major concern for Inuit health and food security (Bordeleau et al. 2016, Oostdam et al. 2005, Kuhnlein and Chan 2000, Laird et al. 2013). Studies have highlighted that snowmelt is a major source of mercury contamination in Arctic freshwater systems, and could increase with future climate change (Dommergue et al. 2003, Gantner et al. 2010, Larsen et al. 2014). Other research has found that climate change may lead to increased bioaccumulation of contaminants in the food chain (Hare et al. 2008, Kuzyk et al. 2010, Larsen et al. 2014, Loring and Gerlach 2015, Macdonald and Loseto 2010), and exposure to infectious and zoonotic diseases (Parkinson et al. 2014), although these types of studies are in their infancy.

Climatic stressors also impact the quality of store foods. Inclement environmental conditions can prevent regularly scheduled air services, and resulting delays may cause a depreciation in the quality or spoilage of perishable food items (Mead et al. 2010).

13.8.1.4 Use

The use of food is less susceptible to climate change when compared to the other three components of food security. However, it has been found that changing weather patterns can impact the use of traditional foods, such as meat fermentation for specialty dishes (Lambden et al. 2007, Loring and Gerlach 2015, Nancarrow and Chan 2010). The caching of meat is highly dependent on the expected

seasons, and with the permafrost period being shortened, the time for caching of meat is also shortened. In Arviat, people have adapted by caching meat later in the fall, and removing the meat before the temperature rises too high in the spring (Government of Nunavut 2005, Sullivan and Nasmith 2010). Recent work has also noted how more unpredictable weather and ice conditions are reducing the ability of young Inuit to engage in land-based activities, therefore disrupting traditional mechanisms of knowledge learning and exchange (including meat storage and preparation), further exacerbating stresses herein (Clark et al. 2016a,b).

13.8.2 Socioeconomic determinants

The impacts of climate change on food security are wide-ranging, but they can only be understood within a broader economic, sociocultural, and political context, in which to determine how climate change impacts are experienced and responded to.

13.8.2.1 Availability

With regards to the sociocultural context, Inuit food security is negatively impacted by a reduction in the number of active hunters procuring traditional food (Beaumier and Ford 2010, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011). This decline has been attributed to illness, injuries, and death (Beaumier and Ford 2010), as well as fewer younger hunters engaging in subsistence-based activities (Beaumier and Ford 2010, Damman et al. 2008, Ford 2009, Petrusek et al. 2013). The decreased rate of hunting amongst youth is attributed to a number of factors, such as increased wage employment that reduces opportunities for hunting, lack of access to funds for purchasing equipment, changing dietary preferences toward store-bought foods, inadequate experience due to requirements of western-style schooling, lack of interest, and increasing participation in organized sports (Chan et al. 2006). A decreasing number of hunters can ultimately translate to decreasing availability of traditional food, which has implications for food security.

Another barrier to food security concerns demographics – more specifically, the age distribution of Canada’s Arctic Inuit population. Research in Nunavut has noted many food security determinants that are related to a rapidly changing population distribution (Ford 2009). Nunavut is characterized by rapid population growth, resulting in a high proportion of children and a low proportion of adults. This has implications for food security because the decreasing number of hunters, as previously mentioned, means that remaining hunters face further demand to provide food for this increasing population. This also leads to variations in the cultural acceptability of food through the influence of schooling and media (Damman et al. 2008, Myers et al. 2005). Damman et al. (2008) suggest that intergenerational differences in food preference have caused reduced consumption of country food and increased consumption of unhealthy store food that is promoted to youth by western images and ideals.

13.8.2.2 Access

The high cost of obtaining food is a prevalent food security determinant throughout the Eastern Canadian Arctic (Arriagada 2017, Beaumier and Ford 2010, Chan et al. 2006, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Ford and Berrang-Ford 2009, Goldhar et al. 2010, Lambden et al. 2006, Loring and Gerlach, 2015, 2009). Prohibitive costs are relevant to both country food and store food. With the increased mechanization of hunting and fishing, financial resources are required in order to procure traditional food (Beaumier and Ford 2010, Chan et al. 2006, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Goldhar et al. 2010, Lambden et al. 2006, Loring and Gerlach 2009, Myers et al. 2004). Equipment such as snowmobiles, gasoline, and firearms are more costly than their traditional counterparts such as dogsleds, dogs, and harpoons. Expenses are also increasing with changing climatic conditions. For example, changes in seasonal freeze-thaw cycles cause increased hunting costs due to the extra fuel required to access hunting and fishing grounds (Ford et al. 2006, Ford et al. 2006, Loring and Gerlach 2015).

For many, the price of store food is extremely high and often unaffordable (Beaumier and Ford 2010, Chan et al.

2006, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Ford and Berrang-Ford 2009, Goldhar et al. 2010, Lambden et al. 2006, Loring and Gerlach 2009, 2015, Myers et al. 2004). Arriagada (2017) reported that in 2015 the cost of a basket of food for a family of four in an isolated Inuit community was \$328-\$488 – more than twice the price of the same basket in Ottawa, ON (\$209). In 2011, Duhaime and Caron (2012) found that for identical baskets of food, the costs were 81% higher in Nunavik than in Quebec. Another reality is limited financial resources, and in 2005 the median income for Inuit was \$16 970 compared to \$26 615 for the total population of Canada (Tait 2006). In terms of measuring poverty in Nunavut, the most commonly-used measure is the level of participation by Nunavummiut in the Government of Nunavut’s income support program (NRPR 2011). Households that rely on income support as a primary income source are more likely to use community-based food programs (i.e., soup kitchen, food bank) and are more likely to report not having enough country food (Ford et al. 2013, Ford et al. 2012, Lardeau et al. 2011). Compounding the issues of high costs and low incomes is concerns over money management skills (Beaumier and Ford 2010, Chan et al. 2006, Damman et al. 2008, Duhaime et al. 2004, Ford 2009, Ford and Beaumier 2011, Ford and Berrang-Ford 2009, Goldhar et al. 2010, Lambden et al. 2006, Loring and Gerlach 2015, 2009), attributed to the relatively recent arrival of monetary transactions among Inuit, as well as limited experience of western concepts of budgeting (Suluk and Blakney 2009).

The strength of food sharing networks has been identified as an important food security determinant (Beaumier and Ford 2010, Chan et al. 2006, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Goldhar et al. 2010, Harder and Wenzel 2012), as sharing networks help communities manage variations in food access and availability, and are effective for managing temporally discrete stresses such as a late freeze up or successive days of fog or high winds (Chan et al. 2006, Ford and Beaumier 2011). Country food has always been shared through principles of “solidarity-affection” to friends, guests, and others, as well as through “respect-obedience” within extended families (Wenzel 2000). Increased reliance on, yet weakening of,

food sharing practices has led to food insecurity (Beaumier and Ford 2010). The cultural practice of sharing may have developed as an effective mechanism to maintain food security in the face of environmental constraints, yet the practice is currently under strain (Chan et al. 2006).

Other factors affecting food security are those related to social issues, such as substance abuse and addiction (Chan et al. 2006, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Ford and Berrang-Ford 2009, Goldhar et al. 2010, Lambden et al. 2006, Loring and Gerlach 2009, Myers et al. 2004), as well as gambling (Beaumier and Ford 2010, Chan et al. 2006, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Ford and Berrang-Ford 2009, Goldhar et al. 2010, Lambden et al. 2006, Loring and Gerlach 2009, Myers et al. 2004), which may both lead to mismanagement of already limited financial resources. These challenges need to be situated in the context of rapid acculturation of Inuit society over the last half century and colonial legacy (Ford et al. 2010, Ford et al. 2006, Wenzel 1991, 1995).

Another common theme affecting food security involves political barriers (Beaumier and Ford 2010, Chan et al. 2006, Damman et al. 2008, Ford 2009, Ford and Beaumier 2011, Ford and Berrang-Ford 2009, Goldhar et al. 2010, Lambden et al. 2006, Loring and Gerlach 2009, 2015, Myers et al. 2004). These may include wildlife management policies, food subsidies, population settlement policies, or gun licence requirements. Hunters historically altered what, where, and when they hunted in accordance with fluctuations and variations in wildlife availability and accessibility, but they are now restricted. Wildlife management policies such as hunting or fishing seasons, quotas, and area closures have impeded access to country food (Armitage et al. 2011, Armitage et al. 2009, Ford et al. 2006, Kendrick 2013, Mcmillan 2015). In the Canadian Arctic, settlement policies during the 1960s led to subsequent struggles for Inuit; by centralizing former semi-nomadic hunting groups into communities located far from their traditional hunting areas, increased capital needs such as snowmobiles and motor boats are required to obtain food (Damman et al. 2008, Wenzel 1991). Chan et al.

(2006) note that gun license delays, poor distribution of funding in the Harvester Support Program, and insufficient government-funded programs negatively influence food security. However, it should be noted that beneficial policy measures have been implemented to make healthy food more affordable in the Canadian Arctic, including food banks, soup kitchens, and the (now outdated) Food Mail Program (Damman et al. 2008). The Nutrition North Canada Program has recently replaced the Food Mail Program, and aims to improve access to perishable health foods in isolated northern communities (Government of Canada 2012). However, the new program since its inception has been plagued with critiques by community and, local and territorial governments, resulting in a review commissioned by the Auditor General in 2014 (Galloway 2014). The results of the audit found that “Aboriginal Affairs and Northern Development Canada has not managed the Program to meet its objective of making healthy foods more accessible, ... or more affordable...” (Michael Ferguson Auditor General of Canada, March 23, 2015). The auditor went on to state that the Department of Aboriginal Affairs and Northern Development had “prepared an action plan to address each of (the auditor’s) recommendations”. In Galloway’s (Galloway 2017) recent follow-up review of the program, they found continued gaps, particularly in terms of coverage and food affordability.

13.8.2.3 Quality

The quality of food is also dependent on socioeconomic factors. With regards to country food, traditional knowledge plays an important role in hunters recognizing the healthiest animals to harvest. For store food, nutritional knowledge is required in order to make healthy food choices. However, language has been identified as a barrier to healthy food choices, as English food labelling at the grocery stores are considered an impediment to the identification of nutritious foods by unilingual Inuktitut adults (Bird et al. 2008).



SARA STRATHAM

13.9 What is being done in the Eastern Canadian Arctic to address food insecurity?

13.9.1 Public mobilization

Coinciding with the UN Rapporteur's Right to Food strategy recommendation and the Minister of Health's subsequent dismissal of said recommendations, there has been recent public mobilization with regards to addressing the issue of food insecurity in Nunavut. This momentum has been propelled in-part by the creation of the "Feeding My Family" (FMF) page on the popular social media networking website, Facebook. The FMF page was created by a mother who wanted to raise awareness about the fact that she, like many other people, struggled to feed her family. Since its creation in May 2012, over 21 000 people have joined the group. Several protests against the high food prices in Nunavut have been staged throughout Canada, from large southern cities (i.e., Ottawa) to small northern communities (i.e., Grise Fiord). Grassroots initiatives have

also taken place, both within Nunavut (i.e., the development of a local food bank in Clyde River by one community member) and beyond the territory (i.e., the creation of the "Adopt a Family" initiative by which people in southern Canada purchase food items at cheaper retail prices and ship them to families in northern Canada). While these initiatives are generous and well-meaning, their long-term viability and impact is uncertain, and more permanent, legislated commitments to addressing food insecurity are also needed.

13.9.2 Policy level

Much investment has been made to understand the determinants of and potential solutions to food insecurity. It is evident that the root causes of hunger in Nunavut are wide-ranging. As such, the solutions to food insecurity must be as well. It is widely acknowledged that addressing this critical and complex issue is broader than the mandate of any one organization (Chan et al. 2006, Huet et al. 2012, NFSC

2014, Rosol et al. 2011). Therefore, an integrated approach is essential. However, until recently, no coordinated action plan to address food insecurity existed in Nunavut.

The issue of food security has been on the Government of Nunavut's radar for some time. The Government of Nunavut's Department of Health and Social Services has long recognized the importance of food security from a nutrition perspective, with two strategic policy documents both emphasizing food security as a key priority action area (Government of Nunavut 2007, Nunavut Department of Health and Social Services 2008).

In 2009, the GN released a statement of priorities, "Tamapta: Building Our Future Together," emphasizing the importance of meeting the basic needs of Nunavummiut (Government of Nunavut 2009). Within Tamapta is an Action Plan for 2009-2013, whereby the GN set various priorities for this mandate. One of such priorities was to reduce poverty. As such, the Nunavut Anti-Poverty Secretariat was established in April 2010 to prepare and implement a poverty reduction strategy for Nunavut. The resulting document, "The Makimaniq Plan: A shared approach to poverty reduction," identifies six themes that frame the Nunavut approach to poverty reduction, one of which being food security (NRPR 2011). Under this theme, one of the goals and objectives is "the establishment of a 'Nunavut Food Security Coalition'" that would convene stakeholders from government, Inuit organizations, non-governmental organizations (NGOs), business, and research to "develop a long term, ongoing, inclusive, and sustainable approach to food security in Nunavut."

In June 2012, The Nunavut Food Security Coalition (NFSC) was established, consisting of seven GN departments and four Inuit organizations who are to engage a broader group of partners for the purpose of establishing a collaborative approach to addressing food insecurity throughout Nunavut. The NFSC is led by Nunavut Tunngavik Incorporated, the Department of Health and the Department of Family Services through its Poverty Reduction Division. The NFSC released their territorial food security strategy in 2014. The Nunavut Food Security Strategy and Action

Plan 2014-16 identified six strategic areas for action; Policy and Legislation, Country Food, Store-bought food, Local Food Production, Life Skills, and Programs and community Initiatives. The strategy outlines multiple objectives per action area and has identified key partners to realise their success. Moving forward, which policies and programs go into future strategies highly depends on our current state of knowledge on the issue of food security. As such, it is important to reflect upon what gaps might exist in the literature to help guide future research agendas.

13.10 Research needs

Climate change has been identified as one of the biggest health threats of the 21st Century (Costello et al. 2009, Watts et al. 2015), and yet there is a paucity of published research examining future health vulnerabilities. Some studies have extrapolated current food insecurity trends to hypothesize that food insecurity in northern regions will increase in the future as climate change further constrains access and availability of traditional foods. Not all communities or regions will be equally affected, and yet only a few are studied thoroughly. Furthermore, opportunities may also develop as new species move north and the open water hunting/fishing season expands (Meier et al. 2006, Wenzel 2009), but have not been examined. There is an emerging area of study that identifies how food systems can be strengthened in light of projected climate change and other stresses, including investing in and enhancing harvester support programs, community freezers and food banks, youth hunting programs, and meat sharing initiatives (Berner et al. 2016, Chan et al. 2006, Damman et al. 2008, Ford et al. 2007, Ford et al. 2010, Furgal and Seguin 2006, Lardeau et al. 2011, Myers et al. 2005, 2004, Rosol et al. 2016, Wesche and Chan 2010). There is concern, however, that while institutional support may increase adaptive capacity, it may not provide an equivalent substitute for traditional sharing networks (Ford et al. 2010, 2006, Lardeau et al. 2011), while recommendations typically follow 'wish-lists' and have not comprehensively evaluated proposed policies in terms of effectiveness, desirability, feasibility, urgency, and durability.

Currently, we have a strong understanding of both environmental and socioeconomic determinants of food insecurity that interact over various spatial and temporal scales to affect rates of food security throughout the Eastern Canadian Arctic. However, there are gaps in the literature:

13.10.1 Lack of intervention studies

There has been significant and growing attention given to the assessment and understanding of food insecurity in Nunavut in recent years, but there have been comparatively few interventions attempted, evaluated, and reported. An evidence base of food security interventions, that also reduce climate vulnerability, is lacking. As such, investment in pilot intervention and evaluation studies and monitoring of food security strategies are required. There is a strong need for evidence-based research to inform policy, including realist review approaches which seek to answer “what is it about this kind of intervention that works, for whom, in what circumstances, in what respects and why?” (Pawson et al. 2005). There are lessons to be learned here from the recommendations existing in the literature on Nunavut and elsewhere, yet we need to determine whether or not common policy recommendations (for example, increased consumption of country food) are viable (i.e., are there enough hunters to harvest it) or ecologically responsible (i.e., are wildlife populations abundant enough to support it in light of climate change and other stresses). The importance of using health research in legislation is increasingly recognized, and should contribute to policies and programs that may eventually lead to desired political – and social – outcomes, including health gains (Hanney et al. 2003). However, to do this, the research agenda must move from identifying “causes of” to “solutions to” food insecurity, as they should more broadly for health issues affecting Inuit (Cunningham 2010).

13.10.2 Need for holistic studies

The nutrition transition is now well described and the magnitude of food insecurity documented. Despite this progress however, there is a shortage of studies characterising how food security in contemporary Inuit settlements is

being affected by the complex interaction of stresses operating over multiple spatial-temporal scales. In particular, research to date has largely examined only specific components of food security (i.e., food quality or food access or food availability), yet food security is a combined property of these components which often interact in complex ways (Ericksen 2008, Loring and Gerlach 2009, 2015, White et al. 2007). Furthermore, studies have focused mostly on the traditional food component of the Inuit food system, have typically assessed the role played by individual and localised stresses, with limited research examining how social, cultural, economic, political and biophysical factors and change operating over multiple scales interact with specific places to affect food systems and security (Cameron 2012, Ford 2009, Furgal and Prowse 2008, Power 2008, Richmond and Ross 2008). Local narratives are also absent from many Inuit food system studies: while quantitative assessments are able to capture the severity of food insecurity and identify statistical associations, they are less able to capture the actual experience of the problem (Hamelin et al. 2002, Power 2008).

13.10.3 Geographic disparities in research

Research in Nunavut is well represented in the literature, reflective of the size of the territory, long history of research in the region, and output of a cluster of scholars working here. There is a preference for working in smaller communities however. While it is these locations that are likely to have enhanced vulnerability due to their isolation, high dependence on environmental conditions, and reflective of indicators of socio-economic well-being (Ford et al. 2010), it is the larger regional centers that are emerging as regional hubs and growing rapidly (Ford et al. 2013, Lardeau et al. 2011). Also noteworthy are research hotspots, with highly studied communities and regions mirrored by research deserts characterized by communities where no studies have been reported on in the peer reviewed study (Ford et al. 2012). This clustering reflects the nature of research history in specific locations, accessibility, and community leadership in encouraging research (e.g., Clyde River, Igloodik), as much as research need *per se*. Geographic

disparities of this nature matter because research shows significant differences in vulnerability between communities and regions, with implications for policy intervention at a local level (Ford and Berrang-Ford 2009, Ford et al. 2010, Furgal and Prowse 2008, 2009, Furgal and Seguin 2006).

13.10.4 Preference for the present

Limited research has examined vulnerability and adaptation to future climate change, with the majority of studies focusing on the past and present. Modeling studies have increased our understanding of how the climate of the Arctic will change and associated impacts but there is a need for studies that examine how projected changes might interact with human systems and assess how socio-economic-demographic trends will affect how communities experience a changing climate. This necessitates place-based research and also a need for downscaling climate impact studies. While modelling studies are not necessary for food policy to integrate a climate change component, they can help identify potential future stresses.

13.10.5 Need for adaptation research

The importance of adaptation to reduce the risks of future climate change impacts is widely acknowledged in the Arctic, and a number of scholars are working with policy makers and communities to identify opportunities for policy intervention. Nevertheless, the literature remains dominated by impacts and vulnerability studies. While many of these projects have documented adaptations and coping strategies currently being utilized, few examine their effectiveness, durability, socio-economic and ecological implications, and long term viability and cost in light of multiple stresses and competing policy priorities. Until these gaps are addressed, anticipatory intervention and external support is likely to be constrained (Ford et al. 2010). Community-based adaptation planning is emerging as an important focus to this end and has an important role to play in reducing vulnerability (Pearce et al. 2012). Many drivers of vulnerability at a local level, however, are determined by processes at larger spatial and temporal scales over which the local has limited influence, with need for comparable adaptation focus

at a regional, territorial/provincial and federal level, along with an examination of how these different levels can come together to enable adaptation.

13.10.6 The needs of vulnerable sub-groups

The general research indicates that sub-populations including the elderly, children, and females could have a higher vulnerability to climate change impacts and will have specific adaptation needs. Except for one study examining gender and food insecurity (Beaumier and Ford 2010), and work focusing on hunters, targeted research on specific sub-populations has generally not been documented.

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Chapter 14 Water Security

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Key implications for decision makers

- Climate change will alter water availability, supplies, and likely affect water quality for residents and industry. Adaptation is possible but will likely require residents to alter water use practice on the land and may require new or more complex handling of water in communities.
- Changes to permafrost have potentially large, but poorly understood impacts on water quality.
- Existing community water systems are already under stress due to infrastructure limitations. In combination with water quality issues, these systems will likely face further operational challenges.
- Research capacity, especially at the community level needs to be expanded to support decision making regarding water security in the region. Initial efforts to develop community-based water research hold promise to improve knowledge and adaptive capacity by residents.

Abstract

Water is a critical need for northern communities, ecosystems and the northern economy. Climate change will alter the availability of water in the region, with important implications for community supplies and the management of water systems to assure supply throughout the year. In addition, climate change is likely to affect the quality of surface water although we have limited means to determine if this will be detrimental due to a lack of research and modelling capacity. Permafrost degradation will further alter water supply and quality, potentially having both cumulative long term and abrupt changes. Many community water systems are already under stress due to limited infrastructure, capacity to operate systems, and nature of water supplies being used (lakes and rivers). Managing future water security in the region will require sustained monitoring and research, along with expansion and coordination of community level efforts to identify priority knowledge gaps and water security issues.

14.1 Introduction

Water is a critical resource for northerners' health and well-being, through the direct needs of residents to the integral role that water plays in Inuit traditional culture, supporting ecosystems and enabling travel and navigation on the land. Water also plays a central role in northern economic development, particularly for the resource industry (e.g., mining, aggregates) and through the potential for renewable hydroelectricity. The daily need for clean, reliable water supplies for all of these important societal purposes represents a key link between climate change and water security in the Eastern Canadian Arctic. As noted in other parts of this report, climate (see Chapter 2) and hydrology (Chapter 6) have already shown evidence for rapid rates of change, and are expected to further change. The climate sensitivity of permafrost (Chapter 4) will have additional cascading effects on hydrological processes (Chapter 6) that remain often poorly constrained with respect to projected climate change. Hence, water security in the Eastern Canadian Arctic is arguably one of the most direct ways in which residents, governments and businesses may expect to face the impacts of climate change, a situation that has been observed elsewhere in the Canadian and circum-Arctic region (ACIA 2005).

This chapter explores and highlights the role of a changing climate in affecting these key elements of water security across the Eastern Canadian Arctic. Considerable research progress has been made in many areas surrounding this issue, both from basic research needs to understanding the processes and sensitivities of water availability and quality, as well as from community perspectives and other user needs and the potential impact of climate change on water source, delivery, consumption and waste disposal systems. In addition to highlighting the key issues related to water security, a series of case studies provide insights into how communities and researchers are working to improve knowledge and capacity to manage risks to water security in the region.

14.2 Communities

14.2.1 Community water supplies in the region

Water security is perhaps most important in the region with regards to communities. The region is characterized by a number of relatively small communities and populations, with corresponding differences in the nature of water infrastructure. In the smaller communities, water is generally collected from a nearby lake (Bakaic and Medeiros 2017), delivered by truck, and stored in tanks in each building (Figure 1). Resolute is the exception to this situation and has a piped water delivery system. Some larger communities, notably the City of Iqaluit, have reservoirs to increase water storage and a network of pipes to deliver water to most businesses and homes. The network of pipes is supported by pump stations and also provides fire hydrant access. Due to the severe climate and the presence of permafrost and bedrock near the land surface, these systems consist of a combination of subsurface and surface pipes, which increases the potential risk to failure, especially during the winter season (Shorter 2012).

The relatively simple nature of water supply systems in the region offers communities both advantages and challenges. Benefits include reduced capital cost to develop water delivery services and adaptability of the system, especially to community growth. On the other hand, truck delivery limits water access, particularly the quantity of water to residents with implications for health of residents, especially in cases where multiple families share a single supply (Daley et al. 2014). Additionally, holding tanks and access piping are subject to winter freezing, which can cause failure or require residents to find other means of accessing water. Delivery vehicles may also represent a risk where a breakdown can limit water access until repairs are possible.

In communities where a water distribution systems exist, initial costs may be high, ongoing maintenance is often challenging, and failure of pipes or pump stations can cause hardship when parts are not available, repairs exceed community capacity, or where failure remains undetected and can compromise water availability. For example, the Resolute water system has continued to generate a number



of operational challenges due to network leaks (Shorter 2012), and winter failures of the water mains in Iqaluit have caused excessive loss before repairs can be made (Globe and Mail 2012).

In all of these cases, community water systems are subject to vulnerabilities that reflect the small community size, limited technical resources to diagnose and repair problems, and access to parts when repairs are needed.

14.2.2 Climate change and community water supply challenges

In addition to distribution and infrastructure challenges, climate change poses a further risk to community water access through changes in available water sources and indirect effects on water infrastructure (Instanes et al. 2016, Medeiros et al. 2016, Bakaic et al. 2017). Projected changes in temperature and precipitation will likely impact the timing and quantity of runoff (Lewis and Lamoureux 2010), although few studies have been carried out across the region. Most community supplies are sourced from nearby lakes or rivers and these supplies are subject to variations

due to changes in the amount of precipitation and altered summer thaw and permafrost (Chapter 6). Some lakes are dependent on snow or rainfall for recharge and may face drought during either season (Bakaic and Medeiros 2017, Bakaic et al. 2017). This is especially a concern in the drier areas in the High Arctic such as Pond Inlet. There are further issues related to changing water quality in these water sources that reflect altered hydrological conditions and permafrost degradation. While these effects have been studied at several locations in the region (see Apex River case study Box A) and suggest possible water supply and quality impacts due to climate change, available research is limited for predicting future related changes. Research elsewhere in Nunatsiavut indicates that communities can adapt to these changes in water availability and quality, but do require sacrifice on the part of residents (Goldhar et al. 2014). Key questions include: changes to the timing and amount of recharge to supplies, impacts of changing permafrost and summer temperature on water quality and potability.

Many community residents also obtain untreated natural water directly from streams, lakes, rivers, and from sea ice,

glaciers and even icebergs (C-CIARN North 2005). Water from traditional sources is often perceived to be superior in quality to chlorinated tap water (Martin et al. 2007, Marina et al. 2008), and procuring, consuming, and sharing this water remains an important source of cultural identity throughout the North (Marina et al. 2008). Martin et al. (2007) estimate that up to 31% of the residents of Nunavik's Inuit communities (northern Quebec) obtain most of their drinking water from traditional sources, with some families using up to 25 liters of raw untreated water daily (Martin et al. 2007). More research is needed to document the extent of use of traditional water sources in Eastern Canadian Arctic communities, and to better understand local water consumption patterns and preferences, including traditional methods to select and assess drinking water sources.

Additionally, permafrost degradation may result in a variety of impacts on water quality, through increased disturbance and sediment erosion, deeper flow in the soil (thus changing water quality), and ponding of water in thermokarst ponds and lakes elsewhere on the land (Figure 2). In order to address this gap in knowledge, a number of efforts have been undertaken in recent years to map community water supplies (e.g., Arviat, Clyde River), and new initiatives have emerged with community research partnerships (e.g., Pond Inlet, Baker Lake). These efforts pair local and government or academic research expertise and offer an important means to identify emergent issues and future risks at the community level, and also complement efforts to improve the basic science of climate change-water impacts in the region.

In addition to direct water supply issues, climate change can have important indirect issues with the water supply systems in the region. Building water tanks require periodic cleaning, a task often informally left to occupants. Warming temperatures and seasonal changes in water quality increases the risk of microbiological contamination in tanks, which has the potential to affect community members (Hennessy et al. 2008, Harper et al. 2011). Regular testing can reduce this risk but requires resources and trained personnel in communities and may exceed existing capacities. Similarly, maintenance of water distribution



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FIGURE 2. Changing climate and permafrost mean that water flows through different pathways on the land and soil. These changes can affect water quality, introducing increased nutrients to water. Blooms of algae in water such as the example in this photograph indicate important potential changes in water quality in the IRIS region (Cape Bounty, Melville Island).

systems requires both personnel and financial resources. In addition, climate related changes may introduce a number of added risks (Hennessy et al. 2008). For example, pipe systems depend on soil stability which may be compromised where permafrost degradation occurs, resulting in progressive added wear on system components that reduce system reliability, or the risk of a catastrophic failure that cause water distribution to end until repairs can be made. The availability of trained personnel to maintain these systems is naturally higher in larger communities. Hence,

BOX A. Collaborative research on the Apex River to build capacity and improve water security in Iqaluit

Iqaluit is a rapidly growing community and the current water supply system (Geraldine Lake) is expected to reach capacity in the near future (Figure A1). As part of plans to supply water for the growing community, the City is pursuing plans to use the Apex (Niaqunguk) River to supplement Geraldine Lake. The Apex River watershed is located immediately to the northeast of the city and the river mouth is located at the Apex community along the southern edge of the city (Figure A2). The watershed is heavily used by residents for a wide range of purposes, including recreation, camping, swimming, fishing and informal water supply.

Given the importance of the watershed to residents and the potential for future use by the City, stakeholders from the Nunavut Research Institute (NRI), the federal, territorial and city government and Nunavut Arctic College (NAC) met in 2012 with researchers to initiate a collaborative research program on the watershed. The research team, funded by ArcticNet and Polar Knowledge Canada, has grown to include university researchers from Queen's, Carleton and the Université de Montréal, with active participation by NRI researchers and students from the Environmental Technology program at NAC. This collaborative research has sought to develop capacity to carry out water research in Iqaluit and to develop sustained monitoring of key water and water quality measurements. Additionally, through partnership with the Analytical Services Unit at Queen's University, laboratory instrumentation at NRI has been maintained and training of northerners has continued to support local water expertise.

Monitoring work was established during 2013 and included fixed water sampling at four locations in the river, snow surveys in conjunction with INAC and NAC students, and systematic water quality measurements during the runoff period (June-October). Additionally, a network of 20 lakes have been sampled each July to determine long term water level and quality changes, and snow surveys and soil water research programs have been established. A weather station and seasonal river discharge stations have also been established to provide further insights into the climatic sensitivity of the Apex River to climate change.



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FIGURE A1. The Geraldine Lake dam located above the city of Iqaluit. The dam increases storage of water for the city supply and is delivered through the pipe located below the dam.



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FIGURE A2. Sampling the Apex River near the outlet in Apex (background), August 2013. The river is near low flow at this time of year.

smaller communities may face the same challenges due to climate change and related impacts on water and permafrost, but local capacity may limit the response of a community to these challenges.

Finally, rapid population growth in the region adds further challenge to managing environmental and infrastructure risks with respect to community water supplies (Bakaic et al. 2017). Nunavut has the highest population growth rate in Canada (2016 census) which has two important implications for water supplies. First, added demand for water by growing community population may tax existing supplies. Population in the city of Iqaluit has grown by 36% between 2001 and 2016, and projected population growth suggests a further 17% growth by 2030 (Government of Nunavut 2017). Given the limited available water supply in the Geraldine Lake reservoir, the city has begun to plan for alternative sources of water to supplement this supply (Golder and Associates 2013), including the nearby Apex River (see Apex River case study Box A). Other communities have also faced depleted supplies, although the link between growing water demand and supply changes is not well established. Further, other communities have begun to explore issues related to limited water supplies, population growth and the potential impacts surrounding water security. Given current knowledge, these issues are likely to be amplified by changing climate and permafrost.

14.2.3 Water quality impacts

The Nunavut Public Health Act specifies recommended minimum frequencies for public water sampling (up to 7 times monthly depending on population) and also indicates maximum amounts of specified water pollutants. These regulations reflect practice elsewhere in North America and are meant to assure quality of drinking water for resident health. Compared to elsewhere in Canada, Nunavut has been noted to have amongst the lowest water supply treatment standards (Ecojustice 2011). The effects of climate change add to the challenges of monitoring water quality through changing water availability and seasonality. These hydrological effects can alter sediment erosion

and effect other important water quality parameters such as turbidity, bacterial load, dissolved oxygen, dissolved organic matter and nutrients (Chapter 6). Some of these effects, such as permafrost-related land disturbance, can occur abruptly and without warning, and result in an immediate impact on water (Lamoureux and Lafrenière 2009), while other effects may be more gradual or sustained (Lafrenière and Lamoureux 2013). These effects may in turn affect aquatic ecosystems that have further impacts on water quality, particularly through microbiological populations many of which have human health impacts (Harper et al. 2011). Relatively infrequent water testing in communities may prevent detection of these changes and result in decreased water quality in communities, or unexpected closure or maintenance of water systems. The emergence of new water-borne pathogens is also a concern associated with climate change and may require new monitoring efforts to protect water supplies (Goodman et al. 2008).

14.2.4 Challenges to community water security

In addition to high population growth in some communities, together with instances of higher occupant density, limited infrastructure, and repair challenges due to isolated locations, climate change adds further challenges through potential impacts on water supply and quality. Predicting these impacts is challenging due to limited research in the region, especially related to the indirect effects of climate change on permafrost and aquatic ecosystems. Hence, small communities in the region face challenges of building and servicing water infrastructure, along with a rapidly changing environment that will affect water security, likely in complex ways that will vary by community. These risks are further heightened by the lack of source water protection in place in Nunavut.

It is important to note that in addition to the supply of water to communities, the disposal of waste water is also a significant problem in the region. Most communities depend on the collection of waste water with trucks and simple water treatment facilities to remove solids and to provide primary

biological treatment. These systems are subject to many elements of climate sensitivity, including a short period of biological functioning due to the cold climate, high natural water inflows during snow melt that can increase waste management problems, and the risk of permafrost change

on the stability of waste treatment ponds and infrastructure. While the emphasis of this section reflects the challenges associated with providing clean water to communities, water waste management adds additional challenges for communities (see Coral Harbour case study Box B).

BOX B. Municipal wastewater treatment in Coral Harbour, Nunavut.

Many communities in Nunavut treat municipal wastewater with wastewater stabilization ponds (WSPs) that eventually discharge into natural tundra wetland areas. New Canadian regulations for wastewater treatment, known as the Wastewater Systems Effluent Regulations (WSER), have been introduced by Environment Canada. However, the WSER is still being formulated for Nunavut, Northwest Territories, and above the 54th parallel in Quebec, and Newfoundland and Labrador, and will need to account for the unique climate and geography of the region.

Wetlands can be used to degrade, transform, and sequester many contaminants found within municipal wastewater. Natural tundra wetland areas are currently used in many Northern communities, and may be an important part of the municipal wastewater treatment strategy for Canada's Far North. However, there are unknowns with respect to the treatment mechanisms which occur within these systems, and the human and ecological health risks associated with discharging partially treated wastewater to these ecosystems. The case study of the natural tundra wetland treatment area in Coral Harbour, Nunavut was undertaken to address these research gaps (Figure B1).

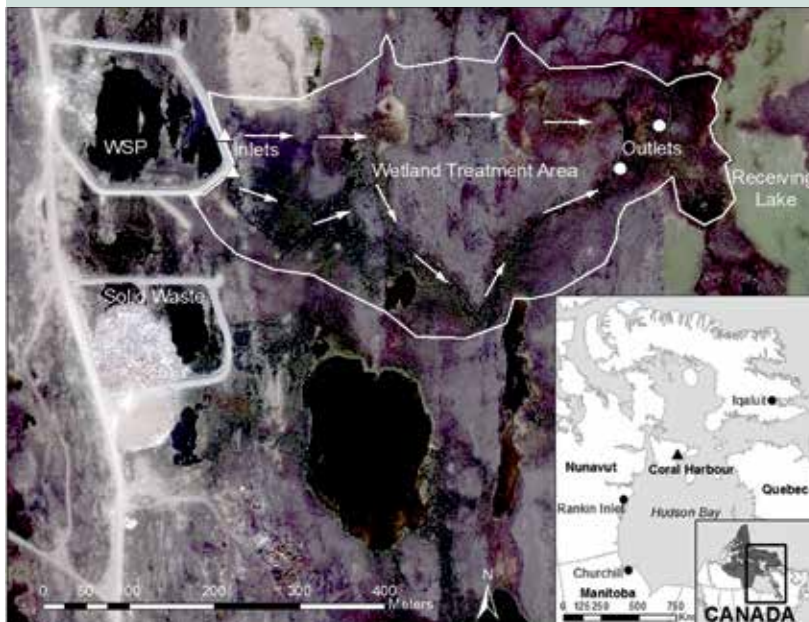


FIGURE B1. Plan view and key map of the Coral Harbour, Nunavut WSP and the wetland treatment area. The arrows denote the direction of effluent flow in the wetland. Quickbird satellite imagery taken on July 13, 2006.

The wastewater treatment system in Coral Harbour is comprised of a single-cell WSP that receives wastewater daily from pump trucks. The wastewater is released (exfiltrates) from the WSP berm at a variable rate over the treatment season, spanning from mid-June to mid-September, into a natural tundra wetland treatment area. A main study objective was to identify the influential hydraulic, biogeochemical, and physical factors that affect the treatment performance of the wetland. Data was collected during the treatment seasons over four site visits spanning from June 2011 to September 2012. Samples were collected from the wastewater trucks, the WSP, and the inlet and outlet of the wetland. The flows were



FIGURE B2. Photographs of the natural tundra wetland treatment area taken from the inlet near the toe of the WSP berm where (a) taken on June 30, 2012 shows much higher flows than (b) taken on July 8, 2012.

measured by stream gauging at the inlet, mid-points, and outlet of the wetland. Basic water quality indicators such as pH, dissolved oxygen, conductivity, and temperature were measured throughout the wetland to characterize the biogeochemistry of the system.

The results showed that the wetland treatment area is characterized by variable wastewater flows and treatment performance over the treatment season (Figure B2). The highest effluent flows were observed during the spring freshet and lowest flows in the mid-summer to fall, which coincided with the worst and best cases in effluent water quality respectively. The wetland treatment area also received hydrologic contributions from upstream watersheds that acted to dilute the effluent. In all cases, the water quality at the wetland outlet met the WSER being applied to southern Canadian systems. The study demonstrated that tundra wetlands can be used to improve effluent quality during the melt season; however, it is vital that the site-specific hydrological context of the wetland be understood in order to assess the performance of the system.

14.3 Water and ecosystem services

14.3.1 Importance of traditional uses of land and water

Inuit share particularly close cultural and spiritual connections with the physical environment. Traditional knowledge of the land, water, and climate have historically linked Inuit communities together and formed the basis for life (Medeiros et al. 2016). Travel is an integral part of Inuit family structure (Gearheard 2010a) and Traditional Ecological Knowledge (TEK) of sea ice, lake and river crossings (Figure 3), and weather has historically been passed down through generations. Hunting, fishing, transportation, recreation, and relational networks (e.g., connecting communities, food sharing) all require detailed knowledge of climate and the environment. For Inuit, ‘moving is a way of living’ (Aporta 2009), and for many communities this requires stable ice conditions for traversing



FIGURE 3. Water as a means of travel. Andy Aliyak crossing the Meliadine River, Rankin Inlet.

across lakes, rivers, and the ocean. TEK of weather is a critical component of safe travel across large landscapes (Gearheard et al. 2010), however, changing weather conditions are constraining the ability for Inuit families to safely navigate and successfully hunt across both winter and summer routes. Residents across Arctic communities have observed changes in river ice conditions, run-off, flow regimes, and water levels, which have impeded access to important fishing areas and makes travel more hazardous (Fox and Huntington 2005). See Chapter 11 for more information on travel and hunting in a changing environment in the region.

14.3.2 Role of water in ecosystem health

The health of Inuit depends on ecosystem condition much more directly than is typical of other North American cultures. Beyond providing the basis for life, the water cycle in the Arctic is fundamental for overall ecosystem function. Arctic ecosystems exist, and are defined by, large gradients in temperature, precipitation, and productivity. Large seasonal transitions in snow, ice-cover, and solar radiation define thermodynamic relationships across multiple environmental scales, such that almost all Arctic aquatic systems depend on the freeze/thaw cycle (Vincent and Laybourn-Parry 2008).

The transition from the terrestrial to aquatic environment is also key for ecosystem function. Physical characteristics (topography, underlying geology, permafrost), the configuration of drainage basins, and catchment vegetation strongly influence the chemical composition of surface waters. Inputs from the terrestrial environment to nutrient-limited aquatic systems highly govern biogeochemical processes that can define subsequent biological communities and affect food-web structure.

14.3.3 Permafrost changes and surface water impacts

The health and sustainability of aquatic systems is highly reliant on the flow of energy, which is dependent on the underlying hydrology governed by the depth of permafrost.

This makes the permafrost horizon arguably the most influential component of hydrology. Permafrost is perennially frozen ground which underlies the active layer (the top soil horizon, which freezes and thaws annually and is typically <1 m in thickness). Permafrost controls the amount of space in the soil matrix available for the movement of water into drainage systems. This results in a large amount of ground saturation from late-lying snow banks that is retained in the active layer above the permafrost horizon (Woo 2012), and which can sustain lake-levels throughout dry periods in the summer.

The permafrost layer also contains ice, which can be arranged in a complex polygon pattern of lenses, irregular masses and wedges. When this ice thaws, the surface can collapse forming thermokarst features (Figure 4), irregular terrain, pits, furrows, and depressions that can fill with water and become temporary thermokarst lakes (Liljedahl et al. 2016). In regions where melting of permafrost may occur, a deeper active layer and a longer unfrozen period results in a reduction of overland flow as both infiltration and active layer water storage capacity increase. Therefore,



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FIGURE 4. Thermokarst disturbance in the Apex River watershed near Iqaluit. Ground ice below the surface has been exposed, resulting in rapid thaw and surface collapse. These types of permafrost and surface changes are reported throughout the Eastern Canadian Arctic.

deepening of the permafrost layer results in a larger portion of water from streams and ponds interacting with active soil layers.

Current warming projections predict the gradual deepening of the permafrost layer will result in a subsequent disappearance of the patchy Arctic wetland that is supported by surface flow from the late lying snow banks (Rouse et al. 1997) and already occurring now (Woo and Young 2006). Similarly, some small lakes and most Arctic ponds exist because the permafrost isolates them from the regional groundwater system or from surface flow (Edwardson et al. 2003). The resulting catastrophic drainage of Arctic lakes and ponds has already been observed in some areas of the Arctic (Smith et al. 2005, Bouchard et al. 2013).

14.3.4 Impact of climate change on surface water

Arctic aquatic systems are considered to be especially sensitive to climate change due to the narrow ecological thresholds which define their existence and function. Many Arctic watersheds are historically characterized by a relatively small runoff during summer rains, due to low precipitation. In addition, the relationship between snow-melt and precipitation is critical for the sustainability of small Arctic lakes and ponds. Late-lying snow is critical for both the aquatic and terrestrial environment in polar desert areas of the High Arctic (Woo and Young 2014). If regions experience particularly dry conditions, especially due to lower snowfall, or warm conditions (enhance evaporation) widespread desiccation can occur (Bouchard et al. 2013). The influence of increased temperature and changes in precipitation on the overall hydrology of Arctic ecosystems is exacerbated by the fragile seasonal dynamics of these Arctic systems.

The influence of warming on nutrient dynamics of Arctic systems is considered to be profound in aquatic systems. Most Arctic aquatic systems are clear, alkaline, nutrient limited, especially during the drier summer months (Medeiros et al. 2012). A substantial amount of the total seasonal nutrient input is dependent on overland flow of

spring melt-waters. Thus, increased depth of the active layer (thawed soil horizon above permafrost) is predicted to alter the hydrological balance of water during this critical period. This has wide-scale implications for the overall biogeochemical balance of aquatic systems, and subsequent productivity. Phytoplankton are limited by low photosynthetic rates in Arctic habitats versus temperate systems due to limited nutrients, cold temperatures, and reduced light availability from snow and ice cover (Flanagan et al. 2003). However, if the length of the ice-free period increases, an increase in the available light and subsequent growing season for both terrestrial and aquatic systems is expected. An increase in available light would therefore allow for an increase in total annual primary production and more complex periphytic communities to develop in freshwater systems (Rouse et al. 1997). Douglas and Smol (1999) also suggest that primary production will be enhanced by an increased available habitat, and enhanced nutrient fluxes from catchments.

14.3.4.1 Streams

The progression of water from temporary ephemeral, seasonal, spring-fed, and year round systems highly depends on the local environment, topography, and regional climate. During the spring melt, water that flows from hillslope areas into channels can cause ephemeral flooding in lowland areas and depressions. The permafrost horizon limits water from percolating beyond a few centimetres into tundra soils, so water levels in streams are close to the surface. Contact between the highly organic tundra soils and pools of water can carry a relatively large amount of nutrients and organic matter to streams and rivers. The progressive flow of water through the thin tundra soil horizon can enrich Arctic streams much in the same way as southern temperate systems (Edwardson et al. 2003). Summer rain events can also cause periodic flooding, and can sometimes match the snow-melt period in terms of flow (Woo and Young 2006). Many Arctic streams are predominantly sustained by spring snow-melt, known as nival systems, and are characterized by high run-off periods and overland flooding during the spring. Thus, as most Arctic streams are only active during the spring and summer months, these systems

depend on the amount of melt-water and/or precipitation of previous years that becomes available for melt in the spring (Woo 2012). However, some years there might be a water deficit in storage at the end of the season that needs to be filled before runoff might occur the following year. For instance, you could have two years with the same amount of snow, but the flows might be different depending on the fall storage situation.

14.3.4.2 Large rivers

The Eastern Canadian Arctic contains many river systems that provide important wildlife habitat. These systems drain large catchment areas and often flow across extensive flood-plain deltas dotted with lakes, ponds, and wetlands. Flow within these large river systems is strongly seasonal, and controlled by snowmelt and presence and rupture of ice dams (Vincent and Laybourn-Parry 2008). Summer flows are elevated by the melting of ground ice in the active layer

and winter flows are diminished by a loss of surface runoff (Woo 2012). High-amplitude peak flow occurs during the spring melt, and during elevated or extreme precipitation periods. This results in the flushing of flood-plain lakes in the spring as the area floods. This flooding can replenish lakes periodically with river water, altering their limnology. During peak flow periods and flushing events there is a large concentration of organic input to the rivers and flooded lakes from the leaching of surface materials (Woo 2012). Later in the season, inputs are mobilized from deeper soils. These systems form a continuum, progressing from a stream-type headwater origin to large rivers that discharge into the Arctic Ocean. Large rivers also act as corridors for migration of fish, but have less diversity of zooplankton and benthic invertebrates due to high flows and turbulence (Vincent and Laybourn-Parry 2008). Large river systems are particularly threatened due to changing climate conditions due to the large spatial gradient in which they flow (Figure 5). Warmer temperatures in the south



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FIGURE 5. Rivers and soils are changing in response to climate. Even reliable summer water supplies such as this glacier near Pangnirtung are retreating, altering long term river flow.

will undoubtedly increase the flood period of large river systems, and ultimately increase the transport of enriched waters across northern deltas and the Arctic Ocean.

14.3.4.3 Lakes and ponds

Lake responses to increased temperature, and a subsequent extension of the ice-free season, include an increase in the length of the stratified season, and an increase in the depth of mixing. This in turn leads to lower oxygen concentrations in the deep parts of lakes and increased stress on cold water-adapted organisms (Rouse et al. 1997). Oswood et al. (1992) argued that for Alaskan aquatic systems, a 4.0°C increase in temperature could potentially represent a 50-100% increase in available degree days, which would highly influence aquatic trophic systems (Medeiros et al. 2011a). The increased weathering of newly unfrozen glacial till has also been observed in limnological trends from Toolik Lake (Alaska), where summer alkalinity has doubled since 1975 (Hinzman et al. 2005). Increasing temperatures, enhanced stratification, and higher inputs of organic carbon, nutrients, and increases in pH would

ultimately destabilize the trophic structure of lakes and ponds and may threaten land-locked fish populations.

14.3.4.4 Water quality changes to surface waters

Increased focus on resource development has added additional stress to water quality issues facing Arctic communities in the future. While changes to climate have resulted in disappearing lakes and streams, especially in the summer months (Bouchard et al. 2013), anthropogenic contamination of water sources has become a pressing issue for many communities (Medeiros et al. 2011b, 2016).

The transport of contaminants to the region, and a number of water quality challenges have caused additional stress on food security for many families (Figure 6). The cost of imported food from the South is often prohibitive, thus there is a continued reliance on traditionally harvested foods. The diet of Inuit is therefore heavily subsidized by 'country foods' or traditionally harvested fish and marine and land mammals. The residents of many Arctic communities often drink untreated water directly from local



FIGURE 6. Water Quality is a key factor for many communities across the Eastern Canadian Arctic. Development pressure from resource industries, legacy contamination, and urban development can all stress water resources. Image of Carney Creek (Airport Creek) in Iqaluit, Nunavut.

streams and rivers due to cultural knowledge and tradition behind drinking flowing water sources. TEK has long recognized the threat of invisible water-borne health threats of stagnant waters. Warming temperatures, as well as point-source contamination from development pressures, may increase the risk of relying on untreated water sources for Inuit hunters and families.

Growth and expansion of several communities is expected to follow increased industrial and resource development projects, which will increase the burden on municipal water services. Likewise, increased municipal and industrial development may result in a variety of contaminated point-sources that would impact aquatic systems, including run-off and leaching from municipal landfills and sewage containment areas, hydrocarbon and chemical spills (waste oil, fuel, lubricants, de-icing liquids), industrial activity, residential waste, stream channel diversion (that often accompanies road construction), and increased sedimentation from gravel haul operations (Medeiros et al. 2011b, 2016). Residues from industrial contaminants (e.g., pesticides, and metals) transported from global sources via long-range atmospheric transport have been a pressing problem for Inuit communities for decades (Indian Affairs and Northern Development 2003) (Figure 7). In addition, increased effluents, tailings, and emissions from resource



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FIGURE 7. Debbie Iqaluk of Rolute has worked with researchers investigating contaminants in fish for decades. Understanding the impact of climate change on water and contaminant cycling is an important concern for researchers and northerners alike.

exploration and industrial development near Arctic communities have renewed concerns over water and food security. Changing climate exasperates these problems as the retention of effluent is no longer as simple as burying the problems in permafrost, as has historically been the ultimate means for disposal.

14.4 Resource development and water

Natural resource extraction represents an important component of the economy for the region. In 2010, the estimated value of mineral production in Nunavut was \$305 million (Mining Association of Canada 2011). Given the comparative mineral wealth of the region, mining has played an economic role for decades and new mines have continued to become operational in recent years. The demand for base metals and gold is expected to be strong in the long term. Increasing gold production at the Meadowbank mine (see case study Box C) near Baker Lake and the recent development of the Mary River iron ore project on northern Baffin Island contribute to overall economic growth for Nunavut and likely make the mining industry Nunavut's largest private-sector employer (Mining Journal 2012) (Figure 8). Additional project developments are underway, including diamond on southern Baffin Island, and base



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FIGURE 8. Mining development offers employment and other benefits to communities, as well as challenges. Development of the Mary River iron ore mine on northern Baffin Island has resulted in many community opportunities (posted at the Pond Inlet Co-op, September 2013).

metals in eastern Kitikmeot. Exploration for new deposits continues in many areas as well, including large recent projects on Somerset and Baffin Islands. Given the scale of many recent and planned mining projects, and the need for water to support mineral processing and related operational

infrastructure such as the camp, water plays a substantial role during the evaluative and environmental permitting phases of development, and during the operational period. See Chapter 19 for more information on mining and communities in the region.

BOX C. Meadowbank Gold Mine: Water quantity management and quality monitoring

Meadowbank is an open pit gold mining operation owned and operated by Agnico Eagle. The site is located approximately 300 km northwest of Hudson Bay in the Kivalliq Region of Nunavut. Prospectors first discovered gold at this location in 1987. After many years of reviews and agreements made with Nunavut, Meadowbank was constructed and reached commercial production in 2010. The mine is expected to produce approximately 360 000 ounces of gold per year (over \$350 million of gold annually) from 2013 to 2015, with a mine life through 2018 (Agnico-Eagle Mines Limited 2013) with the potential to extend mine life with additional ore bodies.

Figure C1 shows the key water management features at the mine. The lakes surrounding the mining pits (Figure C2) have been modified with a network of dams, dikes and ditches to regulate water levels, isolate portions of lake beds

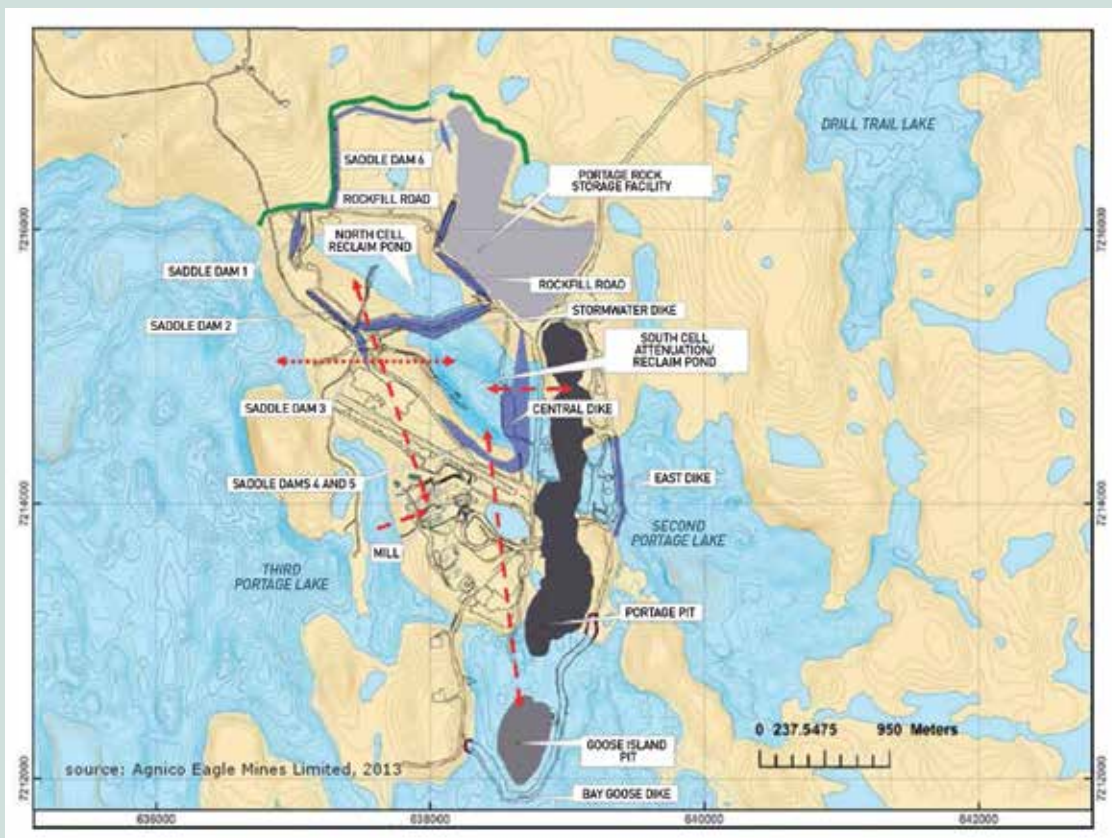


FIGURE C1. Locations of mining pits (shaded areas) and key water management features at the Meadowbank Gold Mine (Agnico Eagle Mines Limited 2013).

from the main lake body, and divert water to prevent effluent spillage. Mill processing and associated operations use the greatest amount of freshwater on-site (90%). However, most of Meadowbank's water requirements are from recycled water in the tailings slurry, hence reducing the need for new water for operations. Following the gold processing, tailings are deposited into a reclaim pond and water from this pond is pumped back to the plant for reuse and reducing the need for fresh water by approximately 60%. It is estimated that beginning in 2013, 1 080 000 m³/year of fresh water from Third Portage Lake is required for maintaining mine operations (Agnico Eagle Mines Limited 2013). The South Cell reclaim pond is used as an attenuation pond for water used in pit dewatering where water is stored, treated, and discharged back to Third Portage Lake for re-use.

Two types of lake water quantity monitoring programs have been implemented at Meadowbank: targeted level monitoring and core receiving environmental monitoring (CREMP). Targeted monitoring is conducted monthly at the effluent discharge station in Third Portage Lake. No substantial change in water levels has been observed since monitoring started in 2009. Furthermore, increased water usages have not caused any erosional or water flow



FIGURE C2. Aerial photo showing the Meadowbank Gold Mine, located on mainland Nunavut. Several lakes surround the site and are used for mining operations.

changes between Third Portage Lake and Second Portage Lake (Agnico-Eagle Mines Limited 2013). CREMP is a larger scale program that aims to detect short and long-term physical and biological changes at the lake and basin level. The program monitors general limnology (freshwater science), water and sediment quality, primary productivity (phytoplankton), and benthic community structure. Sampling stations are located in all three basins of Third Portage Lake, as well as Second Portage and Tehek Lakes, which receive flow from Third Portage Lake (Agnico-Eagle Mines Limited 2013).

Meadowbank also has two comprehensive water quality monitoring programs: compliance monitoring (CM) and event monitoring (EM). The CM program assesses the water chemistry (e.g., pH, conductivity, turbidity, total dissolved and suspended solids, alkalinity, total and dissolved metals, ion concentrations) at specified sites to ensure compliance with regulatory requirements. Testing stations include the camp and mill water (monthly testing), reclaim water intake (monthly), attenuation pond prior to discharge (weekly to monthly), and the tailings reclaim pond and storage facility (monthly to annually) (Agnico-Eagle Mines Limited 2009). Water testing is also conducted at groundwater wells (annually) and ground seeps (monthly). Frequency of testing depends on the life stage of the mine – from early operation to closure. Testing parameters also vary at each site. The EM program is a series of mitigation protocols put into place during an unexpected event or emergency (spills, accidents, and operational malfunctions). The program is designed to verify whether contamination of the surface soil and surface water bodies has occurred as a result of an accidental release of a hazardous material (Agnico-Eagle Mines Limited 2009).

Other resource-related water uses are also of importance in the region, including aggregate extraction for infrastructure like roads and communities, and also for potential development of hydroelectricity as a means of supplying electrical power.

14.4.1 Hydroelectricity

Currently, the region has no operational hydroelectric facilities, compared to other northern territories in Canada where the technology is widely used. All electricity in the region is produced by diesel-fueled generators located in each community and supported by seasonal fuel resupply with ships. Sufficient fuel is stored in each community to meet continuous power generation, and related local

pipelines transport fuel from the coast, to storage tanks, and to the power plant facility. As a result, the cost of electricity production in the region is high compared to elsewhere in Canada and the Arctic, ranging from 60.2 to 114.4 cents/kwh (unsubsidized) for residential customers across the region. Subsidies to lower rates for consumers are substantial, lowering rates as much as 90% or more (Cherniak et al. 2015). The dependency on imported diesel fuel, the related environmental emissions and fuel handling risks, and the high costs of this system are all significant risks to the region.

The abundance of surface water in many parts of the region has resulted in proposals and feasibility studies for hydroelectric development (Figure 9). Two sites have



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FIGURE 9. The potential for hydroelectric production in the Eastern Canadian Arctic is substantial with many areas with large rivers and steep topography (an example near Pangnirtung). Development challenges are substantial, particularly finding appropriate development locations near communities, minimizing environmental impacts, and risks associated with changing climate and river discharge.

been considered near Iqaluit: Jaynes Inlet and the Armshow River, both of which are located across the bay. Of the two sites, feasibility work has been conducted at Jaynes Inlet and suggests up to 14.6 MW generation is possible, sufficient for Iqaluit's current peak demand (Qulliq Energy Corporation 2013). The project would require construction of a 30 m-high dam at the outlet of an existing inland lake and would deliver electricity to Iqaluit using a 84 km-long transmission line. While the project is technically feasible, and the transmission line would also potentially service a second development at the Armshow River (Knight Piesold 2013), the estimated cost of \$200M is not currently possible for the Government of Nunavut and the Qulliq Energy Corporation, hence, the project has not advanced to development. Given the high capital costs of this system, the availability of water supply is of critical concern to ensure operational success.

14.4.2 Mining and water

Mining has a potential impact on the environment, especially on the quality and quantity of freshwater systems. Without proper wastewater management and monitoring implemented at mining operations, water sources are at risk of contamination. Impacts to the environment directly affect human health and the quality of life for northern communities. Clean and abundant water is necessary for safe human consumption, transportation, and cultural activities.

There are three primary uses of water in mining: mineral processing and metal recovery, dust control, and meeting the needs of workers on site. The amount of water used at a site depends on the size of the operation and the type of mineral and metal being mined, but the majority of water used is normally associated with mineral processing.

There are a number of classifications of mine water, which can vary in their quality and potential for contamination: (1) mine water refers to any surface or groundwater present at the mine site or workings, (2) mining water is water which has come into contact with any mine workings, (3) mill water is used to crush and grind ore; (4) process water

is used in the separation and chemical extraction of metals; (5) leachate: water which has trickled through solid mine wastes and may contain dissolved minerals, process chemicals, and/or metals, (6) effluent is processed water which is discharged into the environment after being treated, and (7) mine drainage water is surface or groundwater which flows or has the potential to flow off the mine site during and after the mine is active (Lottermoser 2012).

14.4.3 Impacts of mining on water and water quality

Water contaminated with high concentrations of metals, sulphide minerals, dissolved solids, or salts can negatively affect surface water quality, aquatic ecosystems, and groundwater quality, thereby impacting northern communities (Fraser Institute 20012a). Metal toxicity produces negative effects on human and animal survival, activity, growth, metabolism, or reproduction (Wright and Welbourn 2002, Landis and Yu 2003, Cunningham and Cunningham 2004, Brandl 2005). Certain metals, such as methylmercury, undergo a process called biomagnification, whereby contaminants become more concentrated in tissues of organisms as they move up the food chain. This process results in high trophic level organisms such as the polar bears having concentrations of contaminants thousands or millions times higher than in the water (ACIA 2005). Humans are exposed to contaminants through diffusion into the bloodstream via inhalation of dust or absorption into the skin, drinking contaminated water, and eating animals or plants that have been contaminated (Wright and Welbourn 2002).

The potential for water contamination at mines depends on a number of factors including the type of metal or mineral being mined, the chemicals used in the mineral preparation and metal extraction processes, the geographical location and life stage of the mine, and the environmental management practices in place, are arguably the most critical factors involved (Lottermoser 2012). Environmental impact assessments, modern water management practices, careful engineering, compliance to environmental regulations, and regular monitoring can

greatly reduce the potential for water contamination at mine sites (Fraser Institute 2012a).

An important structure at mining sites to manage waste are tailing ponds or containment facilities. Water containing fine sediments and by-products from the mining process (called tailings) is collected and stored in lagoons enclosed by dams before being treated and released to surface water (Fraser Institute 2012a). A dam failure can result in the release of stored waste water into the surrounding environment, contaminating soil and water bodies. The design and construction of these structures in permafrost environments remains a challenge for engineers. The impacts of thawing permafrost on dams and waste impoundment areas can cause structural instability due to increased pore water pressure and seepage, and possible fracturing of the underlying bedrock during refreeze (EBA Engineering Consultants 2004).

Another potential impact of mining on water are hydrological alterations, which is a physical disturbance to water bodies that may affect the magnitude or timing of natural river flows (Rosenberg 2000, Vörösmarty and Sahagian 2000). In the mining industry, this is done when mines drain or dredge lakes and ponds, modify the bed or bank of a watercourse, build infrastructure (i.e., roads, pipes, bridges, waste containment facilities) that cross a watercourse, introduce large amounts of sediment into a channel, and dam or divert rivers and streams (Kondolf 1997, Nunavut Water Board 2014).

Hydrological alterations can seriously impact the health of downstream aquatic ecosystems. Disruptions to the volume and timing of river flows can effect nutrient delivery to offshore marine areas, impacting the biology, chemistry, and algal ecology of these downstream areas (Ittekkot et al. 2000). The removal of fresh water from Arctic lakes (more than 10% of the ice-free water volume) can result in lower lake levels, leading to impacts on the local aquatic ecosystem (Cott et al. 2008, Sibley et al. 2008). Damming water channels are especially detrimental to aquatic ecosystems. Changing the course and damming rivers can create blockages of normal seasonal migrations for aquatic

species and result in the fragmentation of populations (Dudgeon 2000, Pringle et al. 2000).

14.4.4 Mine water management and demand

Although large mining operations use a substantial amount of water, the industry overall consumes a relatively small quantity of water at national and global levels. Mining accounted for 4% of the water used in Canada in 2005, versus 60% for coal and nuclear electric power generation, 18.5% for manufacturing, 9.5% for municipal water supplies, and 8% for agriculture (Environment Canada 2012). However, there are still challenges for the sustainable use of water for mining in Nunavut and other regions underlain by permafrost.

If adequate water sources are not close to the mining site, surface pipes are required to transport water and are prone to freezing. To address such problems, mines have used, either individually or in combination: anti-freezing agents, transporting water in tankers, heating the water pipes, or air heating (Wandinger 2000). These solutions (often temporary), are collectively time, energy, and cost intensive. Diverting water for these purposes can also stress aquatic ecosystems and limit freshwater use for communities in the area.

14.4.5 Regulatory and licensing boards

Responsible mining practice frameworks developed by public regulatory boards focus on sustainable development. Sustainable development is about meeting the needs of today without compromising the needs of future generations, thereby “improving the standard of living by protecting human health, conserving the environment, using resources efficiently and advancing long-term economic competitiveness” (Environment Canada 2014a). Laws and regulations established by different levels of government are intended to ensure mining operations are sustainable.

Canada’s provinces and territories have primary jurisdiction over mining, however the federal government

has legislation that covers key aspects of the sector. The Minister of the Environment is responsible for the Canadian Environmental Assessment Act, and administering the Metal Mining Effluent Regulations (MMER) under the Fisheries Act. Under this act, dissolved compounds and quality measures including: arsenic, copper, lead, nickel, zinc, cyanide, radium, total suspended solids, pH, and toxicity levels of effluent from mining operations must meet permissible limits (Fraser Institute 2012b). Environmental effects monitoring (EEM) is another key requirement for metal mines regulated under the MMER. EEM involves the sampling of fish and other aquatic species downstream from operations for size, weight and toxicology (e.g., mercury) testing. This is to assess whether or not fish remain a safe food source for nearby communities.

Coal mines, diamond mines, quarries, and other non-metallic mineral mining facilities not captured under the MMER are subject to the requirements of the Fisheries Act. Additional relevant federal laws that may impact mining are the International River Improvements Act, the Migratory Birds Convention Act, the Species at Risk Act, and the Canadian Environmental Protection Act, 1999 (Environment Canada 2014b).

A necessary step in opening and operating a mine in Nunavut is applying for an inland water use license granted by the Nunavut Water Board (NWB). All activities that involve the uses of water and disposal of waste into water require a license. The NWB license applies to inland waters, meaning waters in a liquid or solid state (ice and permafrost), on or below the surface of land (surface water and groundwater). The NWB is an Institution of Public Government created in 1996 following the Nunavut Land Claims Agreement between the Inuit of the Nunavut Settlement Area and the Government of Canada. The Board has responsibilities and powers over the “use, management and regulation of inland water in Nunavut and its objects are to provide for the conservation and utilization of waters in Nunavut in a manner that will provide the optimum benefits for the residents of Nunavut in particular and Canadians in general” (Nunavut Water Board 2014).

Once a completed license application is submitted, NWB gives public notice of the application. If a public hearing is required, the NWB will process the application once the land use planning process and environmental assessment are finished. Licenses issued following a public hearing must be approved by the Minister of Crown-Indigenous Relations and Northern Affairs. The full process can take considerable time depending on the scope and scale of the intended operation. Licenses also need to be periodically renewed by the NWB. Compliance and enforcement of licenses fall under the jurisdiction of the Department of Indigenous and Northern Affairs Canada. Activities are monitored by inspectors appointed by the Minister.

14.5 Summary and outlook

14.5.1 Key issues

The impacts of climate change on water security in the region reflect both the scientific understanding of climate and water related issues, as well as a recognition of the different water needs in the region for communities, resource industries and ecosystem health. Considerable progress has been made in terms of our scientific knowledge regarding the impacts of climate change on the availability and quality of water across the region, particularly given projected climate changes that will affect the seasonality and quantity of water that will be available. This will have direct impacts on community water supplies, and in combination with rapid population growth, may stress availability of water at different times of the year (specifically winter). Changing water supply levels will also have implications for resource developments such as mines and hydroelectric projects, and land use and access to traditional activities such as travel, hunting and fishing.

Water quality changes are less understood in the context of climate change, and water users face additional issues related to water supply infrastructure and new threats to the safety of water through increased microbial activity in water and holding tanks. Water quality research remains localized in the region, and is often dealt with on a short term project basis which limits our ability to interpret

longer term trends or detect emerging issues. Similarly, wastewater treatment in communities is subject to a number of climate-related constraints, and is an issue of concern for communities given capital resource and population or training capacity limitations for management (see Coral Harbour case study Box B).

14.5.2 Research needs

There is a pressing need for research to improve knowledge to support water decision making in the region. There are few on-going water research programs in the region and most deal with selected aspects of water systems. Integrated research focused on developing both broad conceptual frameworks to predict the impact of climate and permafrost change on water has been carried out in a limited way in some parts of the region, but considerable work is necessary to link this work to community, industry and broader environmental needs and decision making.

Additionally, there appears to be a need to develop capacity for communities and residents to contribute to recognizing water-related change and problems and to communicate this information amongst decision makers and other stakeholders, including researchers. While there are indications that these types of partnerships are emerging and will serve as opportunities to serve this set of needs, efforts of this type are new and there is considerable capacity building that needs to be done within all stakeholder groups.

Water security remains a key issue in the region. Faced with rapid climate change, water availability and quality are likely to change. These changes, together with a rapidly growing population, future expansion of the mining industry, as well as potential hydroelectric developments as a means of providing increased energy security, all require that the region develop increased capacity to identify and address emergent water-related issues. Opportunities for collaboration between residents, communities, governments, industry and researchers are evident and offer an important means of increasing water security through improved decision making and planning.

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Chapter 15 Living on Permafrost: Background and Case Studies for Adapting Community Infrastructure in a Changing Climate

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Key implications for decision makers

- Permafrost is warming in the region.
- Climate warming and maladapted infrastructure designs have direct impacts on the permafrost thermal behavior and stability. Permafrost degradation is commonly responsible for significant infrastructure damage and deterioration that are costly for communities and governments.
- In permafrost thaw sensitive communities climate warming will cause ground settling, which in turn will impact housing foundations and the structural integrity of houses resting on them. The need to repair and rebuild housing due to the effects of climate change will raise costs in the community.
- Collecting and transferring knowledge is the cornerstone of a well-planned risk assessment. Planners, decision-makers and construction professionals need to be well informed to better plan, build, manage and assess the efficiency and sustainability of infrastructure in permafrost environments.

Abstract

Permafrost thaw alters the stability of soils and consequently threatens the integrity and functioning of infrastructure and transportation networks that are of central importance to northern communities. Infrastructure in many of the IRIS 2 communities has already experienced extensive damage and costly repairs, as illustrated in selected case studies. Projected climate changes and maladapted infrastructure are likely to disrupt permafrost and the thermal stability of community lands, with significant implications for industrial and socio-economic development. Planning and managing sustainable infrastructure in areas with sensitive permafrost will require stakeholder participation in hazard assessment and cost-of-adaptation mapping to allocate resources in the most cost-effective manner. Regulatory frameworks and appropriate governance for infrastructure design and construction will be critical to ensuring safe and sustainable community development in the region.

15.1 Introduction

Defined by the International Permafrost Association as soil or rock that remains at or below 0°C for at least two consecutive years (Brown and Kupsch 1974), permafrost is a key component in the stability of the Nunavut landscape. In the context of the rapidly warming air and ground temperatures observed at the Arctic scale, permafrost is on the brink of substantial change (ACIA 2005, Rowland et al. 2010, SWIPA 2017). Consequently, as the foundation for infrastructure in IRIS 2 communities, permafrost and its sensitivity to both changing climate and anthropogenic disturbance represent a key vulnerability that is likely to generate significant impacts unless appropriate adaptation strategies are developed and implemented.

15.2 Permafrost and community infrastructure

Permafrost thawing directly alters the stability of soils supporting infrastructure and threatens the integrity and functioning of transportation networks, public administration, and housing that are of central importance to the sustainability and wellbeing of northern communities (Leblanc et al. 2015a, Prowse et al. 2009). Residential and municipal buildings support shelter and community services, while roads, runways and seaports ensure the access and connectivity within and between communities and to the global economy. Hence, permafrost thaw and instability has direct socio-economic, political and health implications for northern communities and regions.

The rapid temperature warming observed since the early 1990s has had demonstrated impacts on northern infrastructure (Fortier et al. 2011, Leblanc et al. 2015a, b). In the sporadic and discontinuous permafrost zones, notably in many Nunavik communities, permafrost related degradation impacts on buildings, roads and runways were observed, with most of them necessitating the development of new adaptation strategies for infrastructure design and management, construction techniques, and urban planning (Allard et al. 2012). In the Inuvialuit Settlement Region (ISR), major linear infrastructure such as the Dempster Highway which

connects several communities of the Mackenzie Delta region has required maintenance and repairs because of permafrost thaw settlement and ice-wedge degradation (Lamoureux et al. 2015). Permafrost instability is also a priority safety concern in the ISR because it threatens the integrity of buried and aboveground pipelines constructed for natural gas. Localized permafrost subsidence may potentially trigger pipeline failures and/or leakage.

Nunavut has also observed infrastructure impacts from permafrost degradation, although the region is entirely contained within the continuous permafrost zone. Indeed, the warming of the uppermost permafrost and the thickening of the active layer in Nunavut (Romanovsky et al. 2015, Smith et al. 2010; see Chapter 4) have already impacted major infrastructure such as the Iqaluit airport (see case study below, section 15.4.1; Leblanc et al. 2015a). Meanwhile, communities are seeking better knowledge of permafrost conditions as crucial baseline information to guide expansion plans and public or private development projects. In response to this knowledge need, the first pan-territorial adaptation workshop held in Yellowknife in 2013 (www.northernadaptation.ca) brought together front-line decision-makers and permafrost experts from Nunavut, Northwest Territories and Yukon to share knowledge on permafrost related issues and discuss adaptation actions and strategies. This chapter focuses on some representative case studies from the region that illustrate the nature of the impacts on community infrastructure and provides examples of how permafrost science can inform adaptation strategies and planning.

15.3 Permafrost stability and infrastructure

Residential, municipal and transportation infrastructure built on permafrost can be affected by thaw settlement and terrain disturbance (e.g., landslide or thaw slumps) related to slope processes and thermal erosion that can be triggered by extreme climate events (Kokelj and Jorgenson 2013). The amount of ground ice content at the interface of the permafrost table and the active layer can particularly influence both thaw settlement and more localized terrain disturbances such as landslide processes (Nelson et al. 2002).

When ground ice thaws, it causes the ground surface to settle and leads to a loss of soil bearing capacity, which varies spatially according to the distribution of the ice content. When permafrost underlying an infrastructure thaws, it settles and this is enhanced by the infrastructure itself that induces uneven thaw strain, causing damage to buildings such as cracks in walls and warped floors (Kneisel et al. 2008). In ice-rich ground, thaw may also change surface and sub-surface drainage and create muddy soils slides that are closely associated with active layer detachments (Figure 1). The spatial variability in volume and depth of ground ice and active layer thickness can vary the permafrost thaw sensitivity across community lands or individual properties, and therefore represent key knowledge gaps to fill prior to land use planning and infrastructure construction.

Infrastructure itself can also destabilize permafrost and exacerbate the impacts of climate change on ground stability. Indeed, many observations of infrastructure damage are directly associated with preparation of the site that supports the infrastructure foundation, or with maladapted construction designs and a poor knowledge of local permafrost conditions (Allard et al. 2012). A common mistake leading to infrastructure issues is the removal of the ground surface vegetation mat before the installation of the foundation material. Stripping the vegetation and topsoil, which acts as an insulating layer, changes the permafrost thermal balance. The choice of site preparation techniques is therefore the first crucial step in a construction project and involves both the local soil properties and the project design. Generally, less ground surface disturbance is better for permafrost stability. The timing of site preparation is also important to minimize any impacts on the permafrost thermal regime. For instance, it is highly recommended to excavate and install a gravel pad that will support a building foundation during fall, in advance of construction the following summer, to allow the disturbed soil and the gravel berm to freeze back during the intervening winter (Andersland and Ladanyi 2004).

Infrastructure may also be considered an additional disturbance source that potentially changes the permafrost thermal regime (L'Hérault et al. 2012). For instance, the



FIGURE 1. Retrogressive thaw slump within the community of Arctic Bay, Nunavut (2009). The slump was triggered by a ground disturbance, but has since stabilized (2017).

heat generated by a poorly designed building may be transferred to the soil through its foundation and hence contribute to permafrost warming and eventual thawing. The choice of the foundation type is crucial for building projects and must be adapted to permafrost properties in order to minimize the thermal impacts and other interactions between the infrastructure and the underlying permafrost (CSA Group 2014). It is not always possible to significantly limit the heat transfer from a building to the ground (e.g., a concrete slab floor on a gravel pad), however, and engineering solutions must be applied to preserve the thermal balance of the permafrost. Thermosyphons and conductive heat drains are examples of engineering solutions that are commonly used, depending on the infrastructure type, to keep the ground frozen and prevent thaw subsidence under the infrastructure.

Infrastructure may have indirect impacts on permafrost stability by altering drainage and snow drifting patterns. Indeed, water ponding and snow banks are two major local factors that contribute to permafrost thawing (Allard et al. 2012, Lamoureux et al. 2015). Snow cover thickness, for instance, is the main thermal factor influencing active layer thickness (Goodrich 1982, Nicholson and Grandberg 1973, Pomeroy et al. 1997). Snow accumulation insulates the ground surface and consequently decreases winter ground

cooling so it remains warmer. As a result, snow banks commonly contribute to deepening of the active layer, which ultimately leads to differential ground settlement and infrastructure damage. For this reason, the Government of Nunavut (2013) in their Homeowner's Guide to Permafrost in Nunavut advises against the use of skirts around the foundation of raised houses (see Box 1). The skirt is typically used by residents to reduce heat loss from the open space underneath the house by reducing airflow under the house and by accumulating snow banks around the house. This is, of course, contrary to the house design, which is built to dissipate any heat loss from under the building through open airflow. The snow banks that build up around the house as a result of the skirting promote permafrost warming and ground settlement, which may ultimately impact the foundations and the structural integrity of the building.

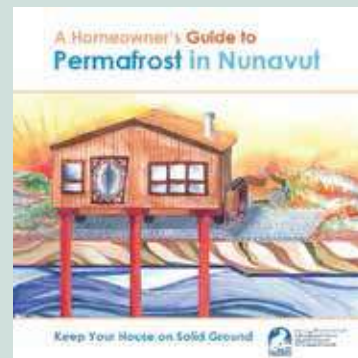
The thermal impact of snow banks is further enhanced by water ponding in depressions created by thaw subsidence (Figure 2). Water ponds absorb more energy from solar radiation, increasing the heat transferred into the ground, which is in turn greatly enhanced by percolation of water into the active layer. The increased amount of water in the active layer also induces a delay in the soil freeze-back in early winter due to the latent heat effect (the additional amount of energy required to transform water from its liquid to solid phase). This cascade of thermal consequences associated with snow banks may sometimes be mitigated by simple actions such as better management of snow clearing and piling in winter. Engineering solutions may also be applied locally when needed. For example, in the construction of road or runway embankments, the use of coarse materials allows convective flow-through of air,

BOX 1. A homeowner's guide to permafrost in Nunavut

The homeowner's Guide to Permafrost in Nunavut is an initiative of the Government of Nunavut's Climate Change Secretariat that was published in 2013. The guide is not conceived as a technical manual, but rather a public reference guide on permafrost concepts and a simple-to-use house management tool for homeowners. The guide explains what is permafrost, how permafrost can change based on local soil conditions, including water and ice content, and ground slope. Also discussed in the guide are the impacts of houses and their maintenance on local permafrost stability and the thermal effects of annual climate variations on ground temperatures. The guide also presents some basic questions for homeowners to help them evaluate the permafrost sensitivity under and around their houses. For example:

- Do your front steps appear crooked (front steps often move relative to your house because they are light compared to your house)?
- Is your roofline straight?
- Are your floors level?
- Do you have cracks in your drywall?
- Do your doors not close properly some seasons?

Also presented are good practices for property management in permafrost environments with respect to snow removal, wind effects, water drainage, water tank overflow, foundation skirting and heating oil tank. The Homeowner's Guide is available at the Government of Nunavut's Climate Change Centre (climatechangenunavut.ca). The Climate Change Centre also maintains a permafrost databank that holds geo-referenced information on permafrost across Nunavut.





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FIGURE 2. Example of a snow bank accumulation along a road embankment (left) that created thaw subsidence (right).

which counters the local thermal impact of snow accumulation (see detailed examples in Allard et al. (2012)).

Linear transportation infrastructure, such as roads and runways, may also impact drainage networks, resulting in modifications to soil moisture levels and natural channel patterns. In addition to creating standing water on the upslope side, linear infrastructure concentrates water flow in ditches, which ultimately cross the infrastructure through culverts or underground along seepage tracks that form in the active layer (McNamara et al. 1999). These surface and subsurface flows carry advective heat (as a function of the kinetic energy) that significantly contributes to locally ground warming. This phenomenon is commonly associated with transversal depressions in the infrastructure due to thaw settlement (Doré et al. 2006, Fortier et al. 2011) and is frequently observed where culverts cross roads and runways (Figure 3). The impact of flowing water and advective heat is not well documented, but recently has been attributed to changes in surface and subsurface permafrost drainage (de Grandpré et al. 2012, Lamoureux et al. 2015). The experimental site on the Yukon-Alaska Highway is an excellent example of diverse adaptive solutions, utilizing insulated culverts, different sized culverts, and variably spaced culverts, to reduce infrastructure damage related to snow accumulation, water ponding and water drainage (Lepage and Doré 2010).

Water flow at the permafrost surface and subsurface is affected as the precipitation regime and the air temperature change. In fact, changes in climate parameters such

as the solid/liquid precipitation ratio, wind intensity and direction, snow drift accumulation, and climate conditions during the spring melt period or fall freeze up have direct impacts on the permafrost hydrology (Woo et al. 2008). These hydrologic changes may trigger irregular permafrost degradation with significant drainage pattern modifications, enhancing thaw and amplifying the impacts on downstream infrastructure. In extreme cases, modifications of drainage patterns may trigger permafrost degradation processes such as landslides (active layer failures), gulying in ice wedge fields (Bonnaventure et al. 2013, Fortier et al. 2007) and rapid riverbank thermal erosion (Costar et al. 2003, Walker and Amborg 1963), all of which may severely damage infrastructure if they occur in a community. These events are often associated with extreme weather anomalies such as, a heat wave followed by an intense rain event (L'Héroult 2009)



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FIGURE 3. Example of transversal thaw settlement (near ATV) in a road created by water seepage. Note also water ponding that creates thaw settlement at the foot of the road embankment.

and may have significant implications for a community's operation and safety. The sudden peak discharge of the Duval River in Pangnirtung in 2008 is described in a case study below and provides a good example of a permafrost degradation process triggered by an extreme weather event (Carbonneau et al. 2012, Gosselin 2013).

15.4 Case studies

The following three case studies are meant to illustrate the various challenges of living on permafrost in a changing climate. Although focused on the IRIS 2 region, they have broad applicability across the Canadian North. In all cases they include infrastructure that was designed and built prior to recognition and full understanding of climate change and its associated impacts on permafrost. The Iqaluit airport is a good example of public infrastructure that was constructed without much knowledge of permafrost conditions and when permafrost was assumed to be permanent and stable (Figure 4).

The Pangnirtung case study was selected because of its challenging permafrost setting for infrastructure development and community expansion (Figure 4). Other IRIS 2 communities are facing similar challenges in expansion,



FIGURE 4. Map showing case study locations.

although the ground conditions and landscape settings may vary. Community hazard mapping has been undertaken for Clyde River, Arviat, Rankin Inlet, Hall Beach, Whale Cove and Cape Dorset in support of their adaptation action planning. More detailed information on these studies and plans can be found on the Arctic Adaptation Exchange website (arcticadaptationexchange.com).

At the heart of the third case study is an economic analysis of adaptation options to permafrost degradation for residential infrastructure. Through modeling, it examines the costs of adaptation options for housing foundations in different areas of permafrost thaw sensitivity in Arviat (Figure 4). It represents another step in mobilizing permafrost science for decision making in communities where building land may be restricted and hard choices need to be made in locating housing in permafrost sensitive areas.

15.4.1 Iqaluit airport: a major infrastructure impacted by permafrost disturbance

Initially built by the US Army during WWII, the Iqaluit airport runway was extended to its current length (2.7 km) at the end of the 1950s and became the largest airstrip in the Canadian Arctic (Eno 2003). The airport is a strategic transportation hub for the Eastern Canadian Arctic and has played a significant role in local and regional economic activities, public safety and national security. The airport site was chosen mainly because of its extended flat topography, associated with a raised delta and outwash complex that formed following the last glaciation. The wide variety of surface and subsurface sediments include glacial (till), glaciomarine and marine (delta, littoral and nearshore), glaciofluvial (esker, outwash plain), alluvial (floodplain terraces) and lacustrine deposits (Figure 5). Many of these deposits host very ice-rich permafrost and as a result of both climate warming and ground disturbance during construction and operation of the airport, the entire airport infrastructure has been affected by permafrost degradation (Figure 6). Given the strategic importance of this transportation infrastructure, the Canada-Nunavut Geoscience Office (C-NGO) along with Natural Resources Canada, Transport Canada and the Government of Nunavut

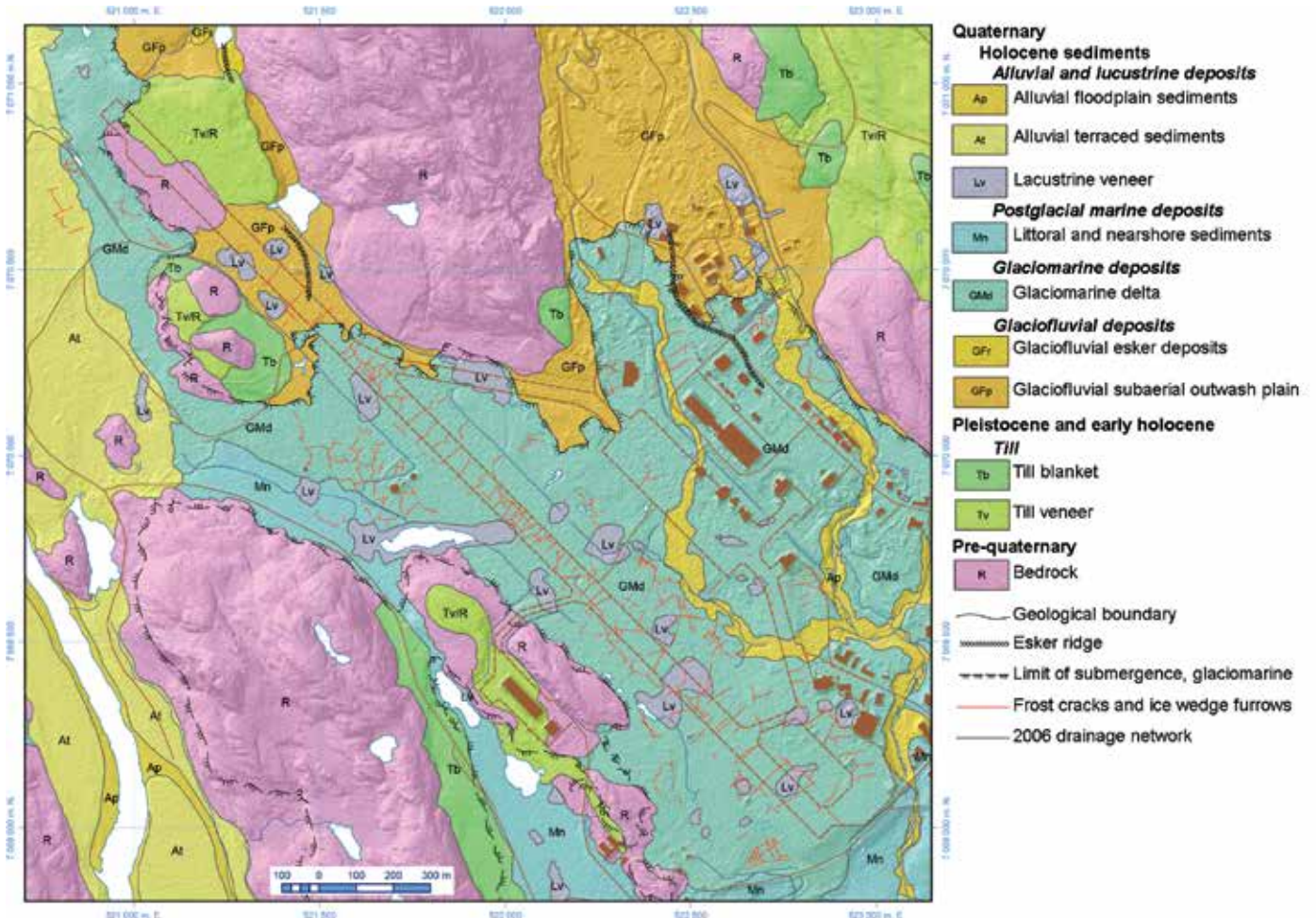


FIGURE 5. Updated surficial geology of the Iqaluit airport site. Modified from Mathon-Dufour and Allard (2015).



FIGURE 6. Linear depression (a), sinkhole in embankment shoulders (b) and differential settlement (c) caused by permafrost degradation at the Iqaluit airport. From Mathon-Dufour and Allard (2015).

partnered in a permafrost survey of the airport facility in 2010, led by CEN's team. The results directly informed rehabilitation and maintenance strategies, expansion plans for a terminal building and related facilities, and infrastructure design in accordance with expected climate changes.

The permafrost survey identified the original permafrost environment prior to airport construction as well as the ground modifications during construction and expansion phases, notably to the surface hydrology (Figure 7). The close correspondence between infrastructure deterioration issues, landscape setting and mapped permafrost conditions clearly indicate that the Iqaluit airport is affected by ice-rich permafrost degradation. For example, the study revealed that a large proportion of the airport infrastructure was built over a network of ice-wedge polygons; the thawing of these ice wedges beneath the pavement of the runway, taxiways and aprons resulted in linear depressions (Figures 6 and 7). Drilling confirmed the presence

of massive ground ice typical of ice wedges at these locations. In addition, the study also revealed that the original hydrological network of lakes and streams that had been partly drained and/or infilled during construction phases continues to impact the permafrost temperature regime. Both the high water content of the active layer and potentially heat-carrying subsurface water flow contribute to ground settlement. The drilling and the geophysical surveys also revealed the presence of ice-rich permafrost in fine-grained sediments just below the base of the active layer under parts of the airport infrastructure. Again, these areas are directly associated with sectors of the airport affected by differential settlement and instability (Figures 6 and 7).

Ground temperature monitoring under undisturbed terrain, paved surfaces and embankment shoulders highlights significant differences in their thermal regimes. For example, due to a lower albedo coefficient, the active layer under dark asphalt pavement thaws for a longer period (about 16 to 27

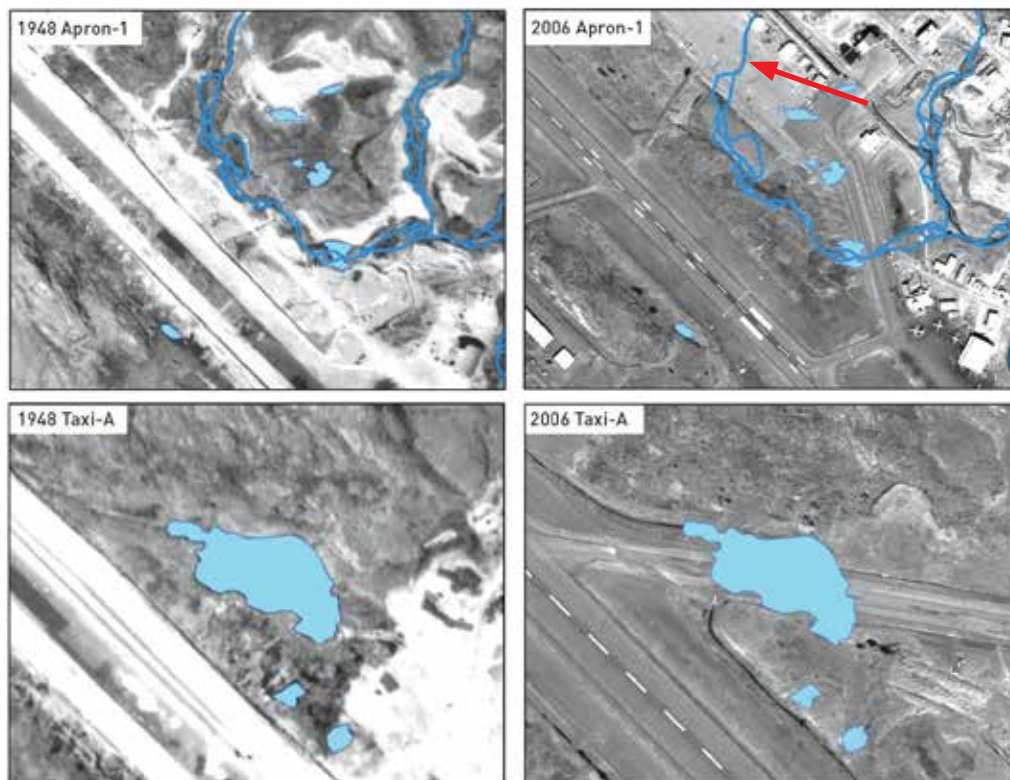


FIGURE 7. Original hydrological network of lakes and streams reworked during the construction of the airport with red arrow pointing to the location of Figure 6b. From Mathon-Dufour et al. (2015).

days longer) and extends to greater depth (about 1 to 1.5 m deeper) than in the natural terrain and under embankments, respectively. This warmer thermal profile likely favours subsurface water ponding, which in turn may contribute (through positive feedback) to increased permafrost thawing and ultimately to infrastructure damage and deterioration.

Results of this study have already informed engineering designs/solutions that are currently implemented for rehabilitation and expansion projects. Ongoing permafrost characterization and monitoring of ground temperatures, together with climate change projections, permit numerical simulations of future thermal regime, which

ultimately provide improved risk assessments and adaptation strategies.

15.4.2 Pangnirtung: Permafrost science in support of community development

Pangnirtung (population ~1500), like many communities in the IRIS 2 region, is experiencing rapid population growth and an infrastructure deficit (Figure 4). Suitable land for both housing and municipal buildings is a critical issue. Community expansion is constrained by its physical setting along the shoreline of Pangnirtung Fiord and backed by steep fiord sidewalls (Figure 8). Duval River fed by an



FIGURE 8. (a) View looking across the hamlet of Pangnirtung towards Pangnirtung Fiord. Photo credit: A.-S. Carbonneau. (b) Oblique simulated view of Pangnirtung community with steep sidewalls of Pangnirtung Fiord in background. From Carbonneau (2014).

upland drainage basin flows through the community and acts as the water source for the community reservoir.

Recent permafrost mapping of the community was triggered by a flash flood of the Duval River in June 2008. An extreme rainfall event in the snow-covered upland basin while the active layer was still frozen generated unusually high discharge for several hours in the Duval River. The impact of this flash flood in the community was striking. The riverbed and the underlying permafrost were vertically incised by roughly 10 m, while the combined action of thermal and mechanical erosion caused significant riverbank retreat. This destabilized the foundations of two bridges (an old one and a new one nearing completion), cutting off a sector of the community from many essential services, such as drinking water supply and sewage services, for several days (Figure 9). There were concerns during the event that the erosion might reach major infrastructure such as the reservoir. The costs associated with the state of emergency that ensued were assessed at CA\$8 million. The occurrence of this extreme event raised safety concerns for the community and questions about the sustainability of infrastructure built on or planned for similar terrain nearby.

In response, the Geological Survey of Canada and the CEN undertook a study of the permafrost conditions in Pangnirtung as part of the Nunavut Landscape Hazard Mapping Initiative,



FIGURE 9. Damage to bridge foundation in Pangnirtung resulting from the down cutting of the river bed by thermo-erosion.

led by the Canada-Nunavut Geoscience Office. One component of the study determined that such a major erosive event had not occurred on the lower Duval River in the past 800 years, despite some occasional high flood levels (Gosselin 2013). Without more information it is difficult to estimate how changing climate might affect the frequency of such extreme events in the future; however, the likelihood of reoccurrence increases with the projected changes in climate for the region including more snow precipitation, faster spring melts and more abundant rainfall (cross reference climate chapter).

The main focus of the Pangnirtung study revolved around permafrost conditions to determine suitability for land development. Over 20 boreholes were drilled in the community to establish the type, depth and ice content of surficial deposits. The results were summarized on a map that shows the distribution of surficial deposits (Figure 10; Carbonneau et al. 2012) and in a table that describes both the constraints for building on each deposit type, based on permafrost conditions, and recommendations on how to adapt construction and maintenance strategies to these conditions (Table 1). In summary, the most stable and low-sloping ground suitable for infrastructure consists of ice-poor, coarse gravel deposits of the ancient (Holocene) alluvial fan (Af on Figure 10) on either side of the Duval River. Much of this area is already developed, particularly to the west. Another suitable deposit for infrastructure construction is the blanket of coarse colluvium overlying fine marine sediments (Cb/Mn on Figure 10), although caution is advised because the frozen marine sediments contain ground ice, which may thaw if ground disturbance or climate warming induces deeper thaw of the active layer (see below). This surficial unit occurs to the southwest of the Duval River and is occupied by the airport and older residential development. The other surficial deposits above and to the northeast of the main townsite present moderate to severe constraints on construction, as they are poorly drained, steeply sloping or underlain by ice-rich permafrost with ice wedge polygons. Drilling and soil pits in this area revealed the presence of abundant ground ice within the upper few metres of the surface.

Space for future development in Pangnirtung is therefore severely limited by suitable building ground. Given that the

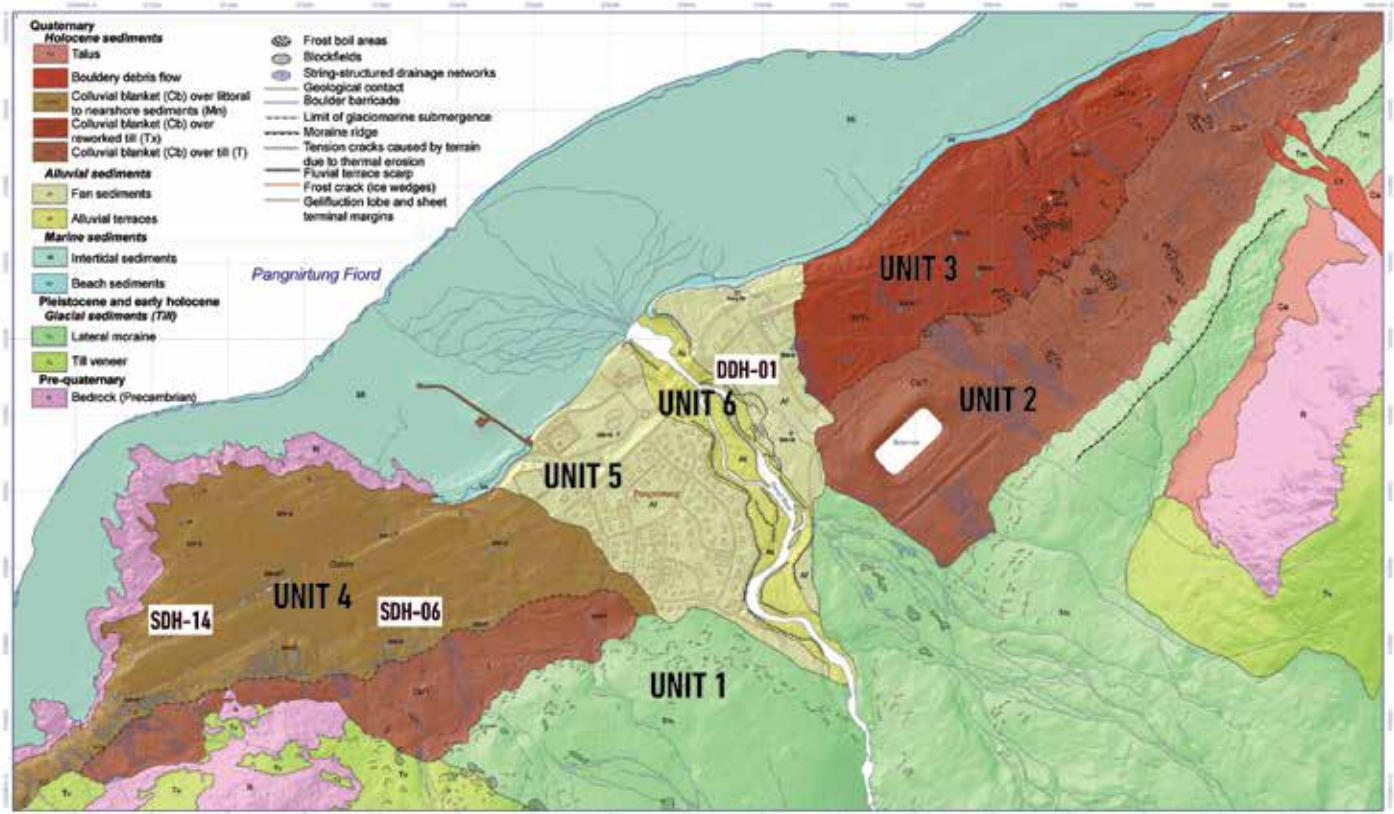


FIGURE 10. Pangnirtung surficial deposit map. Modified from Carbonneau et al. (2012). See Figure 11a and 13a for information corresponding to SDH-06 and DDH-1, respectively. See Figures 11b and 13b for information corresponding to SDH-14.

TABLE 1. Synthesis of type of soil and ice content and recommended actions to minimize permafrost-thawing issues in Pangnirtung.

Geological Unit	Type of surficial deposit	Active layer depth	Type of ground ice	Recommendations
4	Sand varying in thickness from 0.8 to 1.3 m underlain by silt	From 0.8 to 1.8 m	Horizontal lenses up to 80% of the total volume of the soil in the silt.	<ol style="list-style-type: none"> 1. Avoid the impacts on the thermal regime of the permafrost. 2. Piles driven into the underlying bedrock. 3. Surface drainage and culverts designed to avoid permafrost erosion
5	Sand, silt and boulders	2.6 m	Pore ice practically all contained in the voids between sand grains and between stone.	<ol style="list-style-type: none"> 1. No thaw sensitive permafrost.
6	Sand, silt and boulders	n.d.	Pore ice.	<ol style="list-style-type: none"> 1. Bank erosion amplifies with climate warming and the risk of fast spring melts and rains is due to increase. 2. This area is due for other uses than housing.
3	Colluvium up to 4 m deep. Underneath is a till made of silt, sand and boulders.	1.3 m	Ice lenses in the colluvium up to 80% of the total volume of the soil. Pore ice and ice wedges in the till.	<ol style="list-style-type: none"> 1. Avoid any heat transfer to the ground from the buildings. 2. Side slopes of pads and road embankments need to be gentle. 3. Avoid or minimize as much as possible drainage concentration.
2	Stony material (till) belonging to moraine ridges.	n.d.	n.d.	<ol style="list-style-type: none"> 1. Poor surface and active layer drainage. 2. Thawing in summer creates saturated conditions 3. This sector has no buildings and is likely not going to be developed
1	Stony material (till) with a fine-grained matrix	n.d.	n.d.	<ol style="list-style-type: none"> 1. Steep topography that makes access difficult. Any cuts will be unstable and will require a large amount of stabilization work. 2. Controlling overland flow and erosion will be very costly.

airport occupies a large area where future infrastructure could be developed and considering the need to extend the runway to accommodate larger planes for increased passenger/cargo use, the Government of Nunavut and the community are planning the relocation of the airport. In any future development of the airport site the nature of the surficial deposits and their associated permafrost conditions need to be evaluated in the context of changing land use and climate conditions. For example, ground subsidence is likely to occur if the active layer deepens such that it intersects the ice-rich marine sediments underlying the colluvium. This may result from disturbance or removal of the colluvium or changes in the ground thermal regime. The latter scenario is illustrated where the presence of the airport fence causes increased snow accumulation and hence increased ground insulation, resulting in a deeper active layer (Harris et al. 2009). Ground thermal monitoring of undisturbed natural terrain (thermal profile A, Figure 11A) and an area close to the fence (thermal profile B,

Figure 11B) demonstrates the effect of increased snow cover on the depth of the active layer and its penetration into the ice-rich, thaw sensitive marine deposits (Allard et al. 2015). As a direct consequence, depressions have formed along the fence, creating water ponding and causing the fence to lean (Figure 12). The fence movement is also a result of frost heave processes that are favoured by the increased water content of the active layer related to the locally thicker snow cover.

Although the monitoring of ground temperature over recent years (2009-2015) does not show a thickening trend of the active layer in Pangnirtung, it reveals that the main large amplitude variations of the ground temperature profiles occur during winter (dashed lines, Figure 13; Allard et al. 2015). Winter air temperature and snow cover thickness are important factors that contribute to the annual variation in active layer thickness (Harris 1981). The closer the freezing index (cumulative temperature values below 0°C) is to zero,

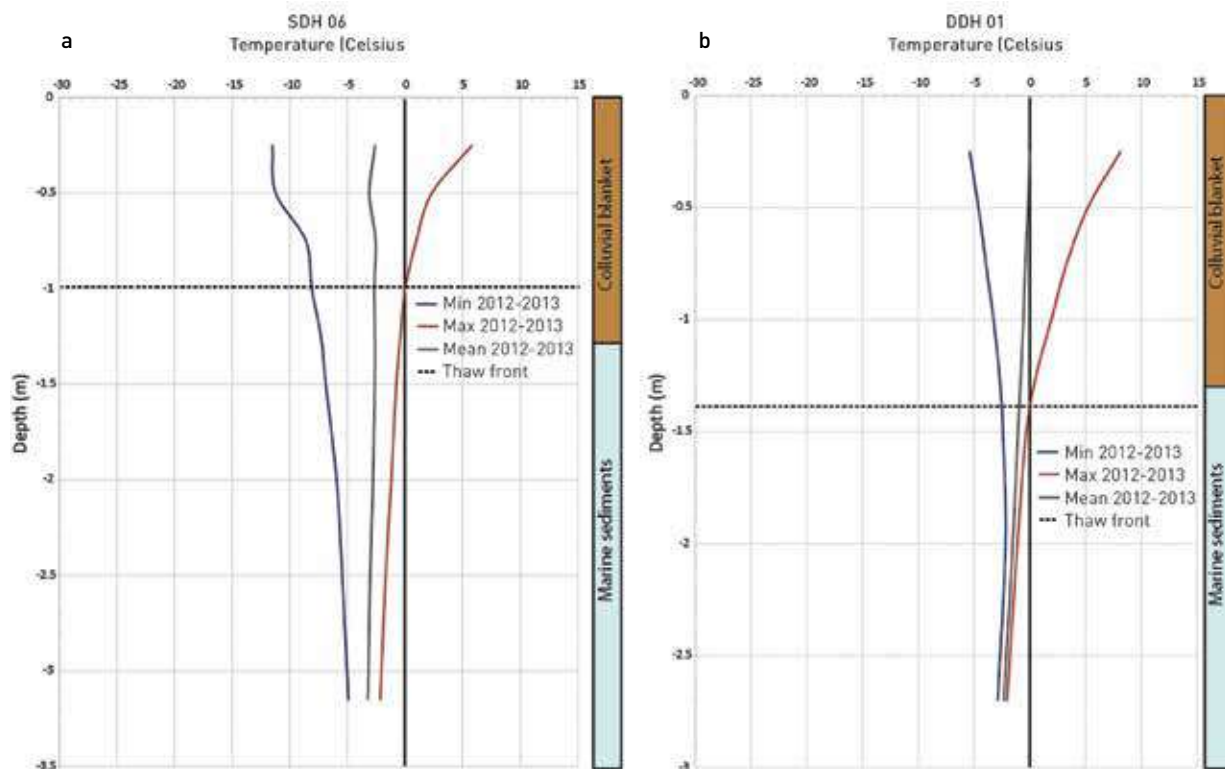


FIGURE 11. Vertical temperature profile for (a) an undisturbed natural terrain with 0.2 m snow cover and (b) for a locally disturbed terrain at the airport margins near a fence with a 1.4 m snow cover. Data from Allard et al. (2015).

the deeper the maximum active layer depth (Zhang et al. 1997). Climate projections for the region (see Chapter 2) indicate that winter conditions are expected to change significantly by 2050, including shorter freezing (15 to 31

days) and snow (14 to 28 days) seasons, increased snowfall amounts and snow cover depth and increased number of winter thaw events. Although model uncertainties make it difficult to precisely evaluate the cumulative impacts of

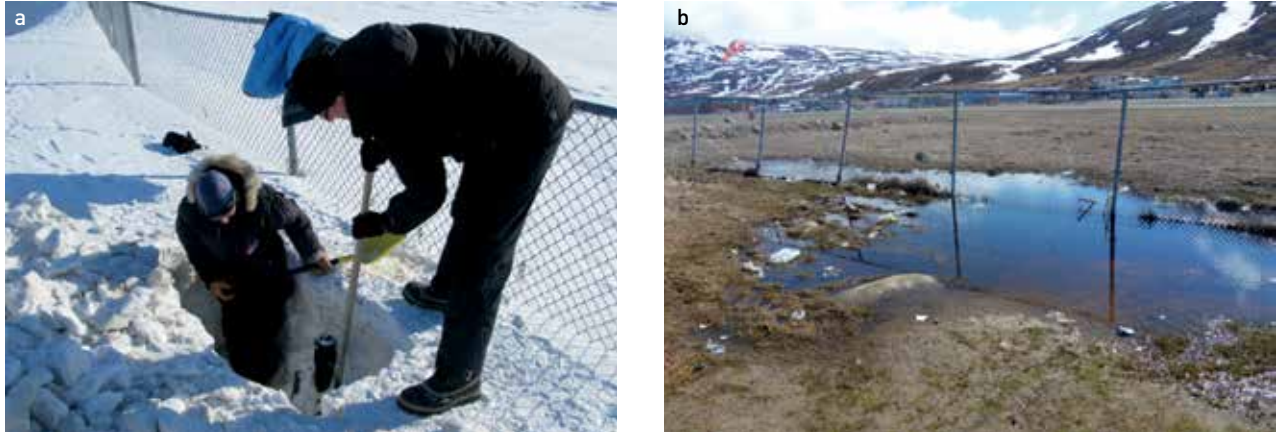


FIGURE 12. Monitoring of a thermistor cable in a borehole established adjacent to the airport fence. (a) The thick snow cover is due to the catching effect of the fence. (b) Thaw subsidence and water ponding causing fence instability.

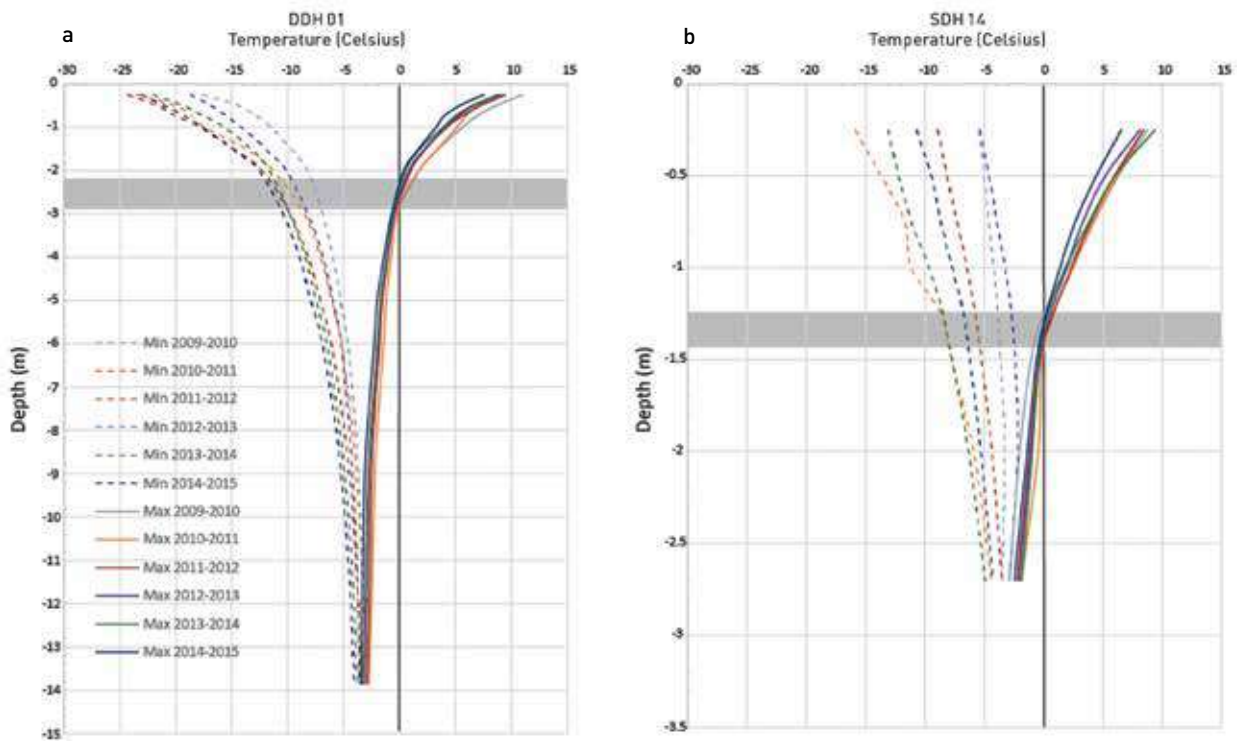


FIGURE 13. Maximum annual depth (m) of the active layer at Pangnirtung DDH01 (a) and SDH14 (b) thermistor cable station for the period from 2009 to 2015. Note that boreholes have different vertical depths. Data from Allard et al. (2015).

these projected climate changes and their effects on the ground thermal regime, permafrost will likely continue to warm and thaw at an even more rapid rate than currently observed. It is possible, however, to provide community planners and engineers with general guidance on permafrost responses and adaptation measures for future development in Pangnirtung (see Table 1).

15.4.3 Arviat: Costing adaptation strategies to permafrost change

Most communities in the IRIS 2 region have infrastructure deficits, particularly with respect to housing. Not only is there insufficient housing, but much of the housing stock is also inadequate and poorly maintained (Canadian Polar Commission, 2014). An important contributing factor to the housing crisis is permafrost thaw, which may compromise the structural integrity, resulting in costly maintenance, early replacement, and other housing issues such as mold and energy inefficiency. Permafrost thaw may be induced by poor site preparation or inadequate building design, construction or maintenance. It may also be a consequence of warming ground temperatures resulting from climate change, an emerging issue that has the potential to severely compound the housing crisis if not considered in land-use planning and housing design.

Community permafrost and hazard maps, such as the one described for Pangnirtung in the previous section, provide spatial information for community planners on the location of thaw sensitive permafrost and other landscape constraints that inform the selection of suitable building land. Although not all communities in the region have thaw sensitive permafrost, many do because of their coastal location and the presence of recently emerged fine-grained marine deposits that tend to be ice-rich with elevated salinity. As a result, planning constraint maps for such communities tend to portray the bulk of community lands as vulnerable for housing development. In this Arviat case study, economically feasible adaptation options for constructing residential housing in areas that are classified as sensitive to permafrost thaw are examined, thus monetizing the costs of adaptation across a range of vulnerable building lands and

demonstrating how informed adaptation choices can benefit communities and create more climate resilient housing.

Building climate resilient housing in a permafrost environment begins with the housing foundation. This case study specifically assesses the impact of permafrost warming on housing foundations, which include both the gravel pad and the actual foundation – for example, space frame or piles – that raises the base of the house above the ground to allow for air flow. While this is a fairly accepted building technique in the region, there are still questions around which foundation is the best choice, and whether it is worth the increased cost to spend more money on a more resilient pad or foundation. Modeling was done to determine what levels of housing costs might be encountered in Arviat given expected ground warming in two different permafrost sensitive areas. The analysis offers a rigorous, detailed way of understanding what the best housing foundation options are from a value-for-money perspective. The “Cost-of-Adaptation Mapping Project” was carried out in Arviat and Old Crow (Yukon), but only the Arviat results are presented here. It represents collaboration between community representatives, university researchers (Memorial University and Yukon College’s Yukon Research Centre), geotechnical engineers (TetraTech EBA) and economists (International Institute for Sustainable Development) and was supported by the Canadian Northern Economic Development Agency and the ArcticNet NCE.

15.4.3.1 Community setting

The hamlet of Arviat, the third largest Nunavut community (population 2318 in 2011), is located in the Kivalliq region, on the western shore of Hudson Bay (Figure 4). As in most communities in the IRIS 2 region, population growth in Arviat (12.5% in 2006-12) is exacerbating a housing shortage that is leading to rapid development. Foundation instability has been identified as a cause of housing envelope damage, even in relatively new homes, suggesting the need to integrate new knowledge of ground conditions into the planning process, engineering design, construction protocols, and maintenance approach. A preliminary surficial geology map of the Arviat region was

a first step in understanding local landscape hazards and thaw susceptible geological materials (Figure 14; Forbes et al. 2013). Deglacial landforms and sediments dominate the region; in particular eskers and moraines that have controlled landscape evolution during postglacial emergence (the land continues to rebound at ~ 9.3 mm per year; Simon

et al. 2014). The overall flatness of the emerged coastal plain together with a network of esker and moraine ridges and the low elevation (much of the community is below 4 m above sea level) have restricted drainage and created a mosaic of shallow ponds and wetlands that experience fluctuating water levels over the summer and fall (Figure 14).

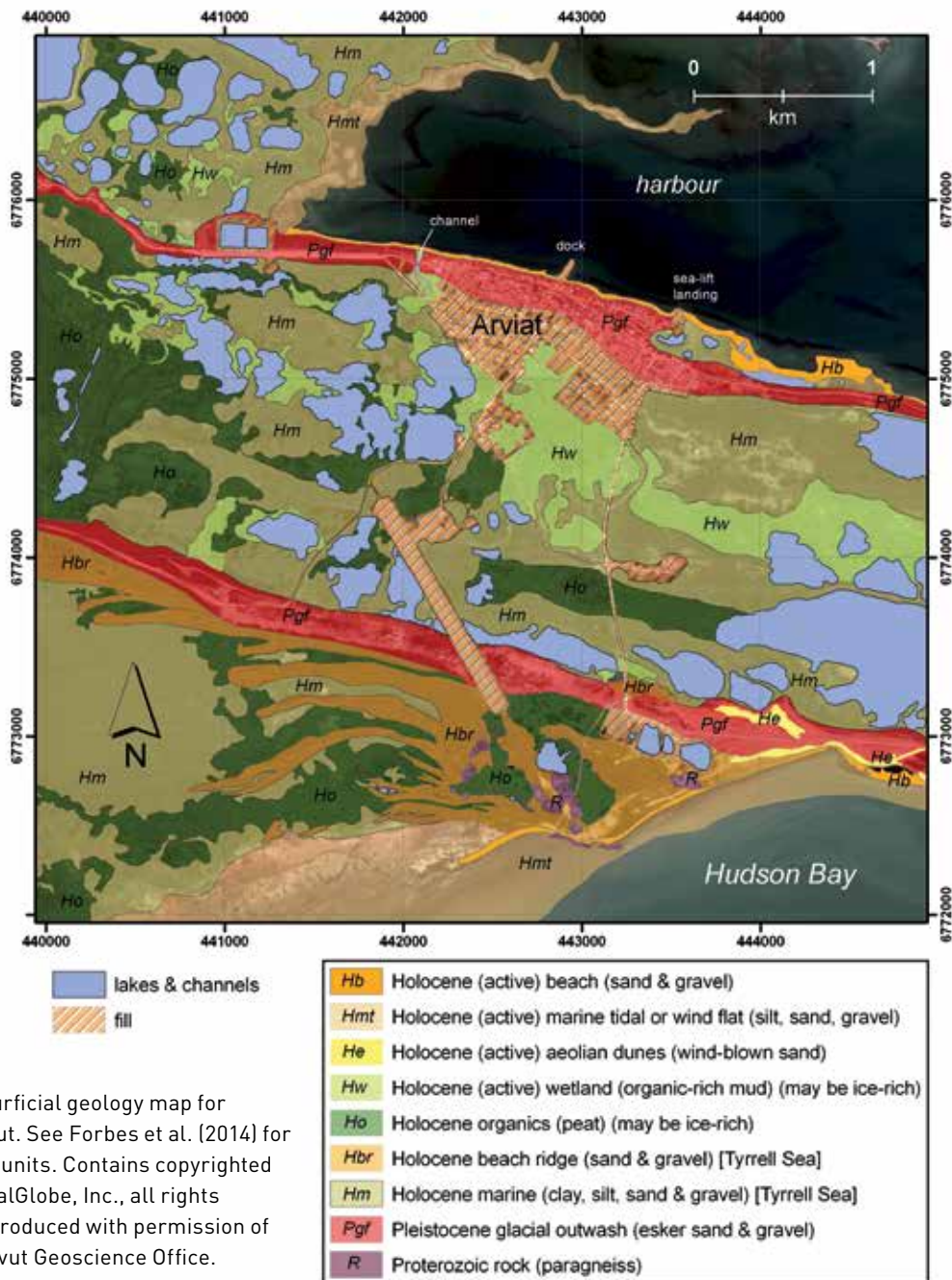


FIGURE 14. Surficial geology map for Arviat, Nunavut. See Forbes et al. (2014) for description of units. Contains copyrighted material DigitalGlobe, Inc., all rights reserved. Reproduced with permission of Canada-Nunavut Geoscience Office.



TREVOR BELL

FIGURE 15. Multiplex housing built on thin gravel fill over wetland in Arviat.



TREVOR BELL



JIM TAGALIK

FIGURE 16. (a) Thixotropic sandy silt and silty sand, known locally as aimayumaima, may lose its bearing capacity when saturated. (b) The aimayumaima sediment has failed, acting like “quicksand”, under the weight of heavy machinery.

The hamlet was initially established on the northern esker ridge but rapid growth has seen new housing and community infrastructure expand to the south and into poorly drained lowlands. As a result, the hamlet has had to fill in shallow ponds to create building lots and the new runway (Figure 15). The delineation of thaw-sensitive permafrost terrain is a particular concern for Arviat where bedrock is deep below the surface and pile foundations have proven problematic. A particularly challenging surficial sediment to build on in Arviat is locally called “aimayumaima” and sometimes referred to as quicksand (Figure 16a). It is predominantly sandy silt or silty sand and outcrops in local pits and river-cut banks. When saturated, the “aimayumaima” may lose its bearing capacity, which has proven problematic in the past (Figure 16b).

Arviat lies close to the southern limit of the continuous permafrost zone (Brown et al 2011), and permafrost is estimated to be 60 m thick under the community (Bell et al. 2016). Active layer depth in Arviat is highly variable, ranging from around 50 cm in undisturbed vegetated areas to over 200 cm in bare “aimayumaima”. As a region once inundated by the Tyrrell Sea (and more recently Hudson Bay), salinity in Arviat permafrost is of concern because porewater salinity in emerged marine deposits directly affects the bearing capacity of foundations in permafrost; saline sediments can bear less load than non-saline sediments. Porewater salinities in samples from across the community range up to 38.3 parts per thousand, according to Hivon and Segó (1993), with higher values at depth and closer to the Hudson Bay shore.

15.4.3.2 Economic modeling: Steps and inputs

Modeling was carried out to determine what levels of housing costs might be encountered in Arviat given expected climate change and permafrost thaw sensitivity. The modeling is Excel-based, and uses the Excel extension RiskAMP to perform Monte Carlo analysis. To describe the different permafrost conditions and their implications, the model uses two different representative zones. For each zone, five different scenarios are run to reflect construction of a single home using each of the five modeled foundation types (see below).

The model contains five linked modules: air temperature, ground thawing, ground settling, foundation effects, and costs. The modules, their data inputs and uncertainties and model thresholds are described in detail in Bell et al. (2016) and briefly outlined below. In summary, the model is driven by a projected temperature change, which causes ground warming and drives ground settling that leads to structural impacts on foundations: ultimately these determine housing construction and maintenance costs in the communities. The relationships that define each of these sequential steps were modeled based on community-level input and data, literature review, and the expert opinions of the project team.

The model assumes a projected air temperature increase consistent with the RCP8.5 scenario in the Intergovernmental Panel on Climate Change (IPCC) assessment reports (IPCC 2013). Based on historical trends, the planet is currently

following the RCP8.5 pathway, which was considered by the project team to be a realistic scenario over the model's time horizon (to 2075; Bell et al. 2016).

As the ground warms and permafrost thaws in response to climate change, the amount of ground settlement is intimately linked to the nature of geological materials and permafrost conditions. Two distinct zones were identified for Arviat: an “esker” zone that consists predominately of sand and gravel and which generally has much lower ice content and is less susceptible to thaw settlement; and a “mixed” zone comprising shallow-marine sediments, emergent tidal flats, and shallow wetlands that are composed predominantly of silty sand, which being finer grained than the esker materials are more likely to contain excess ice, and therefore be vulnerable to settling under warmer ground temperatures (Figure 17; Forbes et al. 2013).



FIGURE 17. Map of the distribution of permafrost thaw sensitive zones – Esker and Mixed – in Arviat, with the location of residential units that suffered various forms of foundation damage since 2010. Most of the damaged foundations are located in the more sensitive Mixed zone, in contrast to only two in the less sensitive Esker zone.

The ground settling anticipated in each zone was linked to how each of five modeled foundation types is expected to respond (Bell et al. 2016). These included space frame (Figure 18a and b) footings on permafrost (also known as Icelandic piles), deep piles in permafrost, thin granular fill and engineered fill. Different foundations will have differing degrees of resilience to settling. For example, gravel pads may prevent or offset ground settling to a certain extent (Figure 18b). In addition, some foundations such as space frames allow for adjustment as the ground settles,

while others such as piles rely on either bedrock or stable permafrost in order to perform well. Assessments of the resilience of foundations to settling are based on the expert opinion of the project team.

The final step in the modeling connects effects on foundations to costs. Different foundation impacts trigger different cost responses in the model. Foundations that experience ‘structural issues’ are expected to require a more moderate intervention than those exhibiting ‘compromised integrity,’ and the levels of costs that they trigger reflect this. A foundation with compromised integrity would no longer be inhabitable and therefore requires that the house be rebuilt in full, whereas a foundation with (less severe) structural issues would remain inhabitable but require some type of maintenance or repair. Therefore, in cases of ‘compromised integrity’ the cost of rebuilding both the foundation and the house is triggered, and in cases of ‘structural issues,’ the cost of the foundation is triggered, which from a cost perspective amounts to rebuilding the foundation but not the house that stands on it. Clearly the costs of different types of maintenance and repair interventions would vary considerably from this simple estimate.

Once the impacts on foundations have triggered costs across the entire time horizon of the model, they are summed up for each foundation type to provide a total ‘present value’ figure. This figure discounts future costs, providing a way to compare costs across foundations and over time in a way that weighs nearer term costs more heavily than future ones. The resulting discounted total cost figures can be interpreted as the time-weighted cost of different foundation choices, given their risk of possible future structural issues due to the effects of climate change and the need to either maintain/repair or rebuild them in response.

15.4.3.3 Economic modeling: Highlights and sensitivities

Detailed model results are reported in Bell et al. (2016) and only the modeled costs and implications are reported here. First and foremost, the results show that Arviat’s housing stock will be affected by climate change due to its



FIGURE 18. (a) Close-up view of space frame foundation sitting on gravel pad. (b) New multiplex housing under construction (2009) using space frame foundation resting on a gravel pad.

anticipated effect on permafrost and the ground settling that will occur as a result. As these impacts are increasingly experienced, housing foundations will require more maintenance and repair, and houses resting on those foundations will likely suffer structural effects. The need to repair and rebuild housing due to the effects of climate change will raise costs in the community.

Because some foundations are less resilient to climate change-driven ground settling and tend to require more repair and rebuilding, the total expected lifetime costs for housing built on those foundations will vary by foundation type (Figure 19). For example, gravel pads are one of the lowest-cost types of foundation at the time of construction. However, because they are so much less resilient to settling than other types, once their lifetime costs are considered houses built on them typically become the most expensive, up to \$250 000 over and above initial construction costs according to this economic analysis. In contrast, space frame foundations, which are more resilient to the effects of climate change, are far less costly over their lifetimes (only \$11 000 more) because they tend to require so much less repair and replacement. They are the most cost-effective of the five foundation types evaluated.

The cost difference between space frames and the cheapest alternative option is the cost of adapting to the impacts of climate change on housing. It is approximately \$15 000 per house in Arviat. This money is well spent, since it helps to avoid the larger future costs that using other types of foundations would lead to.

There is a difference in expected lifetime costs of housing by permafrost thaw sensitivity zone in Arviat, which is also calculated by foundation type in Figure 20. Costs are higher across all foundation types for the more sensitive permafrost zone, reflecting the higher modeled ground settlement rates. Regardless of the degree of settling expected, however, space frames are found to be the most cost-effective option in both zones.

Sensitivity analyses of model results showed that there is little effect on cost outcomes of either a more moderate temperature increase projection (RCP4.5) or an invariant

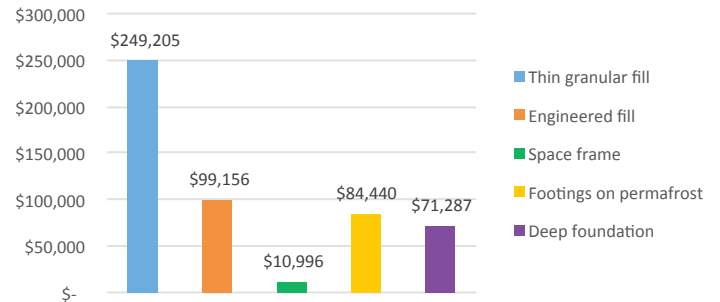


FIGURE 19. Expected lifetime repair/maintenance costs per house in present value terms over the model's 50-year time horizon for the five foundation types, *over and above* the initial cost of construction. In other words this is the estimated cost of the expected impacts of climate change on housing foundations. From Bell et al. (2016).

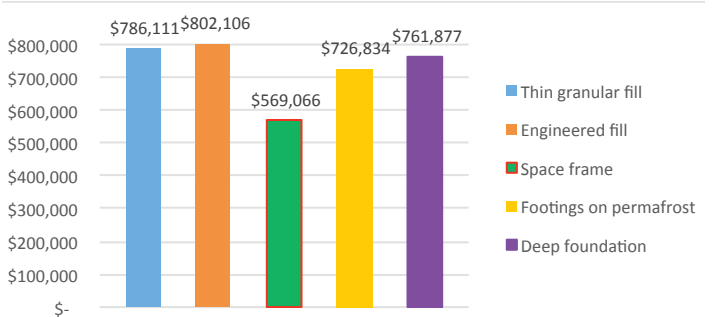
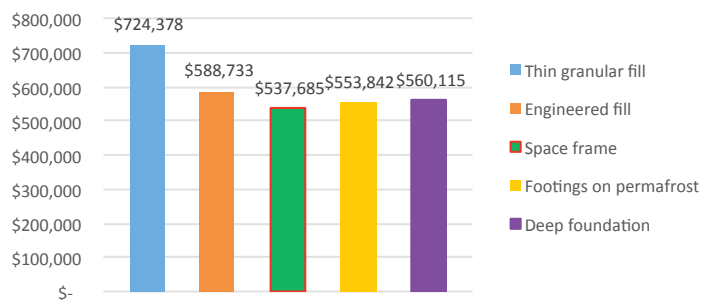


FIGURE 20. Comparison of the total expected lifetime costs for housing in present value terms for each of the five foundation types over the model's 50-year time horizon for the Esker (top) and Mixed (bottom) permafrost thaw sensitive zones in Arviat. These costs reflect the original cost of constructing the home on the given type of foundation, as well as any future costs stemming from repairs or from the need to rebuild, arising from structural damage due to permafrost thaw and ground settlement. From Bell et al. (2016).

foundation maintenance/repair cost regime. This is primarily due to the fact that: 1) costs that are further off in the future are discounted more when projected temperature differences are expected to be greater; and 2) because the primary driver of cost outcomes is replacement costs, rather than maintenance or repair costs.

The Arviat case study identified cost-effective adaptation options that allow for the construction of sustainable housing in areas with sensitive permafrost. The analysis revealed that it is important to pay attention to the type of foundation to be used for residential development, as there are considerable performance differences. Space frames prove to be the best option for Arviat, even though their initial cost is comparatively high. The analysis also showed that it can pay off, quite literally, to think long term. While many communities cope with a housing crisis that makes long term planning difficult, calculating immediate or short term costs against long term costs and savings is crucial for sustainable infrastructure development.

This exploratory cost-benefit study showed the opportunities for identifying economically feasible adaptation options for northern communities. While conditions, needs, and preferences may vary greatly from community to community, some of the lessons learned may be applicable across the IRIS 2 region. Communities are encouraged to engage in cost-of-adaptation mapping exercises in order to allocate sparse resources in the best possible manner.

15.5 *Atuliqtuq*: Climate change action and adaptation in Nunavut

In 2006 the communities of Clyde River and Hall Beach (Figure 4) were involved in a climate change adaptation planning process that involved community members, scientists and professional planners. The outcomes of this planning process led to several initiatives including:

- the establishment of the Nunavut Climate Change Partnership (climatechangenunavut.ca);
- the preparation of a planning workbook for use by other Nunavut communities;

- the production of new scientific information on sea-level change, permafrost landscape hazards and freshwater supply, and;
- the creation of tools to collect, publish, share and communicate knowledge about climate change adaptation.

These first initiatives were also introduced as community engagement activities held in Arviat and Cape Dorset in 2014 (Figure 4), bringing together stakeholders in workshops to gather and share information on local permafrost challenges and changes. These activities were part of an initiative by the Government of Nunavut that aimed at mapping the suitability of land for future development in a total of seven Nunavut communities. These activities engaged community members, community planners and land administrators, local businesses, the housing sectors, Elders and youth. The project partners in support of these activities included Université Laval, Memorial University, Yukon College and 3V Geomatics.

The community engagement workshops and activities were based on discussions on the suitability of future development areas and the rationale for choosing one area over another within the communities (for example, areas that would be challenging engineering-wise, too close to sewage treatment areas, too costly to service, etc.). Efficient foundation types and suitable building designs that take account of local climate characteristics were popular topics. Some knowledge transfer and exchange activities also took place during these workshops.

15.6 Conclusions

Infrastructure vulnerability to climate change is a priority concern in the IRIS 2 region, as it is in other IRIS regions (Allard and Lemay 2012, Stern and Gaden 2015). With the exception of bedrock, frozen ground can no longer be considered a permanently stable foundation for infrastructure in the region. Communities are already facing the double challenge of adapting their existing infrastructure to changing permafrost conditions, while planning for expansion on suitable building land. Many of the documented infrastructure issues are attributed to the observed ground warming over the past several decades and complicated by the

infrastructure design itself. Projected climate changes will potentially increase the vulnerability of IRIS 2 infrastructure unless appropriate adaptation actions are implemented.

Several cases of thawing permafrost-related damage have been linked to maladapted designs that would have benefited from better accommodation of environmental conditions. An enhanced coordination at all levels and among all stakeholders is necessary to achieve suitable infrastructure designs and strategic adaptation plans. The current situation where maladapted infrastructure has contributed to permafrost degradation partly results from the absence of regulatory frameworks, poor knowledge of local permafrost conditions, and appropriate governance structures for construction in the IRIS 2 region. Publications such as the Nunavut homeowner's guide (Box 1) show that regional governments have already started to promote best practices for construction and maintenance of housing. The recently formed panel of experts with a mandate to formulate construction and engineering standards for Arctic regions represents important progress towards climate-adapted building codes for the region (e.g., CSA Group 2014).

Given the uncertainties in climate projections it will be critical to monitor infrastructure performance, design and adaptation practices in a warming permafrost environment. Without baseline information and knowledge of local permafrost risks, informed decisions cannot be made, which ultimately may lead to significant downstream costs for local and regional governments. Cost-benefit analyses such as described for housing foundations in Arviat in this chapter must also be used to assist decision-makers in choosing appropriate cost-effective mitigation solutions.

This chapter focused on the effects of permafrost degradation on community infrastructure, but it is important to emphasize that other landscape- and climate-related hazards may expose communities to risk (e.g., coastal flooding, Chapter 8; diminishing sea ice, Chapter 11). Where possible, it is recommended that communities conduct integrated hazard assessments (meaning the consideration of multiple hazards in addition to permafrost alone) as a means to ensure safe and sustainable community development in a changing Arctic.

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Chapter 16 Climate Change Impacts on Managed Wildlife

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Key implications for decision makers

- Wildlife is culturally important to Nunavummiut and represents a critical source of country food. It is central to food security.
- Responsibility for management of wildlife is shared by territorial, federal and local agencies. Wildlife is thus co-managed.
- Climate change has broad-sweeping effects on wildlife including changes to timing of biological events (phenology), distribution, demography, food web and habitat.
- Despite potentially increasing cumulative impacts, industry can contribute in meaningful ways to management of wildlife by investing in baseline monitoring and research.

Abstract

Wildlife and hunting are culturally entrenched in the “values, world-view, language, social organization, knowledge, life skills, perceptions, and expectations” associated with *Inuit Qaujimaqatuqangit*. Wildlife species are important to Inuit as they form the basis of the traditional food system that remain prevalent in contemporary Inuit diets. In Nunavut, the responsibility for management of wildlife is shared among the Government of Nunavut, the Government of Canada, the Nunavut Wildlife Management Board (NWMB) and the Designated Inuit Organizations (Nunavut Tunngavik Incorporated, Regional Wildlife Organizations, and Hunters and Trappers Organizations). The Nunavut Land Claims Act (NLCA) defines the wildlife management system, objectives, and principles of conservation. Studying the impacts of climate change on wildlife is difficult and effects are broad-sweeping, ranging from changes in phenology resulting in trophic mismatch, shifting species distributions including invasive species, habitat loss in terrestrial and marine (including ice) ecosystems, and changes to the Arctic food web. Economic development is predicted to increase, with potential cumulative impacts, but industry can play an important role in monitoring and research.

16.1 Introduction

16.1.1 Importance of wildlife to Nunavummiut

16.1.1.1 Culture

Wildlife and hunting are culturally entrenched in the “values, world-view, language, social organization, knowledge, life skills, perceptions, and expectations” associated with *Inuit Qaujimaqatugangit* (IQ). Of the 13 principles that comprise IQ, five explicitly relate to hunting and/or stewardship of wildlife. The principle of “Surattittailimaniq” indicates that one must hunt only what is necessary and avoid waste; “Ilijaaqaqtailiniq” requires that harvesting must avoid cruelty to animals. Similarly, “Sirliqsaqattittailiniq” requires that harvesters avoid causing unnecessary harm to wildlife. The principle of “Akiraqtuutijariaqanginni” explicitly recognises that “the animals and land cannot be owned”, and “Nirjutiit Pijjutigillugit Ikpigusuttiarniq” obliges harvesters and others to treat all wildlife with respect.

16.1.1.2 Country food and food security

Wildlife species are important to Inuit as they form the basis of the traditional food system that remains prevalent in contemporary Inuit diets. A traditional food system includes all processes involved in feeding a population from local natural resources that are culturally accepted (Kuhnlein and Receveur 1996), and includes all aspects of hunting, harvesting, preparing, sharing, and consuming country food.

Country food is accessed locally from the natural environment, and is obtained from both terrestrial and aquatic environments. Country foods include a variety of locally obtained non-domesticated wildlife/flora and fauna such as caribou, seal, fish, mollusks, and berries. Consumption of country food varies seasonally as well as at the individual, household, and community level. Country food has excellent nutritional value, plays a critical role in Inuit culture, and contributes to strong, sustainable, self-reliant communities (Nunavut Food Security Coalition 2014). For many indigenous peoples, the traditional diet is not only a

vital source of nourishment, but is also an integral part of emotional, spiritual, and cultural well-being.

Consumption of country food is closely tied to food security amongst Inuit populations. Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life. The 2007-2008 Inuit Health Survey reported that nearly 70 % of Inuit households in Nunavut were food insecure (Rosol et al. 2011). In response to this startling statistic, the Nunavut Food Security Coalition was established to develop a long-term, ongoing, inclusive, and sustainable approach to food security in the territory. See chapter 13 for more information on food security.

The Coalition has outlined four components of food security: availability (enough wildlife on the land or groceries in the store), accessibility (adequate money for hunting equipment or store-bought food, and the ability to obtain it), quality (healthy food that is culturally valued), and use (knowledge about how to obtain, store, prepare, and consume food). Wildlife plays an important role in each of these four components. For example, in 2015, the decline of the Baffin Island caribou herd led to a nine-month moratorium that severely impacted caribou *availability*. In winter 2010/2011, freeze-thaw cycles in Iqaluit caused vegetation to become locked into the ice, leading caribou to forage further inland, increasing travel distances for hunters and therefore impacting *accessibility*. Microbial risks in caribou, such as *Brucella*, *Giardia*, and *Toxoplasma*, can impact the health of the animal, influencing *quality*. And decrease in the intergenerational transfer of traditional knowledge, such as how to hunt, butcher, and prepare caribou, affects negatively its use. Similar narratives can be applied for other wildlife species.

Achieving food security must be done in a manner consistent with Inuit Societal Values, principles of conservation and sustainability, and the rights of Inuit as enshrined in the Nunavut Land Claims Agreement (NLCA) (Nunavut Food Security Coalition 2014). The Coalition aims to seek a balance between the needs of Nunavummiut and the

principles of wildlife conservation (Nunavut Food Security Coalition 2014).

16.1.1.3 Biodiversity

The United Nations Convention on Biological Diversity defines biodiversity as “the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems, as well as the ecological complexes, of which they are part; this includes diversity within species, between species, and of ecosystems”.

In addition to its intrinsic worth (CAFF 2013a), Arctic biodiversity provides innumerable services and values to people. Arctic habitats are home to species with remarkable adaptations to survive in extreme cold and highly variable climatic conditions. Millions of migratory birds breed in the Arctic and then fly to every continent on Earth, contributing to global biodiversity and ecological health. More than a tenth of the world’s fish catches by weight come from Arctic and sub-Arctic seas.

Climate change is expected to result in shifts in biodiversity as well as in the ranges of animal and plant species important to northern people in the Eastern Canadian Arctic (Tews et al. 2007, White et al. 2007, Eberle et al. 2009).

16.1.1.4 Ecosystem Services

The Millennium Ecosystem Assessment advocated that humans gained tangible services from ecosystems that were derived without cost, and could be characterized in terms of economic benefit (Millennium Ecosystem Assessment 2005). The report further categorised “Ecosystem Services” as supporting services necessary for the production of all other ecosystem services, provisioning services for any and all natural products (e.g., food, clean water, raw materials, etc.) obtained from ecosystems, benefits derived from regulatory statutes associated with environmental mitigation (carbon sequestration, waste disposal, pest control) and cultural services or non-material benefits that people acquire from functioning ecosystems (e.g., spiritual enrichment, recreation, and aesthetic experiences).

Within the context of provisioning, wildlife species most often consumed by Inuit in Nunavut include Arctic char (*Salvelinus alpinus*), caribou, and ringed seal (*Pusa hispida*). Arctic char and caribou are traditionally consumed in every community across Nunavut. Ringed seal are the most abundant sea mammal, and are harvested in nearly every community except for land-locked Baker Lake. Other species are more geographically targeted; for example, the narwhal (*Monodon monoceros*) is a very valuable food source for communities in the Qikiqtaaluk Region. Although muskoxen (*Ovibos moschatus*) are found throughout the Kivalliq, Kitikmeot and Qikiqtaaluk Regions, they are more commonly hunted in the Kitikmeot and Kivalliq.

16.1.2 Wildlife management framework

In Nunavut, the responsibility for management of wildlife is shared (co-management) among the Government of Nunavut, the Government of Canada, the Nunavut Wildlife Management Board (NWMB) and the Designated Inuit Organizations (Nunavut Tunngavik Incorporated, Regional Wildlife Organizations, and Hunters and Trappers Organizations) (Article 5, NLCA).

16.1.2.1 Government of Nunavut

The Government of Nunavut (GN) is the authority for all terrestrial mammals (including polar bear (*Ursus maritimus*) and birds of prey. The Minister of Environment retains the ultimate authority over terrestrial wildlife in Nunavut as per the NLCA. The department conducts research, collects IQ, and makes recommendations to the NWMB. Conservation Officers enforce the Wildlife Act and regulations. The Government of Nunavut, Department of Environment (GNDoE) Wildlife Management Division has legislated responsibility for the management of terrestrial wildlife in Nunavut. The department is also responsible for fulfilling obligations outlined in national (e.g., Species at Risk Act) and international legislation, treaties and agreements (e.g., Migratory Bird Treaty Act). The Wildlife Management Division uses IQ and scientific information for decision making in wildlife management and land-use activities including the development of



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management plans; the GNDoe actively manages barren-ground caribou (*Rangifer tarandus groenlandicus*), grizzly bear (*Ursus arctos* ssp.), muskox, peary caribou (*Rangifer tarandus pearyi*) and polar bear. In addition, the Wildlife Division oversees and enforces regulatory compliance as outlined in the Wildlife Act. Activities involving the development of industries associated with fisheries and sealing including implementation of the Nunavut Fisheries Strategy are administered and regulated by the Fisheries and Sealing Division. The division promotes sustainable harvest of resources for food and fur, and represents the interests of the territory federally and internationally.

16.1.2.2 Nunavut Wildlife Management Board

The NWMB is the main instrument of wildlife management and the regulator of access to wildlife in the Nunavut Settlement Area (Article 5, NLCA). NWMB decisions are subject to the approval of the relevant Minister. The Nunavut Settlement Area includes most of the terrestrial areas of Nunavut, the marine areas of the Arctic Archipelago, Hudson Strait, Foxe Basin and northern Hudson Bay, and the marine areas out to the 12-mile limit. Primary wildlife management responsibilities of the NWMB are: research, harvest studies, setting total

allowable harvest (TAH), assessing basic needs levels, allocation, and setting non-quota limitations. The Board also approves plans for wildlife management and protection of wildlife (e.g., species-at-risk) and wildlife habitat.

16.1.2.3 *Department of Fisheries and Oceans*

Fisheries and Oceans (DFO) is a federal government agency that is “responsible for developing and implementing policies and programs in support of Canada’s economic, ecological and scientific interests in oceans and inland waters” (including marine mammals other than the polar bear). DFO delivers its mandate under the authority of the Fisheries Act, part of which is conservation (via the science branch of DFO) and sustainable use (in cooperation with the enforcement branch) of Canada’s fisheries resources. DFO mainly concentrates its efforts on conservation and harvests of salt water fisheries on the Atlantic, Pacific and Arctic coasts; formal agreements with provinces and territories ensure conservation and protection of inland freshwater fisheries.

16.1.2.4 *Environment and Climate Change Canada (Canadian Wildlife Service)*

In Nunavut, Environment and Climate Change Canada is responsible for protection of migratory birds through implementation of the Migratory Birds Convention Act, the Migratory Birds Regulations and the Migratory Birds Sanctuary Regulations. Implementation is achieved through setting of daily and possession bag limits, fines, prohibitions and hunting methods (including equipment), retrieval of harvested birds immediately, as well as restrictions on the use of bait and description of hunting zones. Non-resident hunters require permission from the Regional Inuit Association to hunt on Inuit Owned Lands. Environment Canada stipulates that non-toxic shot must be used to hunt migratory game birds and upland game birds.

16.1.2.5 *Parks Canada*

Parks Canada is responsible for protection of nationally significant natural landscapes, whilst ensuring that ecological

and commemorative integrity of national parks is maintained for current and future generations. The agency is the authority for all wildlife within park boundaries, and uses ecological integrity as underlying philosophy for management of wildlife. Ecological integrity is defined as “a condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biological communities, rates of change and supporting processes.”

16.1.2.6 *Regional Wildlife Organizations*

The role of Regional Wildlife Organizations (RWO) in Nunavut is defined in 5.7.6 of the NLCA. These roles include, but are not limited to, regulating the activities of Hunter and Trappers Organizations (HTO) including allocation of TAH among communities, and distributing accumulated harvest credits as required to cover accidental, defence, or illegal kills. The RWO may also return credits annually to augment a community’s harvest. Credits may not be transferred among communities that share any given wildlife population without the written consent of the community that accumulated the credit.

16.1.2.7 *Community based Hunter and Trappers Organizations*

The role Hunter and Trappers Organizations (HTOs) is defined in sections 5.7.2 and 5.7.3 of the NLCA. These roles include, but are not limited to, regulating the harvesting activities of their members, which includes all beneficiaries within the community. This includes allocation of tags in species with TAH, and setting of harvest seasons. As per the NLCA, the HTO may develop rules for non-quota limitations.

16.1.2.8 *Nunavut Tunngavik Incorporated*

Inuit have exchanged Aboriginal title of traditional land in the NSA for the rights and benefits established under the NLCA signed in 1993; NTI safeguards and promotes the agreement on behalf of Inuit beneficiaries. Within the

context of wildlife management, NTI coordinates and manages Inuit responsibilities for wildlife and works with federal and territorial governments to ensure that their obligations are met.

16.2 Climate effects on wildlife

Studying the impact of climate change on wildlife is difficult (Berteaux et al. 2006). Physical systems such as the permafrost or the oceans should respond to temperature increases in a predictable manner, following well-known physical laws. This is not the case for animals, especially homeothermic animals as they can maintain homeostasis within their body independently from environmental conditions over a wide range of temperature (Gilg et al. 2012).

16.2.1 General effects of climate change

16.2.1.1 Phenology and the match/mismatch hypothesis

Phenology can be defined as the timing of plant and animal seasonal activities (e.g., bird migration, plant flowering, hibernation), which are generally related to seasonal climatic variations. Across all trophic levels, organisms have evolved to match their phenology with seasonal environmental conditions such that fitness is maximized; for example, insectivorous birds match the timing of maximum food requirement of their young with maximum arthropod availability (Visser and Rosenheim 1998, Visser et al. 1998). The match/mismatch hypothesis assumes that if the phenology of a consumer matches the phenology of its food, fitness of the consumer is maximized (Durant et al. 2007). Changes in climate influence the phenology of organisms at lower trophic levels more strongly than organisms at higher trophic levels, potentially creating a mismatch, which can lead to reduced overall productivity and ultimately population declines (Both et al. 2009, Miller-Rushing et al. 2010).

In the Arctic, a match between the phenology of consumers and their food is even more important than at southern latitudes because the growing season is short and seasonal transitions are rapid (Berteaux et al. 2004). Temperatures

in the Arctic are rising at almost twice the rate of the rest of the planet (Trenberth et al. 2007), which is advancing spring snow melt and vegetation green-up in tundra ecosystems, creating a high potential for phenological mismatch between a variety of wildlife species and their food in Nunavut and other Arctic regions. This phenomenon is amplified in long-distance migrants because their arrival time in the Arctic may not advance quickly enough if warming along their southern migratory routes is slower than on their northern breeding ground (Both et al. 2009). Examples of mismatch have been documented in the Arctic tundra. High spring temperatures on Bylot Island, NU, creates a mismatch between hatching date of Greater snow geese (*Chen caerulescens atlanticus*) and the peak in plant nutritive quality, which reduces gosling size and mass at fledging (Doiron et al. 2015). Similarly, a reduced synchrony between the timing of hatching and the peak in insect availability, which is largely driven by temperature (Bolduc et al. 2013), lead to a reduction of chick growth in shorebirds, also on Bylot Island (McKinnon et al. 2012). In West Greenland, an advancement in the growing season has created a mismatch between caribou calving and vegetation green-up increasing offspring mortality rates and decreasing population productivity (Post and Forchhammer 2008). Increasing mismatch between herbivores or insectivores and their food sources could pose a serious threat to Arctic ecosystems (Gauthier et al. 2013).

16.2.1.2 Distribution

Paleoecological research has shown that the geographic ranges of terrestrial species are linked to broad-scale climatic variables; the rapid warming currently taking place in the Arctic is, therefore, likely to affect the distribution of wildlife (Callaghan et al. 2005). Increases in temperatures are leading to longer growing seasons, which is also increasing primary production and arthropod abundance (Bolduc et al. 2013, Gauthier et al. 2013). As a result, Arctic ecosystems are able to support a higher diversity of birds; this has been demonstrated by the northward expansion of the distribution of a variety of song birds and shorebirds (Callaghan et al. 2005, Brommer et al. 2012, Sokolov et al. 2012).

While models of species-climate response surfaces predict a poleward expansion of the ranges of boreal and temperate species, the spatial extent of Arctic species' ranges are predicted to retract (Callaghan et al. 2005). Habitat loss will likely be a major driver of range retractions in the Arctic as the tundra-boreal forest interface moves north (Skre et al. 2002) and sea-ice habitat declines (Derocher et al. 2004).

The distribution of Arctic wildlife within a species' range can also be affected by climate change. In addition to warming temperatures, the frequency and severity of summer rain storms are predicted to increase in the Arctic, which can reduce the availability of arthropods for insectivores (Schekkerman et al. 2003). Distributional shifts of species within their geographic range have the potential to change community structure and interrupt important ecological interactions.

16.2.1.3 Invasive species

Lesser snow (*Chen caerulescens caerulescens*) and Ross' (*Chen rossii*) goose nesting success at Karrak Lake in the Central Arctic was found to be inversely related to flea abundance in nests, although the overall effects of fleas on goose nesting success have thus far been small (Harriman and Alisauskas 2010). Such situations may become more common as a northward increase in the number of parasites is expected with warming.

Competition is expected to increase as temperate species invade marine areas that were the exclusive home of arctic-adapted marine mammals. For example, negative health and demographic effects of disease and contaminants may increase with climate change impacting the ice whales and seals. Killer whales (*Orcinus orca*) tend to avoid areas with extensive ice cover. A reduction in the extent of sea-ice cover in the Hudson Bay, Hudson Strait and Foxe Basin region since the 1950s has coincided with an exponential increase in killer whale sightings (Higdon and Ferguson 2009). Killer whales are major predators and may reshape the Arctic ecosystem via a top-down effect.

16.2.1.4 Habitat loss

One of the most severe and obvious examples of habitat loss in the Arctic is the reduction in the thickness, extent and duration of sea-ice coverage (Maslanik et al. 2011), which is predicted to continue to decline (IPCC 2013). Sea ice is critical habitat for polar bears because they rely on the platform it creates to hunt seals and other marine mammals. Declining sea-ice availability has been linked to reduced body condition, reproduction and population size for polar bears across the circumpolar Arctic (Sahanatien and Derocher 2012, Iverson et al. 2014, Rode et al. 2014). With less sea ice available for hunting marine mammals, polar bear depredation on colony-nesting birds has increased (Iverson et al. 2014).

Pacific walrus (*Odobenus rosmarus divergens*) also rely heavily on sea ice as a place to rest (haul-out sites) between feeding dives. As sea ice continues to decline, walrus are predicted to shift northward as they follow the remaining sea ice, increase their use of coastal haul-outs and experience population reductions as near shore environments become the only available foraging habitat (MacCracken 2012).

Climate change is also predicted to cause a major loss of tundra habitat as the tundra-boreal forest interface moves north. Models based on climate alone predict between 11-50% of tundra habitat could be converted to boreal forest over the next 100 years. As tundra habitat is lost, the bird community will likely shift to boreal forest specialists at the expense of local tundra-adapted species (Sokolov et al. 2012). Furthermore, as boreal forests and shrublands move north, forage availability for caribou, especially in winter, will likely decline while competition from other browsing ungulates increases (Lenart et al. 2002). Drying out of wetlands due to increased evaporation (Smol and Douglas 2007) or drainage due to thawing of permafrost (Berteaux et al. 2017) are also occurring in some areas and may result in significant loss of some habitats for species like ducks and geese.

16.2.1.5 Demographics

Climate can directly affect vital rates like survival, reproduction or recruitment of animals by changing the abiotic

conditions they are physiologically adapted for (Jenouvrier 2013). Weather conditions can directly affect the mortality of individuals, especially young which are sensitive to cold temperature or high precipitation events. Arctic peregrine falcons (*Falco peregrinus*), for example, are affected by increases in the frequency and intensity of summer rain storms. Heavy rain while peregrine chicks are young and unable to thermoregulate can negatively affect population productivity directly by increasing nestling mortality (Bradley et al. 1997, Anctil et al. 2014). Heavy rain also decreases the abundance of insectivorous birds in the Arctic (Robinson et al. 2014), a major prey group for peregrines, which could indirectly reduce peregrine productivity through malnourishment or starvation. Most climate warming scenarios predict that not only total rainfall should increase but that it should be concentrated in more intense episodes, which should be detrimental to the productivity of many raptor species.

Documenting an effect of climate on various demographic parameters is relatively easy but it is far more difficult to show how it will affect the population dynamic of a species (Jenouvrier 2013). Climatic effects can vary throughout the annual cycle of an animal, sometimes with antagonistic effects, especially in migrating species which are exposed to very different climatic regimes between seasons. One example of this is provided by the Greater snow goose, where van Oudenhove et al. (2014) showed that temperature could have both positive and negative effects depending on the vital rate and season. Thus, population models integrating climatic effects during the whole life cycle of an animal are required to project the response of populations to future changes.

One of the best examples of climatic effects on the population dynamics of arctic animals is the case of lemmings living under the snow in winter. Snow provides insulation from the harsh Arctic weather and limits predator access to the subnivean space where they live. In Greenland and some parts of Fennoscandia, lemming population cycles have recently shown a decreased amplitude of cycles (Ims et al. 2008). Change in snow characteristics (duration, depth, density and structure) caused by warming has been

invoked as a leading cause for these changes because a poor snow cover year can increase winter mortality and curtail reproduction (Aars and Ims 2002, Kausrud et al. 2008, Gilg et al. 2009). Even in the Canadian High Arctic, where change in snow characteristics have been less drastic than in other areas, the amplitude of lemming population fluctuations is still affected by snow quality (Bilodeau et al. 2013). The ongoing and future changes in temperature and snow conditions could therefore have important consequences for the population dynamics of lemmings and of the diverse predator community that depends upon them for their survival and reproduction (Bertreux et al. 2017, Ims and Fuglei 2005, Schmidt et al. 2012).

Extreme climatic events can have a major impact on the population dynamic of several arctic wildlife species (Hansen et al. 2011). Rain-on-snow events are a prime example of that as they have the potential to render food unavailable to herbivores due to the formation of a thick crust of ice on top of snow or of ground ice under the snow. Intense rain-on-snow events have been shown to cause catastrophic mortality in caribou both in northern Canada and in Svalbard (Miller and Gunn 2003, Hansen et al. 2011). The population dynamic of both caribou and voles in Svalbard have been shown to be closely correlated and periodic, large-amplitude population declines have been related to intense snow-on-ice events, indicating that herbivores living both on top and under the snow can be equally affected (Stien et al. 2012). These situations are likely to become more frequent and widespread, even in the High Arctic, as climate will continue to warm (Rennert et al. 2009).

16.2.1.6 Predation

Killer whales could alter the marine ecosystem through a top-down effect of predation. If killer whale predation increases with loss of sea ice, then the possible predator-prey relationships with other marine mammals may result in distributional changes of prey and changes to the marine food web. In Nunavut, local residents and scientists have observed killer whales feeding on marine mammals including narwhal (Campbell et al. 1988, Laidre et al.

2006, Higdon and Ferguson 2009). Killer whales may be an important predator of beluga (*Delphinapterus leucas*), narwhal, and bowhead (*Balaena mysticetus*), as indicated by their behavioural responses to killer whale presence (Campbell et al. 1988, Laidre et al. 2006). DFO is working with Nunavut HTOs to gather information on killer whale abundance and distribution in Nunavut, to evaluate their impact on marine mammals (Ferguson et al. 2012).

16.2.1.7 Reduction in sea ice

Ice-dependent marine mammals, such as polar bears and the ice seals, are possibly threatened by reductions in duration of the sea-ice season and in the spatial extent of summer ice. Earlier ice breakup and later ice formation can impact these species by extending the period of minimal food intake for polar bears (i.e., longer duration of open water season) and causing disruption of critical life history events for the ice seals (i.e., loss of ice for pups in spring). Predictions are for increased risk of declines for marine mammal populations over the next few decades (Laidre et al. 2008). To provide adaptive management, a coordinated marine mammal monitoring plan needs to be developed and implemented.

16.2.1.8 Industrial activity

Increasing disturbance to marine mammals will likely occur with oil/gas and mining industries. In the Eastern Canadian Arctic, exploration, development, and production phases of the hydrocarbon industry may cause displacement of marine mammals from important feeding habitats, challenges to maintaining their underwater acoustic requirements, and an impact to calving, nursing, and migratory areas. Increased mining development in the Eastern Canadian Arctic could impact marine mammals through increased shipping activity in coastal areas, resulting in noise pollution, displacement, and possible contamination. The end result includes possible direct mortality due to oil spills or contamination and indirect effects on individual health and fitness due to changing food quality and availability and changes in habitat protection from killer whale predation. The risks of population declines for

marine mammals can be assessed through environmental assessments, mitigation, monitoring and committed work with local communities to ensure local harvests are sustainable. Knowledge on how to assess and predict impacts of cumulative impacts of numerous developments in the region is required.

16.2.1.9 Indirect and food web effects

Climate change can affect a wildlife species through indirect pathways, for instance by affecting other species of plants or animals with which it has a trophic link. A clear example of indirect effect is provided by the trophic mismatch, which can negatively affect the reproductive success of several species and ultimately their population dynamic (Miller-Rushing et al. 2010; see section 17.2.1.1 for examples). Because arctic food webs are relatively simple with a small number of species, there is generally little functional redundancy (Gauthier et al. 2011, Gilg et al. 2012). Changes in the phenology, distribution or other traits of a species may therefore have disproportional impacts on the abundance and dynamics of other species and disrupt the functioning of the food web. This is why it is important to take into account species interactions when trying to understand or forecast the impacts of climate change on the tundra ecosystem (Van der Putten et al. 2010). Predation in particular may be an important structuring force in the tundra and change in predator abundance or diversity may have a strong impact on food webs (Legagneux et al. 2012, 2014).

Strong indirect interactions may occur in the tundra food web due to shared predators, a phenomenon called apparent competition. The Arctic fox (*Vulpes lagopus*), an important predator of the tundra, primarily feeds on lemmings but uses birds as alternative prey, especially goose eggs. Since lemming populations are highly cyclical, foxes must switch to their alternative prey (geese) when lemmings decline (Bêty et al. 2002). This may have cascading effects on lower trophic levels as well because, when lemmings are high, goose production is high due to reduced predation which subsequently leads to a high grazing impact of geese on plants (Bêty et al. 2014). In addition, predation rates on other prey incidentally consumed by foxes, such as shorebirds



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and passerines, is also influenced by lemming predation. Lemming grazing and browsing can also be significant and even limit in some areas the expansion of shrubs in response to climate warming. Therefore, if the amplitude of lemming cycles decreases or if they disappear completely in response to climate warming (see section 17.2.1.5), this may not only affect their predators but may also have far-reaching effects on the whole food web, including on other herbivores, small insectivores and plants (Nolet et al. 2013, Bêty et al. 2014).

Other indirect effects of climate change include the impact of increased anthropogenic presence in the Arctic. For example, the decrease in sea ice has increased the length of the shipping season and as a consequence, shipping traffic has been increasing (Arctic Council 2009). Shipping can impact marine wildlife via an increase in ambient underwater noise, increased risk of ship strike as well as

an increased risk of accidental oil spills as well as oil contamination through ballast water (Reeves et al. 2014).

The loss of sea ice and the increase in extreme weather conditions may lead to increased incidence of hypothermia, drowning, and stranding from exhaustion of ice-dependent marine mammals. The transmission of infectious disease might change via alterations in host-pathogen association leading to potential new epidemic diseases (Burek et al. 2008). Body condition may deteriorate and result in decreased immune function as well as decreased fitness (Harwood et al. 2000). For marine mammal species that haul out on ice, the decrease in the availability of suitable haul out sites might increase the density of individuals at these sites leading to increased disease transmission rates (Lavigne and Schmitz 1990).

16.3 Impacts of climate warming on key wildlife species

16.3.1 Marine mammals

Arctic marine mammals are of particular concern since they are adapted to living on sea ice which has shown consistent declines with global warming (Laidre et al. 2008). Loss of sea ice will affect all of the marine mammal populations in the Eastern Canadian Arctic, including the ice whales, beluga, narwhal, and bowhead whales, the ice seals, the ringed and bearded seals (*Erignathus barbatus*), and the atlantic walrus (*Odobenus rosmarus rosmarus*). All three whale species seasonally migrate from the Baffin Bay-Davis Strait-Labrador Sea areas in winter into Hudson Bay and the Arctic Archipelago regions during the ice-free season. The ice seals and walrus (along with the polar bear) remain year-round within the region, although seasonal migration occurs to various degrees. All seven of the ice-adapted marine mammals living in the region depend on sea ice for survival and reproduction. The seven arctic

marine mammal species found in these marine waters are important to Inuit that generally depend on harvesting for subsistence food, economic benefits, and cultural well-being. For example, Repulse Bay hunters gained \$266 504 for beluga and \$321 500 for narwhal hunting as an economic use value (Hoover et al. 2013). In Nunavut, 74% and 45% of participants in the Inuit Health Survey (2008) reported eating ringed seal meat and beluga mattaaq, respectively.

In addition to the Arctic species, two Subarctic ice seals, the harbour seal (*Phoca vitulina*), harp seal (*Phoca groenlandica*) and hooded seal (*Cystophora cristata*) are found in the waters of the Eastern Canadian Arctic. Also, a number of whale species including, grey whale (*Eschrichtius robustus*), killer whale, sperm whale (*Physeter microcephalus*), northern bottlenose whale (*Hyperoodon ampullatus*), minke (*Balaenoptera acutorostrata*), and humpback (*Megaptera novaeangliae*) occur occasionally in the region (Higdon et al. 2012). Limited information on abundance and distribution of whales and pinnipeds in the Eastern Canadian Arctic make it difficult to assess status



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and trends and to relate trends to climate change. Thus, changing relationships between species ecology and sea ice as well as predictions for future climate change are difficult to determine. Most current research is directed at stock assessment that is relevant to management, while little basic research assists with larger scale understanding of conservation. Understanding the degree to which marine mammals contribute to the structure of marine ecosystems (Bowen 1997), provides impetus to understand basic ecological functioning and develop adaptive responses for local people in order to maintain the important cultural and socio-economic value of Arctic species.

16.3.1.1 *Walrus*

The Atlantic walrus that inhabits the region is divided in seven stocks: the South and East Hudson Bay, the Northern Hudson Bay-Davis Strait, the North Foxe Basin, Central Foxe Basin, the Baffin Bay, the West Jones Sound, and the Penny Strait-Lancaster Sound stocks (Stewart 2008). There is evidence that some of the stocks, such as the Baffin Bay stock, are shared between Greenland and Canada (Wiig et al. 2014). Commercial harvesting of Atlantic walrus is illegal in Canada. However, there is subsistence and sport hunt of this species. In Nunavut, the hunt is co-managed by the Nunavut Wildlife Management Board, Regional Wildlife Organizations, Fisheries and Oceans Canada, and Hunter and Trapper Organizations.

Atlantic walruses mate and give birth on sea ice (Sjare and Stirling 1996). They require large areas of open and shallow water for foraging, with suitable substrate (e.g., land or ice) nearby to haul out on (Freitas et al. 2009). Atlantic walruses are also very gregarious and form groups that vary in size and composition depending on the time of the year (Mansfield 1958). The location of these aggregations tend to be predictable (Born et al. 2005). Suitable ice haul out sites might become less available with changing climate and might result in over-crowding haul out sites. This over-crowding might result in more intraspecific competition for food and more chances of stampede-related mortality (Kovacs et al. 2011).

Changes in sea-ice availability might increase the predation pressure on Atlantic walrus. Decreased availability of suitable haul out sites on ice might lead Atlantic walruses to use haul out sites on land and increase their vulnerability to polar bear predation (Thiemann et al. 2008). Increased presence of killer whales in some regions of the Arctic due to the longer ice-free period (Higdon and Ferguson 2009) might increase their predation on Atlantic walrus. Lastly, as availability of sea ice decreases, hunting pressure on Atlantic walruses will likely increase (COSEWIC 2006).

16.3.1.2 *Bowhead whale*

Inuit have sustainably hunted bowhead whales for centuries; however, abundance of Atlantic bowhead whales was severely depleted by the early 1900s as a result of commercial whaling that ended in 1979. In Canada, Inuit are authorized to hunt bowhead whales in the NSA starting in 1996 and for the next 20 years, the NWMB slowly increased the harvest up to the current 4/year.

Studies in West Greenland and Baffin Bay suggest that copepods, euphausiids and mysids are a primary food source for bowhead whales (Finley 2001, Laidre et al. 2007, Simon et al. 2009, Pomerleau et al. 2012). Biomarker analysis of the Eastern Canadian-West Greenland (EC-WG) bowhead whale tissue (stable isotope analysis of skin and fatty acid analysis of blubber) suggests that their diet consists mainly of pelagic and epibenthic prey (Pomerleau et al. 2011, Pomerleau et al. 2012).

Influential bowhead habitat features may include the presence of suitable ice cover to reduce predation, bathymetry or bottom slope for nursery functions, oceanographic features that concentrate prey and enhance opportunities for intensive foraging (e.g., troughs, upwellings, eddies, funneling ocean currents, and water mass boundaries), and complex coastal areas that provide cover from predation and calm waters for newborn. As ice breaks up in spring, bowhead whale movements through thick ice reduces their risk of encounters with killer whales and access to open-water polynyas may provide an abundant food source in the early open water season (Reinhart et al. 2013). During

summer, the Gulf of Boothia has moderate ice coverage (54–62%) and the dive characteristics of satellite tagged bowhead whales suggest that it is an important summer feeding area by bowhead whales from different regions (Pomerleau et al. 2011). During the autumn and early winter periods feeding is concentrated along the outlets of fiords of eastern Baffin Island (Richardson et al. 1995a). Feeding likely continues over winter while they are in the moving ice of Hudson Strait (Matthews and Ferguson 2015). Changes to habitat, prey availability, and increased natural mortality may lead to changes in bowhead abundance, distribution and stock structure (Laidre and Heide-Jørgensen 2005, Laidre et al. 2008).

Ecosystem changes associated with environmental changes will likely also result in increased marine vessel activity, associated with tourism and industrial development (e.g., commercial fishing, mining and hydrocarbon exploration). Increased vessel traffic may cause acoustic disturbance to bowhead whales, negatively impact critical habitat areas, and increase the frequency of ship strikes in migration corridors (e.g., Hudson Strait, Foxe Basin, Lancaster Sound, Davis Strait, Baffin Bay). Bowheads are specialized filter feeders, and may be at physiological risk if their baleen plates are fouled by fuel oil or become entangled in nets or debris. Also, the warming of the Arctic is expected to favour smaller and leaner zooplankton species from more temperate waters, which would affect the prey quantity, quality, and availability for bowheads (Pomerleau et al. 2012).

The EC-WG bowhead population ranges from the southern ice edge in Davis Strait to the North Water in the High Arctic, and from the Arctic Archipelago and Baffin Island east to the Greenland coast (Heide-Jørgensen et al. 2003). Within this range, individuals travel extensively and their movements are closely linked with seasonal changes in sea ice (Ferguson et al. 2010). Scientific studies demonstrated that in the winter, bowheads from both Foxe Basin and Baffin Bay regions share common ranges found in Hudson Strait, Davis Strait, and southern Baffin Bay (Finley 1990, 2001).

Bowheads occur near Disko Bay, West Greenland in late winter-early spring (Heide-Jørgensen and Finley 1991,

Reeves and Heide-Jørgensen 1996, Heide-Jørgensen et al. 2007, Laidre et al. 2007). Bowhead whales tagged in West Greenland moved across Baffin Bay in spring into Canadian waters (Heide-Jørgensen et al. 2003, Heide-Jørgensen et al. 2006). In summer some of them entered the Canadian Arctic Archipelago and moved west through Barrow Strait into adjacent fiords, including Prince Regent Inlet, while others remain along eastern Baffin Island (COSEWIC 2009).

DFO (2008a) recommended that critical habitat for EC-WG bowhead whales should include the following areas: (1) overwintering habitat in Hudson Strait and Davis Strait associated with avoidance of risk of ice entrapment and Killer whale predation; (2) the northern Foxe Basin calving area associated with habitat used to shelter neonates and juveniles; (3) the Gulf of Boothia-Prince Regent Inlet region associated with nursing female bowhead accompanied by calves; and (4) the mid-eastern Baffin Island coastline waters of Baffin Bay where consistent major feeding occurs.

In 2009, COSEWIC assessed the status of the EC-WG bowhead whale population and recommended that it be listed as Special Concern under the Species at Risk Act (SARA). Bowhead whales are characterized as a long-lived species (>200 yr) with late sexual maturity of around 25 yr of age, and low fecundity combined with a long inter-birth interval (George et al. 1999). These particular biological characteristics make this species more vulnerable to the effects of climate change, to increasing killer whale predation and to the impacts of human activities (e.g. shipping, mining, oil and gas field exploitation), especially those occurring near or within their feeding or nursery areas (Higdon and Ferguson 2009).

Bowhead whales are also among the largest animals on earth and the amount of body fat is extremely high, up to 60% body mass. Due to their large body mass and fat composition, bowhead whales are expected to have high energetic requirements. Although bowhead whales are recovering from pre-exploitation population sizes in eastern Canadian waters, concerns remain regarding their future because of anthropogenic factors such as climate change.

16.3.1.3 *Beluga*

There are four beluga management units that inhabit or visit the region: the Cumberland Sound, the Eastern High Arctic-Baffin Bay, the Eastern Hudson Bay, the Western Hudson Bay and the James Bay stocks (Richard 2010). The belugas from the Eastern Hudson Bay stock are listed as Endangered by COSEWIC (2004a) and the main factor limiting their recovery is overexploitation (Hammill 2001, Bourdages et al. 2002). Belugas from the Cumberland Sound stock are listed as Threatened (COSEWIC 2004a). The belugas from the Eastern High Arctic-Baffin Bay and Western Hudson Bay stocks are listed as Special Concern (COSEWIC 2004a). Belugas from all four stocks are subject to a subsistence hunt. In Nunavut, a number of beluga populations are co-managed by Inuit groups, Hunters and Trappers Associations, the Nunavut Wildlife Management Board, and Fisheries and Oceans Canada. The Eastern High Arctic-Baffin Bay stock is also shared between Canada and Greenland (Innes and Stewart 2002).

In the summer, belugas are found along the coastline and in relatively shallow waters when they visit estuaries and fiords (Richard et al. 2001). During that period, belugas molt and care for calves (St Aubin et al. 1990, Kilabuk 1998). Aggregations of belugas tend to be predictable on their summering grounds (Richard et al. 2001). In mid to late September, belugas move toward their wintering grounds in recurring leads and polynyas (Richard et al. 1998, Heide-Jørgensen et al. 2013). In late spring, they wait along the ice edges and use leads to access their summering grounds. Changes in ice formation pattern and timing might lead to increased frequency of ice entrapments (Heide-Jørgensen et al. 2002).

Belugas will likely experience changes in prey availability as a consequence of climate change. Evidence from stable isotopes have shown that belugas in Cumberland Sound may have switched their diet from Arctic cod (*Boreogadus saida*) to capelin (*Mallotus villosus*) (Marcoux et al. 2012) corresponding to possible change in prey availability.

Indirect impacts of climate change on belugas include increased shipping traffic in the Arctic. Shipping is a major

source of noise pollution in the ocean (Richardson et al. 1995b). Belugas produce sound that they use to navigate, hunt and communicate. In addition, they use naturally occurring sounds to gain information about their environment. Thus, shipping noise can affect belugas in several different ways. Noise can mask important environmental sounds and communication calls of belugas (Erbe and Farmer 2000). As a result, navigation and intra-specific communication can be compromised or made impossible (Clark et al. 2009). Noise can disrupt important behaviours of belugas such as feeding, breeding, and caring for their calf (Richardson et al. 1995a) and, as a result, change their energy budget. Noise can change the habitat of belugas by displacement of potential prey which can cause belugas to relocate (Richardson et al. 1995a). Finally, loud noise can also cause temporary or permanent hearing loss (Finneran et al. 2002).

16.3.1.4 *Narwhal*

Narwhal inhabit the marine waters of the northern third of the northern hemisphere including the open waters of Canada (Nunavut), Greenland, Iceland, Norway (Svalbard), the Russian Federation and the United States (Alaska). However, the vast majority of narwhal and narwhal hunts occur in Canada and Greenland, where they are currently only hunted by Inuit. Narwhal hunting is integral to Inuit and provides widespread economic, social and cultural value for Nunavut.

Prior to 1971, hunting and trade of narwhal in Canada was unregulated by government. In 1971, the Government of Canada enacted the Narwhal Protection Regulations that established a narwhal annual catch quota for individual Inuit hunters. This was replaced in 1977 by quotas assigned to specific communities or settlements. Because of the limited biological information available to estimate sustainable harvest levels, quotas were based on historic local catch records. In 1993, the Narwhal Protection Regulations were revoked when the Marine Mammal Regulations were enacted. In 1999, the NWMB instituted a community-based management initiative to share the harvest management responsibilities (Table 1) with the RWOs and HTOs under the NLCA. In 2009, the NWMB discontinued the

TABLE 1. Summary of narwhal management units and Nunavut harvesting communities.

Management Unit	Harvesting Communities
Somerset Island (SI)	Resolute Bay, Taloyoak, Gjoa Haven, Kugaaruk, Cambridge Bay, Igloodik, Hall Beach
Admiralty Inlet (AI)	Arctic Bay
Eclipse Sound (ES)	Pond Inlet
Parry Channel, Jones, Smith Sounds (PJS)	Grise Fiord
North Hudson Bay (NHB)	Repulse Bay, Coral Harbour, Chesterfield Inlet, Rankin Inlet, Cape Dorset, Whale Cove, Kimmirut
East Baffin Island (EB)	Clyde River, Qikiqtarjuaq, Pangnirtung, Iqaluit

full community-based management program but retained harvest limits and quota flexibilities. In 2013, an Integrated Fisheries Management Plan was approved by the Minister of Fisheries and Oceans and the NWMB pursuant to NLCA. The narwhal fishery in the Nunavut Settlement Area is currently co-managed by Fisheries and Oceans Canada (DFO), the NWMB, RWOs, and HTOs, and Nunavut Tunngavik Inc. (NTI) in accordance with the NLCA, and the Fisheries Act. Narwhal are considered Special Concern by COSEWIC (2004b). The SARA listing process for narwhal is pending an agreement on harmonization of the provisions of SARA with the Nunavut Inuit Land Claims Agreement.

Sea ice, bathymetry, and upwellings may all play roles in habitat selection by narwhal (Heide-Jørgensen et al. 2002, Laidre et al. 2004). Narwhal overwinter in the deep water of Baffin Bay-Davis Strait-Hudson Strait, where they appear to feed intensely on Greenland halibut (Laidre and Heide-Jørgensen 2005), although other fish are seasonally important. Narwhal summer ranges, where most calves are born and nursed, are generally in coastal areas with deep water that offer shelter (e.g., fiords). During fall migration and on their winter ranges, narwhal are found in deep water and on the continental slope, typically within pack ice in winter (Dietz et al. 2001, Laidre et al. 2002, Watt et al. 2015). Narwhal tend to return to the same locations each summer (Dietz and Heide-Jørgensen 1995, Heide-Jørgensen et al. 2003, Laidre et al. 2004, Dietz et al. 2008, Watt et al. 2013).

There are two narwhal populations in the Eastern Canadian Arctic: the Northern Hudson Bay (NHB) narwhal

population and the Baffin Bay (BB) narwhal population. This separation is based on evidence from satellite telemetry, genetic, and contaminant data. Telemetry data shows geographic separation especially in their summer ranges and genetics and contaminant level differences reflect winter distribution (Richard 2010, Watt et al. 2013). The NHB population's summer range includes the area surrounding Southampton Island and winter range occurs in southeast Davis Strait and/or eastern Hudson Strait (Richard et al. 2001). Narwhal typically arrive on their summer range in late July and then leave by mid to late August. The BB narwhal population is considered to be a shared stock with Greenland since its distribution includes the Canadian Arctic Archipelago and northwest Greenland (Watt et al. 2013). Narwhal from Canada and Greenland over winter together in Baffin Bay with the Canadian component of the Baffin Bay narwhal population migrating seasonally from its wintering grounds in Baffin Bay to recurring summer aggregations in the Canadian High Arctic. Five management stocks have been provisionally recognized that correspond to these recurring summer aggregations (DFO 2008b). The relationship of narwhal summering in Jones Sound/Norwegian Bay and Smith Sound/Kane Basin to other BB narwhal is not known.

Narwhal is an ice-associated species, and the potential effects of climate change are under study. Changes to habitat, prey availability, and increased natural mortality may lead to changes in abundance and stock structure (Laidre and Heide-Jørgensen 2005, Laidre et al. 2008, Watt et al. 2015).



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16.3.2 Terrestrial mammals

16.3.2.1 *Polar bear*

The polar bear is distributed throughout Nunavut and the circumpolar Arctic. Polar bears require both marine (sea ice) and terrestrial habitat. They are highly specialized carnivores and are dependent on sea ice to access marine mammal prey. Polar bears are found in greatest numbers on annual sea ice over the continental shelves and shallow basins where their prey, mainly ringed seals and bearded seals occur in highest densities. But polar bears do make regular use of multi-year sea ice and off-shore pack ice. Sea-ice habitat selection studies have found that ice concentration is the most important factor for polar bears. Terrestrial habitat is used by polar bears in summer when the sea-ice melts and by pregnant females in autumn and winter for maternity dens. When on land, bears tend to remain close to the coastline but can also be observed hundreds of kilometres inland.

For management purposes, subpopulation units are delineated and within the Eastern Canadian Arctic there are 8 units: the Arctic Basin, Norwegian Bay, Kane Basin, Lancaster Sound, Baffin Bay, Davis Strait, Foxe Basin, and Gulf of Boothia. It is not possible to estimate the total number of bears within the region as there is no abundance information for the Arctic Basin, outdated information for four units, and only current information for 3 units. Within Canada there are between 15 000-16 000 polar bears and the species has been designated and listed under the Species at Risk Act as Special Concern. The primary concern and threat to the future of polar bears is sea-ice habitat loss caused by global climate warming. It is possible that the Arctic will be ice-free during the summer by 2050 but the timing of predictions varies widely. The direct impact of sea-ice habitat loss is reduced foraging time and access to marine mammal prey. Declines in sea-ice availability have negatively affected polar bear body condition, adult and juvenile survival, reproduction, and abundance.

Other threats include human-caused mortality (hunting and defence kills), disease and parasites, pollutants, oil spills, displacement or disturbance by industrial development, and ship traffic (cargo and cruise).

16.3.2.2 Peary and Barren-ground caribou

COSEWIC (2004c) estimated that the total population of Peary caribou in the Canadian Arctic to be 7890 individuals (range 5971 to 9146) distributed among four distinct populations; the Queen Elizabeth Islands (ca. 2160 adults), Banks and northwest Victoria Islands (ca. 1832 adults), Prince of Wales and Somerset Islands (ca. 60 adults) and Boothia Peninsula (ca. 3329 individuals). The overall population has experienced significant declines with declines estimated to be 72% since 1980 and 84% since the 1960s.

Similar declines have been experienced at the population level; in the Queen Elizabeth Islands, caribou have declined by 37% since the 1980s with the greatest decline (86%) occurring from 1961 to 1987. The Banks Island population declined by 50% from 1961 to 1987. Although the Prince of Wales/Somerset population experienced a decline of 99% from the 1980s, the Boothia Peninsular population increased by 10% over the same period.

Despite historic population estimates of 100 000 animals for the “Dolphin Union” barren-ground caribou herd (which migrate between mainland Canada and Victoria Island), the herd declined to very low numbers by 1924, and subsequently recovered to 25% of historic numbers (COSEWIC 2004c). Ice formation under snow or dense and hard packed snow limits access to lichen and high quality vegetation



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and forces caribou to forage in poor habitats where snow is scarce or windblown (Miller et al. 1982). Winters with heavy and persistent snow, particularly in association with warm temperatures and freezing rain, that can result in deep crusted snow, have played an important role in the major decline in caribou numbers (COSEWIC 2004c). The availability of food during the 10-month season of snow and freezing, directly influences the fate of caribou, and is thus largely governed by winter climate variability and is highly sensitive to climate change.

Severe winter weather with twice long-term average snowfalls during three consecutive years (1994-1997) resulted in a drastic decline in Peary caribou of the western Queen Elizabeth Islands through massive deaths from malnourishment (43% decline only during winter/spring 1996/1997) leading to a 94% decline in the mean estimated number over the last 36 years (Gunn and Dragon 2002). At least two other major die-offs in this area (1973-1974 and 1989-1990) were attributed to severe winter with greater than average snowfall (COSEWIC 2004c).

Bad winters between 1990 and 1993 resulted in lower rates of calf production and survival in the Porcupine caribou (*Rangifer tarandus granti*) herd. Cold spring and late thaws could be preventing them from reaching their customary calving grounds in Arctic National Wildlife Refuge (Wildlife Management Advisory Council (North Slope) 2007). Severe winter weather also caused die-offs on Banks Island during winters 1987-1988, 1988-1989 and 1990-1991 (Larter and Nagy 2000). A major icing event eliminating about 50% of the winter foraging range on Banks Island in the winter 1993-1994 did not result in a significant die-off, yet calf production the following summer was the lowest recorded over the last 7 years (Larter and Nagy 2000).

Change in summer weather indirectly affects caribou populations through the plant community. Although warmer temperatures may result in overall increases in primary productivity, these ecosystem level changes may contribute to distributional changes of caribou in the Arctic Archipelago and lead to greater plant growth and increases in some caribou food species. However, these ecosystem changes could

also favour the invasion of the Arctic Archipelago by the barren-ground caribou leading to interspecific competition for food resources (COSEWIC 2004c).

A longer period of open-water and high temperatures could also increase evaporation and cloud cover thereby reducing plant growth (COSEWIC 2004c). Warmer spring weather and earlier snowmelt can also hasten plant green-up and flowering phenology. This may benefit caribou during late gestation in spring but the disruption in the synchrony between plant phenology and Peary caribou life cycle could also prove detrimental (COSEWIC 2004c). Warmer and wetter summer weather could lead to greater exposure to diseases and parasites, which have not previously been implicated in population declines. Inuit from the Queen Elizabeth Islands report that mosquitoes and black flies have increased along with warmer weather in certain areas (COSEWIC 2004c). Changes in the time of break-up/freeze-up of ice could also have important impacts on populations migrating between islands or from the mainland to islands in their yearly cycle (COSEWIC 2004c).

16.3.2.3 Grizzly bear

Barren-ground populations of grizzly bears are adapted to the low productivity and high seasonality of the Arctic with risk-spreading adaptations (later age at maturity, longer interbirth interval, greater longevity) reducing the effects of the stochasticity of the arctic environment on their life-history (Ferguson and McLoughlin 2000). The scarcity of food resources in Nunavut compared to the remainder of the grizzly bear's geographic range probably explains why their home range is the largest in Canada (COSEWIC 2012) and their densities are in the lowest reported for the species. In western Kitikmeot, densities were estimated at approximately 5/1000 km² in the vicinity of Kugluktuk (Dumont et al. 2015), and 3.5/1000 km² in the Lac de Gras area (McLoughlin and Messier 2001). The lack of information on grizzly bear movements and population delineations in Nunavut, as well as the absence of density estimates in the Kivalliq region, make it difficult to determine the total population size for the whole

territory. A crude estimate of 1530 to 2000 bears has been suggested (M. Awan, pers. comm.) based on the current information.

Very little research has been conducted on the effects of climate on grizzly bears. Nielsen et al. (2013) observed that warmer summer and spring temperatures, as well as higher winter precipitation appear to benefit grizzly bears and might result in larger cubs, probably through indirect effects providing energetic benefits to the mother or cubs. More generally, longer growing seasons might also benefit grizzly bears in Nunavut, considering the short duration of the growing season on which they depend upon to maximize their energy storage before winter hibernation. An increase in primary productivity at higher latitudes could allow an expansion of their geographic range towards the Arctic Archipelago. While grizzly bears have been reported to occur occasionally in the Canadian Arctic Archipelago since the early 1950s (Manning and Macpherson 1958), Nunavut harvest data from 2000 to 2014 have shown an increase in the harvest of grizzly bears in the southern islands of the Archipelago (i.e., Victoria and King William Islands, Government of Nunavut, unpublished data). Doupé et al. (2007) also recently reported the most northerly observation of a grizzly bear in Canada on Melville Island. The recent increased occurrence of polar/grizzly bear hybrids reported in this area (Kelly et al. 2010) might also be linked to recent climatic changes, also possibly supporting this northern range expansion hypothesis.

16.3.2.4 Wolf

Wolves are relatively abundant in the region and still occupy their whole traditional range. Two sub-species are recognized: the tundra/timber wolf (*Canis lupus occidentalis*) and the high arctic wolf (*Canis lupus arctos*). Many tundra/timber wolves travel above and below the treeline, crossing between Nunavut and adjacent provinces, following migrating barren-ground caribou herds but some are also known to remain and occupy den sites within Nunavut mainland through the whole year (Hillis 1990), relying mostly on resident populations of barren-ground caribou and muskox. The high arctic wolf occupies the islands of the Arctic

Archipelago and relies mostly on caribou, muskox and arctic hare (*Lepus arcticus*) populations present on those islands.

The main threat from climate change on wolves appears to be through indirect effects on their main prey populations. There is a broad consensus that severe winter weather such as an icing event preventing access to the vegetation can result in massive die-offs of muskox and caribou populations (Forchhammer and Boertmann 1993, Larter and Nagy 2000, Miller and Gunn 2003, COSEWIC 2004c). Mech (2004) recorded a total absence of reproduction and a decline in the local wolf population in Eureka area on Ellesmere Island between 1998 and 2003, following two years of severe winter (1997 and 2000) that had resulted in failure to reproduce and important mortality in muskox and hare populations. The low density and the insular and disjointed nature of High Arctic wolf populations may also render them particularly vulnerable to localised extinctions (Marquard-Petersen 2012).

16.3.2.5 Wolverine

Wolverines (*Gulo gulo*) are well adapted to their cold and low productivity niche characterized by a short growing season and limited food resources (Inman et al. 2012a). Their compact body and large plantigrade feet allow them to travel easily over deep snow, and their dense pelage is resistant to snow and frost build-up which protects them from the cold temperatures. They usually exist at low densities throughout their circumpolar distribution and utilize large home ranges to fulfill their nutritive needs (Magoun 1985, Krebs et al. 2007, Persson et al. 2010, Inman et al. 2012b). There is currently no total population estimate for wolverines in the Eastern Canadian Arctic but according to harvest data, the wolverine population in Nunavut is believed to be healthy and stable (M. Awan, personal communication). However, due to the absence of harvest reporting requirements from Inuit, monitoring the population trend and the extent of the harvest is difficult.

Persistent spring snow cover during the denning period (i.e., until mid-May (Inman et al. 2012a)), appears to be the most critical climate-related habitat requirement for

wolverines (Magoun and Copeland 1998, Aubry et al. 2007, Copeland et al. 2010) determining their global distribution. Spring snow cover in the circumpolar Arctic has been melting earlier during the last decades (Stone et al. 2002, Foster et al. 2008). However, climate projections predict both warmer temperatures and increased snow fall in the region (Chapter 2). Consequently the net impact of climate change on spring snowmelt is difficult to predict.

The wolverine's reproductive ecology is particularly well adapted to their low productivity environment. While mating usually occurs between May and August, the fertilized eggs remain in the blastocyst stage until implantation occurs, usually between November and March (Pasitschniak-Arts and Larivière 1995). This delayed implantation allows the wolverine to adapt their reproductive effort to the food resource availability (Persson 2005). The average parturition dates for wolverines is the earliest of all arctic carnivores that do not hibernate (Inman et al. 2012a). Reproductive success is highly dependent on winter food availability (Persson 2005). Since food availability and predictability is relatively low during winter, it

is believed that wolverines are highly dependent on food caches accumulated prior to parturition which probably fuel much of the period of early lactation and are consequently critical for neonate survival (Inman et al. 2012a). Cold temperatures are therefore necessary to inhibit consumption of food caches by insects and bacteria but wolverine's reproductive success might be susceptible to icing events preventing them from accessing their cached resources. Copeland et al. (2010) hypothesized that such specialized adaptations of wolverine to their cold, low productive environment allows them to avoid competition with other species less adapted to such conditions that are currently limited in their geographic range by the colder climate of northern latitudes.

16.3.2.6 Arctic fox

Arctic foxes are valued for their pelts and trapping is still an important subsistence activity in Nunavut. In addition, the Arctic fox is a keystone species in the tundra ecosystem (Ims and Fuglei 2005). A good understanding of the status and health of populations is thus important, as well as a good



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understanding of current and potential future effects of climate change on populations. The Arctic fox is abundant in Nunavut. However, the larger Red fox (*Vulpes vulpes*) has been expanding northward (Gagnon and Berteaux 2009), leading to increased competition with the Arctic fox for resources. Long term monitoring at Bylot Island has shown a relatively stable Arctic fox population and stable reproductive rates despite the presence of Red foxes, probably because the latter have until now remained at low population density.

16.3.3 Ducks and Geese

16.3.3.1 Brant

The brant (*Branta bernicla*) is a harvested species. There are 4 main subpopulations breeding at least partly in the Canadian Arctic: Atlantic brant (*B. b. hrota*), Eastern High Arctic brant (*B. b. hrota*), Black brant (*B.b. nigricans*) and Western High Arctic brant (intermediate between *B. b. hrota* and *B.b. nigricans*). Reed et al. (1998) reported large fluctuations in the population size of the Atlantic population (Reed et al. 1998) between more than 200 000 individuals in the 1950s to 45 000 in 1978-1979, apparently as a result of severe winter weather in the 1970s (Reed et al. 1998). The population has apparently stabilized since then and was estimated at 149 200 individuals in 2012 (Canadian Wildlife Service Waterfowl Committee 2013). The eastern high arctic population, which winters in northwestern Europe (primarily Ireland) increased from 10 000 in the late 1960s to more than 42 000 in 2012 (Canadian Wildlife Service Waterfowl Committee 2013). Although there is no estimate for Black brant breeding in the Western Canadian Arctic, a 2013 combined estimate for Arctic Canada, Alaska and western Russia was 146 800 individuals (Canadian Wildlife Service Waterfowl Committee 2013). In years of low temperature and high snow cover, proportionately fewer adults attempt to breed, lay date is delayed and clutch size is reduced (Barry 1962, Reed et al. 1998).

16.3.3.2 Greater snow goose

The snow goose is a harvested species. The Greater snow goose breeds throughout the eastern Canadian Arctic

Archipelago, from central Baffin Island to northern Ellesmere. There has been a large and rapid increase in population from around 25 000 birds in the mid 1960s to about 1 million birds in 1999 (Gauthier et al. 2005). This population increase was largely due to food subsidy derived from feeding in agricultural land in winter. This population was declared overabundant by the Canadian Wildlife Service in 1999 and special conservation measures were introduced to increase harvest by sports hunter on southern migratory and wintering grounds. Since then, the population has fluctuated mostly between 800 000 and 1 000 000 birds (Canadian Wildlife Service Waterfowl Committee 2013). Bylot Island, Nunavut, is the largest known breeding colony of this subspecies with approximately 15% of the total population breeding there (Reed et al. 2002). Periodic surveys conducted every 5 years from 1983 to 2008 suggest that the population trend of this colony has been similar to the overall population.

Most breeding parameters are strongly affected by climatic factors. For example, on Bylot Island fewer than 30% of females may breed in years of extensive snow cover in spring compared to greater than 80% when snow cover is low (Reed et al. 2004). Delayed laying and reduced clutch size also occur in years of low spring temperature and high snow cover but nesting success increases in years of high precipitation (Dickey et al. 2008, van Oudenhove et al. 2014). First-year survival is also positively related to high late summer temperature although, surprisingly, accession to reproduction by juvenile females decreases with warmer climatic conditions during the non-breeding season (van Oudenhove et al. 2014). Summer climatic conditions are therefore an important determinant of annual productivity (Morrissette et al. 2010). Despite the warming trend observed on Bylot Island over the past 3 decades, snow geese have not advanced their laying date which suggests that they are not adjusting to changing conditions (Gauthier et al. 2013).

16.3.3.3 Lesser snow goose

The Lesser snow goose breeds mainly along west Hudson Bay, southwest Baffin Island, the coastal areas of the Nunavut mainland and the southern portion of the

Canadian Arctic Archipelago in the west. The largest colonies are located along Queen Maud Gulf, the Great Plain of the Koukdjuak and Southampton Island. This population has experienced considerable increase in size since the middle of the 20th century for the same reasons as the Greater snow geese and is also considered overabundant (Jefferies et al. 2003). There is great uncertainty with respect to the size of this population. Counts conducted on the wintering grounds, which are known to be an underestimation, suggest a population of about 4 000 000 birds in 2012 but indirect population estimates derived from banding data suggest a population as high as 15 000 000 birds (Canadian Wildlife Service Waterfowl Committee 2013). This high density of geese has resulted in the degradation of several coastal marshes due to goose overgrazing, especially along west Hudson Bay and along the Queen Maud Gulf (Abraham et al. 2012). This has led to the instauration of special management actions to increase harvest by hunters and stop the growth of the population but these actions had a limited success.

MacInnes et al. (1990) reported that the breeding season had advanced by ~20 days for the Hudson Bay colonies from 1951 to 1986. The authors reported that clutch size was overall reduced over the period despite increased clutch size in years of early nesting. The strong link between climate and breeding success was demonstrated by Skinner et al. (1998); laying and hatching date were negatively related to spring and early summer temperatures, and to total degree days in spring and early summer precipitation. Spring weather parameters were all important predictors of total clutch size. Inclement weather in late spring and early summer were good predictors of pre-incubation failure while overall weather during breeding period predicted total breeding failure. Gosling growth rate was slower in years with delayed laying and in seasons with cold, wet weather.

16.3.3.4 Canada goose and Cackling goose

These two species (considered a single species until recently) are harvested species. The Canada goose (*Branta Canadensis*) has a wide distribution across Canada but the

smaller Cackling goose (*Branta hutchinsii*) is restricted to the tundra. Only two of the 15 populations of these two species breed in the Canadian Arctic. The Tall-grass Prairie Population is composed almost exclusively of Cackling geese and breeds on Baffin, King William and Southampton islands and on the Nunavut mainland primarily near the McConnell and Maguse rivers (western Hudson Bay), though the population has been expanding northward in recent years. The total population estimated in 2012 from wintering ground surveys was ~500 000 individuals which represented a 25% increase over the 2005 estimate (Canadian Wildlife Service Waterfowl Committee 2013). The Short-grass Prairie Population is a mixture of both species and breeds in the Western Canadian Arctic on Victoria and Jenny Lind islands, and on the Nunavut and N.W.T. mainland from Queen Maud Gulf to the Mackenzie River. The total 2006 population estimate from wintering ground surveys was 234 700 individuals. Cackling geese have generally increased in recent decades. Numbers during midwinter counts increased from about 325 000 in the 1970s to an average of 687 000 birds during the period 2002-2011 (Canadian Wildlife Service Waterfowl Committee 2013). However, indirect population estimates derived from banding data suggest that the population may have exceeded 2 000 000 birds during the recent period. Aerial survey of the Great Plain of the Koukdjuak on Baffin Island indicated a relatively stable population from 1996 to 2009 around 160 000 birds (Canadian Wildlife Service Waterfowl Committee 2013). This population has reportedly declined since 1997 at a rate of 10% per year. However, breeding ground surveys suggest a stable or increasing population with a possible northward expansion of their range. Life expectancy and annual survival declined from 1992 to 2000, from 7.1 years to 3.4 years for life expectancy, and from 0.87 to 0.74 for annual survival (Canadian Wildlife Service Waterfowl Committee 2013). An advancement of approximately 20 days of geese breeding season in Hudson Bay from 1951 to 1986 was reported but there was a concomitant overall reduction in clutch size (MacInnes et al. 1990). Clutch size was smaller in years of late snow-melt and late nesting (MacInnes and Dunn 1988).

16.3.3.5 Ross's goose

Ross's goose is a harvested species. Historically, almost all of Ross's geese nested in Queen Maud Gulf Migratory Bird Sanctuary (now still approx. 95% of the population) (Canadian Wildlife Service Waterfowl Committee 2006). Population estimates in this area increased from 44 000 in 1965 (Dzubin 1965) to 188 000 in 1988 and 982 000 in 1998 (Canadian Wildlife Service Waterfowl Committee 2006). Most recent estimates indicate a population around 1 500 000 in 2006 (Alisauskas et al. 2012). New colonies have gradually appeared eastward, usually interspersed with Lesser snow geese, in areas such as Southampton Island, western Hudson Bay and southwestern Baffin Island, and in the Western Canadian Arctic on Banks Island. More than 90 000 geese were nesting in McConnell River area in 2005, and more than 10 000 on Baffin Island (Canadian Wildlife Service Waterfowl Committee 2006). The expanding population of Ross's geese have contributed to habitat degradation due to overgrazing in the Queen Maud Gulf area, along with the Lesser snow geese (Abraham et al. 2012). This species is thus also considered to be designated as overabundant by the Canadian Wildlife Service along with the snow goose (Canadian Wildlife Service Waterfowl Committee 2006). Ryder and Alisauskas (1995) reported that arrival at migration stopovers was associated with a 4 °C isotherm, the start of snowmelt and exposure of vegetation. Initiation of nesting was delayed and smaller clutch size were more common in years of late spring, but the period between successive eggs was reduced when nest initiation was delayed (Ryder and Alisauskas 1995).

16.3.3.6 Greater white-fronted goose

The Greater white-fronted goose (*Anser albifrons*) is a harvested species. Although there are 3 geographically distinct populations in North America, only the Mid-continent population breeds in the Canadian Arctic, mostly in the Nunavut mainland (Ely and Dzubin 1994). A long-term positive trend was reported for this population from the late 1960s up to recent years. Midwinter counts, however, suggest a relative stability from the late 1990s until 2012,

with a population averaging 724 000 from 2010 to 2012 (Canadian Wildlife Service Waterfowl Committee 2013). Population estimates derived from banding data suggest however that real population size could be closer to 3 500 000 birds in the Canadian Arctic. Although arrival at the breeding ground appears independent of weather condition, nesting was dependant on availability of snow free nest sites and was delayed by as much as 2 weeks in years of late snow melt (Ely and Raveling 1984). In addition, for birds breeding in Alaska, clutch size was highly negatively correlated with date of nest initiation (Ely and Raveling 1984).

16.3.3.7 Common eider and King eider

The Common eider (*Somateria mollissima*) and King eider (*Somateria spectabilis*) are important harvested species. In the Western Canadian Arctic Aerial surveys from 1991-1994 around Amundsen Gulf and Beaufort Sea provided a breeding population estimate of 200 000 to 260 000 King eiders in the Western Canadian Arctic (Dickson et al. 1997). Aerial surveys of Queen Maud Gulf area in 2005-2006 by the U.S. Fish and Wildlife Service, provided a population estimate for the King eider of 52 700 individuals while the Common eider was estimated at 9200 individuals (Conant et al. 2006, Conant et al. 2007). These estimates are considerably lower than the 900 000 eiders estimated by the Canadian Wildlife Service Waterfowl Committee (2006) which suggests a potential decline in the Western and central Canadian Arctic. Apparent decreases of more than 50% in populations of King and Common eiders migrating through Point Barrow (Beaufort Sea) between 1976 (King: 800 000; Common: 156 000) and 1996 (King: 350 000; Common: 73 000) (Suydam et al. 2000). The total Common eider population estimate for the Eastern Arctic is somewhere between 350 000 and 450 000 individuals (CAFF 2001). There is a long-term decreasing trend, except for Labrador populations which appear to be increasing (Circumpolar Seabird Working Group 1997). A good estimate of total King eider populations in the Eastern Arctic is lacking. According to surveys at wintering and moulting grounds in Greenland, a substantial decline occurred in the Eastern Arctic King eiders population (Canadian Wildlife

Service Waterfowl Committee 2006). Surveys conducted in 1994-1995 in the Rasmussen Lowlands (Gratto-Trevor et al. 1998) also indicate a substantial decline in population compared to 1975-1976.

In the Hudson Bay, there was an important decrease (75%) in Belcher Islands Common eider populations since mid-1980s, according to a 1997 survey by Robertson and Gilchrist (1998), but an apparent increase (4-5 times) in Digges Sound Common eider populations since early 1980s, according to a 1999 survey by Hipfner et al. (2002). Extensive snow cover is associated with delayed laying date and smaller clutch size while cold temperature during pre-laying period results in smaller egg size (Robertson 1995). Heide-Jorgensen and Laidre (2004) reported a decreasing trend in proportion of open-water habitat at important wintering and spring locations of Common and King eiders in Lancaster Sound, Baffin Bay and Davis Strait. Changes in Hudson Bay ice conditions during winter may be responsible for the decline in the Belcher Island Common eider populations (Robertson and Gilchrist 1998). Areas that have been historically free of ice now freeze during some winter months. The polynyas and open-water leads in the Belcher Islands are the only permanent open water areas accessible to birds and marine mammals during winter in southeastern Hudson Bay. Freezing of these areas may result in important die-offs from overwintering populations dependant on these resources (Robertson and Gilchrist 1998).

16.3.4 Land birds

16.3.4.1 Gyrfalcon

Although the Gyrfalcon (*Falco rusticolus*) is circumpolar in distribution, approximately 1500 to 3000 breeding pairs are estimated for Canada (Kirk and Hyslop 1998). Mossop and Hayes (1994) estimated 2500 to 4000 individuals including about 750 breeding pairs in Yukon, while Shank et al. (1994) estimated a population of 5000 individuals in Northwest Territories including around 1300 nesting pairs. There are few data sets for northern Quebec but Clum and Cade (1994) estimated 500 to 1000 pairs

for Ungava and Labrador. Although breeding success is thought to be irregular and related in part to the cyclic fluctuations of ptarmigan, the North American population including Nunavut is considered to be stable (Clum and Cade 1994, Kirk and Hyslop 1998). Although low spring temperatures are associated with later arrival at nesting territories in Nunavut (Poole and Bromley 1988), there was no effect on lay dates. However, Poole and Bromley (1988) indicated that increased spring precipitation (snow) reduced reproductive success. Norment et al. (1999) reported an expansion of Gyrfalcon range into the Thelon River Valley during the mid to late 1900s. Gyrfalcons are currently one of the raptor species monitored as part of the Baffinland Mary River Iron Mine environmental impact assessment.

16.3.4.2 Snowy owl

The Snowy owl (*Bubo scandiacus*) is circumpolar in distribution. This species is highly dependent on lemmings for breeding and will move considerable distances from year to year (up to 1000 km or more) to breed, in search of high lemming densities (Therrien et al. 2012, Therrien et al. 2014a, b). On Bylot Island, the species breeds only every 3 to 4 years in response to fluctuations in lemming abundance, which makes monitoring of their population very difficult (Gauthier et al. 2004, Therrien et al. 2014). Although some individuals move to southern Canada in the winter, with periodic irruptions, most adult breeding females appear to remain in the Arctic for the winter, many of them using the sea ice for extended periods of time where they feed on seabirds in polynyas (Therrien et al. 2011). The total Canadian population has been previously estimated at 10 000 to 30 000 breeding pairs (Kirk and Hyslop 1998). However, recent estimates have suggested a worldwide population of no more than 14 000 pairs. Therefore, the Canadian population is certainly lower than the previous estimates. There is little information on population trends though no changes have been observed over the past 20 years on Bylot Island (Gauthier et al. 2013) or during the winter in southern Canada over a longer period (Kirk and Hyslop 1998, National Audubon Society 2002). Nonetheless, the species potentially faces challenges due



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to climate effects on lemming cycles because of its high reliance on cyclic lemming populations for breeding and on seabirds in winter (Therrien et al. 2011, Schmidt et al. 2012).

16.3.4.3 Rough-legged hawk

The Rough-legged hawk (*Buteo lagopus*) has a circumpolar distribution. It is a specialised predator feeding primarily on small mammals during the summer and thus its breeding activity is generally related to the local abundance of lemmings (Therrien et al. 2014a). However, individuals appear faithful to their nesting site and in locations where ground squirrels are entirely absent, they may forego breeding or have a low success when lemmings are low in contrast to Snowy owls which are truly nomadic (Bechard and Swem 2002). Kirk and Hyslop (1998) estimated the Canadian Rough-legged hawk breeding population to be

approximately 10 000 to 25 000 pairs. The species is considered to be stable despite periodic fluctuations possibly related to lemming population cycles (Kirk and Hyslop 1998, Bechard and Swem 2002, National Audubon Society 2002). Bechard and Swem (2002) indicated that lay date was associated with spring temperatures and snow free ledges, but Potopov (1997) reported no effect of snow melting date or spring/summer temperatures on number of nesting pairs. Individuals that nest on steep slopes prone to slumping are at risk of failure. On Bylot Island, Nunavut, 28% of 82 nesting structures monitored for up to 8 years were damaged by slumping, sometimes causing breeding failure (Beardsell et al. 2017). This hazard may increase in future years if warming leads to increased precipitation or permafrost thawing, two factors that may trigger slope movements, but may have no effect on population trend given that stable nesting habitat is common throughout the Arctic and Subarctic.

16.3.4.4 *Peregrine falcon*

The Peregrine falcon (*Falco peregrinus tundrius*) is one of the most well-studied raptor species in the world (Hickey 1969, Ratcliffe 1980, Cade 1982, Mearns and Newton 1988, Cade and Burnham 2003, Dawson et al. 2011, White et al. 2013, Anctil et al. 2014, Barnes and Gerstenberger 2015). In North America, interest in the species over the course of the last 50 years was in large part due to widespread population declines associated with contamination from organochlorine pesticides (Enderson et al. 1968, Peakall and Kiff 1988, Risebrough and Peakall 1988, Ellis et al. 1989, Court et al. 1990, Franke et al. 2010). Declines in North America were extensive in the United States (with virtually total extirpation in the east and severe declines in the west), and throughout southern parts of Canada east of the Rocky Mountains (Hickey 1969). Use of organochlorine pesticides was banned in Canada and the United States, in 1970 and 1972 respectively (USFWS 2008).

In the United States, the Arctic peregrine and American peregrine were removed from the list of endangered species in 1994 and in 1999, respectively (ESA 1973, as amended). In Canada, the Arctic peregrine and American peregrine were evaluated together (rather than as separate sub-species) and designated by COSEWIC to Special Concern (2007), and were legally listed as such on Schedule 1 of the Species at Risk Act in 2012 (SARA 2002, as amended). In the United States, legal harvest of peregrines was re-instated in 2009, and the current harvest level allows an annual take of up to 116 nestling and post-fledging first-year Peregrine falcons from the nesting period through 31 August west of 100 degrees W longitude (including Alaska), and an annual take of up to 36 first-year migrant peregrine falcons from 20 September through 20 October from anywhere in the U.S. east of 100 degrees W. Take of nestling peregrines is administered by the individual States, and take of passage peregrines in the U.S. is agreed upon, and allocated by, the Central, Mississippi, and Atlantic Flyway councils (USFWS 2008).

Anctil (2012) combined nest observations with a field experiment to investigate the direct effect of rainfall on

survival of Peregrine falcon nestlings in the Canadian Arctic. The authors indicated that the direct effects of rainfall caused more than one-third of the recorded nestling mortalities. Nestlings sheltered from rainfall by a nest box had significantly higher survival rates. The long-term decline in productivity (Franke et al. 2010) was associated with an increase in the frequency of heavy rain over the last three decades was likely an important factor explaining the decrease in annual breeding productivity of the population (Anctil et al. 2014).

Franke et al. (2011) evaluated the effect of climate across the annual life cycle (breeding, outward migration, wintering, and inward migration) on apparent annual survival of arctic-breeding Peregrine falcons. Apparent annual survival of adult Peregrine falcons was correlated with the North Atlantic Oscillation Index (NAO) during outward migration (i.e. flight from the Arctic breeding grounds). The combined effects of Outward NAO at time t (positive) and Outward NAO at time $t-1$ (negative effect) explained 35% of the variation in apparent survival. Local rainfall and local summer temp in Rankin had no effect on survival, despite long-term changes in the precipitation regime (Anctil et al. 2014) and summer temperature (Franke et al. 2010). Although positive NAO is associated with storms during the period of outward migration, positive NAO was directly correlated with survival, and may be related to the north-east trade winds that may improve conditions for migration despite increased frequency of storms. The negative effect of NAO $t-1$ was explained as an indirect effect of poor weather in year $t-1$ which potentially reduced prey availability in year t . So, on the basis of this study, a low NAO in year $t-1$ followed by a high NAO in year t would be the best conditions for survival of Peregrine falcon in year t , because year $t-1$ would be associated with high food availability (potentially resulting in better over winter survival), and year t would be associated with good weather conditions for migration.

Franke (2016) used a Lincoln-Petersen model to estimate the population size of northern-reared Hatch Year (the cohort of individuals known to have hatched during the calendar year in which they were banded) for Peregrine



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falcons based on mark and recapture data from northern North America (including Greenland) from 1970-2010. The analysis supported a previous finding that migratory populations in western and eastern North America tend to remain separate, and are best analysed as two distinct populations. The annualized Lincoln-Petersen estimate for the western population was $16\,035 \pm 2\,040$ falcons and $5\,245 \pm 500$ falcons for the eastern population, or approximately 21 000 Hatch Year falcons when summed. Using productivity of 1.4 young/occupied site resulted in an estimate of the northern breeding population of more than 15 000 pairs or 30 000 breeding adults. Assuming that the number of non-breeding adults was equal to the number of breeding adults, the estimated total annualized adult breeding-aged population was in excess of 60 000 falcons, and the total combined population at the end of a breeding season was in the order of 80 000 falcons by the year 2000. The Peregrine falcon is no longer legally threatened in Canada or the United States, and legal harvest

of wild-caught migratory Peregrine falcons is permitted for the practice of falconry. Using the United States Fish and Wildlife Service harvest guideline, and the annualized estimate of Hatch Year falcons reported by Franke (2014) (after mortality), it appears that the combined annual harvest limit in Canada, the United States and Mexico could be conservatively set at 840 Hatch Year falcons without negative impact to the breeding population.

16.3.5 Fish

16.3.5.1 Arctic char

Arctic char (*Salvelinus alpinus*) are the most northerly freshwater fish and have a circumpolar distribution. Arctic char are found in marine, brackish, and freshwater environments along the coasts of Nunavut. Arctic char are well suited to the variable arctic habitat; many populations of Arctic char have been documented exhibiting at least three life history forms – landlocked, resident and anadromous

(Loewen et al. 2009, Moore et al. 2013). It is common for Arctic char populations to exhibit different life history forms as the species is considered very adaptable and plastic (Jonsson and Jonsson 1993). Landlocked Arctic char are in lake systems with no access to the sea (A. Young, personal communication). Resident Arctic char are defined as individuals who reside in freshwater environments, have access to the marine environment but select not to migrate. Anadromous Arctic char are individuals who overwinter and reproduce in freshwater but migrate to saltwater for feeding during the open ice periods. The two latter life history forms differ in their migration behaviour, and age and size at first maturity (Loewen et al. 2009). Despite these life history differences resident and anadromous Arctic char are able to reproduce successfully with each other (Moore et al. 2013). It is important to understand the variability of Arctic char populations to understand how a changing climate in climate may affect different life history types (or populations) of this species.

There are hundreds of Arctic char populations in Nunavut, each individual river, river/lake or lake system with Arctic char present is typically seen as an individual population. Movements within and among these populations are not well understood. We do know that annually most anadromous Arctic char move from the freshwater environments to the saltwater environments in the spring, typically during spring break-up (Jonsson and Jonsson 1993, Loewen et al. 2009). In the saltwater environment the Arctic char feed on marine invertebrates and other prey sources (Loewen et al. 2009), but movements and potential migrations within the marine environment have not been studied in detail. In the late summer or early fall anadromous Arctic char migrate back to the freshwater environment for the purpose of reproducing and/or overwintering. Moore et al. (2013) studied the rate of dispersal among anadromous Arctic char populations in Cumberland Sound and found dispersal rates to be high (15-25%) compared to other salmonid species, but that most individuals who were documented as dispersers were not in a reproductive state leaving the gene flow between populations low. This complex migration is thought to be an adaptive strategy for Arctic char persistence. Climate change may affect the water levels that provide fish passage. For

example, in recent years stranding and subsequent death of anadromous Arctic char have been documented when water levels in rivers drop too low (R. Tallman, Fisheries and Oceans, Winnipeg MB, personal observations). Individuals from those populations who have dispersed to other locations may survive the winter and are assumed to return to their natal stream for reproduction in future years. Any changes to water levels within the Arctic may directly affect Arctic char by making rivers impassable due to water being too low during times of drought or currents being too fast during times of additional precipitation or melt.

Climate change is expected to raise ambient and surface sea temperatures which will in turn affect the length of the ice-free period in Arctic waters (Maslanik et al. 2011). Longer ice free seasons have already been noted by local fishermen in Nunavut (Z. Martin, Fisheries and Oceans Iqaluit, NU. pers. comm.). Higher sea water temperatures will increase the ice-free season which may allow Arctic char longer access to marine food sources and may provide arctic char a longer growing season in their optimal growing temperature (Reist et al. 2006). In contrast, extended ice-free periods may result in increased predation from marine mammals, and unexpected mismatch timing of Arctic char migration and marine food source presence. It is not known how Arctic char populations will react to the increased sea water temperatures, monitoring and research are required.

Climate change has resulted in southern fish species expanding their ranges into Arctic waters (Marcoux et al. 2012). In recent years there has been a study conducted on the diet shifts of Arctic char with the presence of a novel species – Capelin. Ulrich (2013) documented that within the last decade Arctic char in Cumberland Sound have shifted their marine diet from zooplankton to capelin. Foraging capelin may result in increased growth for Arctic char, as capelin are a high-quality food source (Ulrich 2013). In contrast, Arctic char that consume capelin may be less economically valuable due to potential changes in the colour and taste of the meat (Z. Martin, Fisheries and Oceans Canada, pers. comm.). In addition to the presence of new prey species, Arctic char in Europe may be faced

with more inter-species competition for resources should competitive species such as brown trout (*Salmo trutta*) extend their range (Amundsen and Knudsen 2009). Arctic char are known to be a non-aggressive species and when coexisting with competitive species tend to be highly specialized to small niches compared to when they exist as the sole species in an environment (Saksgard and Hesthagen 2004, Amundsen and Knudsen 2009). The range extensions of southern fish species are expected to greatly impact Arctic char populations, it is unknown if these impacts will be positive or negative, monitoring and research are required. Arctic char are an important subsistence resource for local Inuit (Mead et al. 2010), thus changes to Arctic char populations, will directly impact Nunavummiut.

16.3.5.2 Capelin

In the last decade it has been observed that capelin, a pelagic forage fish, have invaded the Cumberland Sound area (Marcoux et al. 2012). Other northern regions, such as Hudson Bay, have also experienced increases in capelin availability (Gaston et al. 2003). These observations support the suggestion of Huse and Ellingsen (2008) that capelin would establish new spawning areas in response to predicted climate change scenarios. Capelin populations have historically undergone extensive distribution shifts that have been linked to the species' ability to respond quickly to changes in ocean temperatures, which led Rose (2005) to call capelin a "canary" of the sea with respect to climate change. Changes in capelin populations can have a cascading effect on ecosystems as they are a key forage species for a wide range of predators, including finfish, marine mammals, and seabirds (Gaston et al. 2003, Krumsick and Rose 2012, Marcoux et al. 2012).

In addition to distribution, there are documented cases of changes in capelin reproductive biology linked to climate conditions (notably water temperature), which include changes in timing and location of spawning, natural mortality, and recruitment (Carscadden et al. 2001, Davoren 2013). Capelin are a short-lived (3 to 6 years), schooling species that are characterized as having high mobility, high energetic needs, and variable recruitment (Carscadden

et al. 2001). In general, capelin mature at 3 to 4 years of age in June, July, or August, and the location of spawning is either intertidal or demersal (Carscadden et al. 2001, Davoren 2013). The feeding ecology of capelin has not been described in the Cumberland Sound region, but capelin diets described from West Greenland and the North Atlantic had similar prey items (O'Driscoll et al. 2001, Hedeholm et al. 2012). Important prey items for capelin in these regions include copepods, hyperiid amphipods, and euphausiids (O'Driscoll et al. 2001, Hedeholm et al. 2012). Capelin is known to be an important forage species for Arctic char in regions where ranges of these two species overlap (Dempson et al. 2002). In Labrador, drastic changes in capelin availability have been linked to shifts in Arctic char diet and proposed changes in Arctic char population characteristics (Dempson et al. 2002, Dempson et al. 2008). More specifically, Arctic char growth rates decreased during a period of anomalous climate conditions that was accompanied by significant decreases in capelin availability (Michaud et al. 2010). This evidence shows that with the presence of capelin in Arctic waters fish communities and populations are being impacted. Further, it is known that the presence of capelin is directly linked to increasing sea water temperatures. What is not yet known is how the presence of capelin in the long-term will impact the Arctic marine food-web and Arctic fish community – this requires monitoring and research.

16.4 Outlook for managed wildlife

Notwithstanding the importance of the effects of climate change, the outlook for managed wildlife in Nunavut will depend on the manner in which wildlife agencies interact with one another, and the ways in which competing territorial priorities are set.

Wildlife in Nunavut is co-managed and involves varied perspectives and objectives of multiple agencies. In addition, management efforts are now commonly undertaken within the context of species-specific management plans that explicitly recognize scientific knowledge and *Inuit Qaujimajatuqangit*. A multi-stakeholder approach to wildlife management is entrenched in the NLCA.

As with other Arctic jurisdictions, ongoing population-level management of wildlife in Nunavut will be increasingly complicated by the interacting pressures associated with a growing human population (and its demands on the landscape), cultural importance of wildlife (Wenzel et al. 2016), changing climate (Post 2013), food security (Ford et al. 2016, MacDonald et al. 2016) and societal impacts (positive and negative) associated with a developing economy (Rixen and Blangy 2016). Increased community-based monitoring of wildlife could contribute to ensuring ongoing Inuit engagement in science and monitoring, and improve data collection for population trends and harvest estimates. Ensuring that environmental stewardship does not become secondary to a developing economy is likely to become one of the greatest challenges for managing wildlife.

The main management species in Nunavut are marine mammals including polar bear, caribou, muskox and furbearers (fox, wolverine, and wolf), the latter being managed to a lesser degree. Wildlife in Nunavut is generally managed for harvest and/or to prevent populations from becoming too small or too large. Information on abundance and distribution of some species (e.g., whales and pinnipeds) is limited, making any assessment of current status and trends very difficult and projections of climate-related trends even more challenging. Seven Arctic marine mammal species found in Nunavut marine waters are important to Inuit with respect to harvesting for subsistence, economic benefits, and cultural wellbeing (Egeland et al. 2010, Hoover et al. 2013). It is almost certain that these species will remain culturally important and will continue to be an important source of country food in the region.

Climate warming will likely affect access to hunted species; for some species, access is expected to decrease due to changes in distribution (e.g., beluga), abundance (e.g., walrus), or due to sea-ice conditions that result in reduced safety for hunters traveling on the ice. (e.g., thin ice or more frequent storms). On the other hand, accessibility to open water species (e.g., whales) may increase as a result of longer ice-free periods and better access to modern sea-going watercraft.

The Report for Policy Makers of the Arctic Biodiversity assessment (CAFF 2013b) emphasized that climate change is the most significant driver of overall change in biodiversity in the Arctic. However, the effects of climate change will occur within the context of cumulative pressures including industrial development, contaminants and hunting (e.g., caribou, polar bear, and narwhal), and competing priorities among government and Inuit agencies promoting environmental stewardship and economic development.

The challenge for Nunavut will be to mitigate cumulative impacts. This will be particularly important for critical areas, such as calving grounds, den sites, feeding grounds, migration routes and moulting areas. This will mean protecting important habitats such as wetlands and polynyas at scales that preserve functional connectivity, ecosystem resilience and facilitate adaptation to climate change.

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Chapter 17 Marine Biodiversity Conservation

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Key implications for decision makers

- A network of Marine Protected Areas (MPAs) could protect biodiversity from species to ecosystem, help to maintain the protection of unique, endemic, rare, and threatened species and protect ecological processes which are essential for ecosystem functioning, such as spawning and nursery habitats. In light of climate change, this MPA network could enhance ecological resilience to anthropogenic disturbance and increase the social and economic benefits by promoting cultural heritage, sustainable fisheries, and more effective outreach and education.
- A total of 29 Ecologically and Biologically Significant Areas (EBSAs) from the Hudson Bay Complex, Eastern Arctic, Arctic Basin and Arctic Archipelago are present in the IRIS 2 region. EBSAs were based mostly on large animals and the shallow coastal zone was poorly considered in the selection of these areas. A re-evaluation of EBSAs is in progress.
- There is a need for long-term environmental monitoring and prediction of change by setting up a series of indicators (both for physical and biological features), to truly understand arctic ecosystems, as well as manage human activities and cumulative impacts. Community-based monitoring initiatives for the shallow coastal zone is needed to improve monitoring and detect ecosystem change.
- Parks Canada, the Government of Nunavut, and the Qikiqtani Inuit Association (QIA) have been working since 2009 to collect information and consult on the creation of a national marine conservation area in Lancaster Sound (called Tallurutiup Imanga, in Inuktitut). In 2017, these groups announced the final boundary for a national marine conservation area in this region.

Abstract

Bearing in mind the impact of climate change and ocean warming on marine ecosystems and their biodiversity, the Government of Canada is developing a national network of Marine Protected Areas (MPAs) in collaboration with the provinces and territories. Particular attention has been paid to the Arctic where few bioregional initiatives have yet been implemented in an effort to conserve marine resources. Based on guidance developed by Fisheries and Oceans Canada, 29 Ecologically and Biologically Significant Areas (EBSAs) were identified in the Eastern Canadian Arctic. The outstanding biological/ecological features require a more advanced characterization of the sites, including western and eastern Hudson Strait, Hatton Basin and entrance to Hudson Strait, south Baffin Bay Narwhal overwintering area, Lancaster Sound, North Water Polynya and Arctic Basin multi-year pack ice and Arctic Archipelago Islands. The development of MPAs will help mitigate the impacts of climate change on marine ecosystems and on terrestrial species associated with the marine environment.



JEAN-JACQUES PANGRAZI/ARCTICNET

17.1 Introduction

The past decades have seen the development of many indicators for marine biodiversity monitoring, since efforts by national and international organisations have been aimed at better protecting ocean resources and academic studies have shown increasing global pressure on those resources (Jackson et al. 2001, Halpern et al. 2008). The Government of Canada is working with the provinces and territories to conserve Canada's marine ecosystems through the development of a national network of Marine Protected Areas (MPAs). Canada has the world's longest coastline, 16.2% of the world coastline, of which the Arctic contributes 10% (Archambault et al. 2010), three oceans, the Great Lakes and a sea of Arctic ice - all of which support an elaborate web of marine life. The assessment of biodiversity is a way to measure ecosystem health and inform management aimed at gaining and maintaining long-term benefits for Arctic marine ecosystems.

As defined by the International Union for Conservation of Nature (IUCN), a MPA is "a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values." There are different types of MPAs in Canada and these have been designated using federal, provincial and territorial legislation. While some are fully protected, most allow multiple uses, or integrate fully protected zones within larger multiple-use areas. Some MPAs offer year-round protection while others are seasonal; seasonal protection is appropriate for spawning or nesting sites or for buffering sensitive areas that may be threatened by human activities at specific times of the year.

Canada's national network of MPAs will be composed of 13 bioregional networks (Figure 1) - 12 within Canada's oceans, one in the Great Lakes. All of these bioregional networks will share a common foundation, including

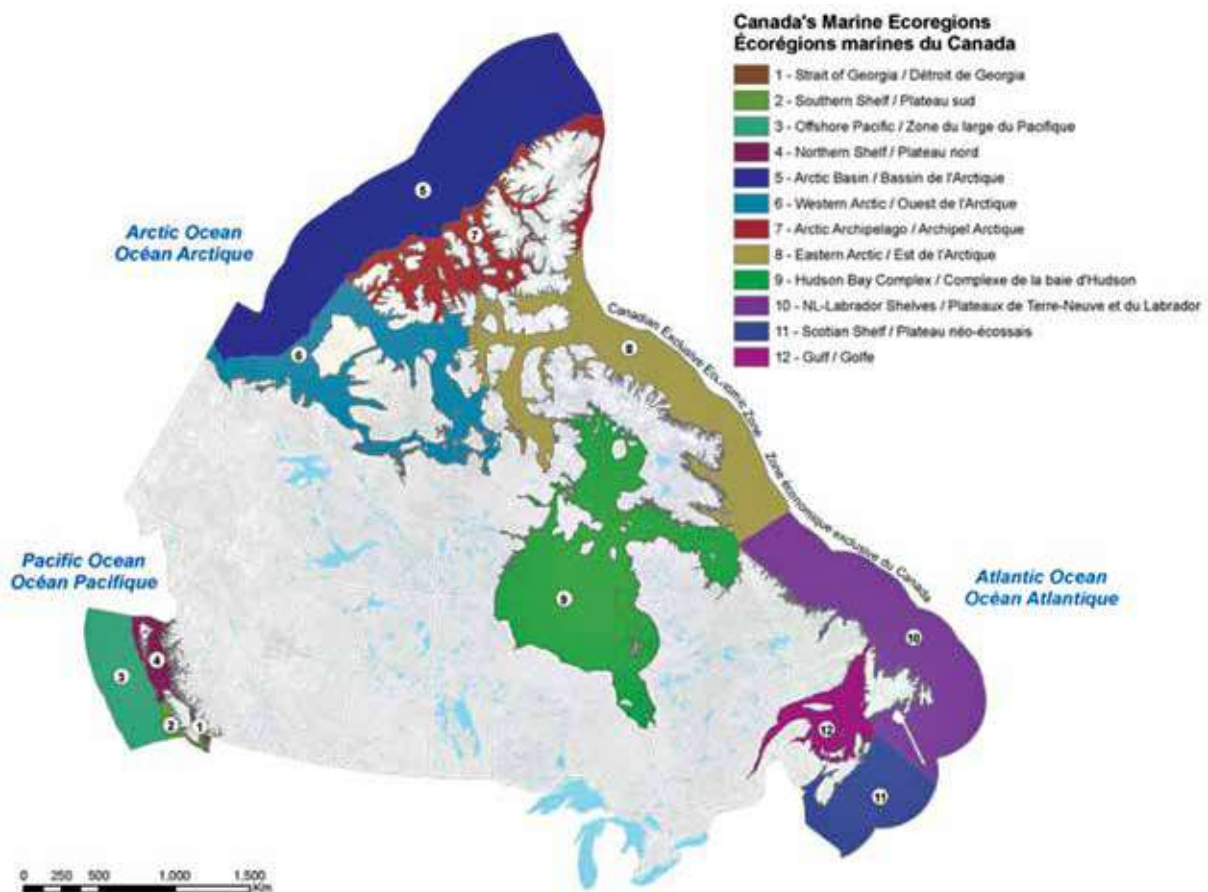


FIGURE 1. The recommended major biogeographic units for Canadian marine areas (DFO 2009).

vision, goals, principles, design properties and eligibility criteria, as outlined in the National Framework for Canada's Network of MPAs (Government of Canada 2011). Each bioregional network will be designed to suit its own unique geography, management tools, and ecological and socio-economic objectives.

The Eastern Canadian Arctic overlaps four bioregions: Arctic Basin, Arctic Archipelago, Eastern Arctic, and Hudson Bay Complex (Figure 1). The Nunavut Planning Commission identified areas of important marine habitat that should be considered for protection and management: the North Baffin Regional Land Use Plan and the Keewatin Regional Land Use Plan have recently been approved (Nunavut Planning Commission 2000). These land use plans will provide guidance and direction for the conservation, development and utilization of land within the respective planning regions. At this time there are no active bioregional planning initiatives by governments in the Eastern Arctic, since the intensity of uses in the surrounding waters were historically limited. However, since climate change and reduced sea-ice cover may lead to poleward expanded fisheries in the near future (Christiansen et al. 2013), many efforts are now deployed to protect and preserve intact parts of the marine ecosystems so as to conserve Arctic marine biodiversity.

In this chapter we outline tools that have been developed to call attention to areas that have particularly high ecological or biological significance (EBSAs, Dunn et al. 2014) and we present marine biodiversity conservation areas in the Eastern Arctic.

Conservation is defined as: “a scientific enterprise and social movement that seeks to protect nature, including animals, plants, and ecosystems. Conservation scientists apply principles from ecology, population genetics, economics, political sciences, and other natural and social sciences to manage and preserve the natural world” (Kareiva and Marvier 2011). More simply, conservation is also defined as sustainable use that protects ecological processes and genetic diversity for present and future generations.

17.2 Ecologically and biologically significant areas in the Eastern Canadian Arctic

In October 2012, the Convention on Biological Diversity (CBD) proposed seven scientific criteria for identifying Ecologically and Biologically Significant Areas (EBSAs) in need of protection in open-waters and deep-sea habitats: (1) uniqueness or rarity, (2) special importance for life history stages of species, (3) importance for threatened, endangered or declining species and/or habitats, (4) vulnerability, fragility, sensitivity or slow recovery, (5) biological productivity, (6) biological diversity, and (7) naturalness. At that time, many countries already had an objective to facilitate the description of EBSAs.

In Canada, a national science advisory process (Canadian Science Advisory Secretariat - CSAS) was held in Winnipeg (Manitoba) in June 2011 to provide science advice on the identification of EBSAs in the Canadian Arctic based on guidance developed by Fisheries and Oceans Canada (DFO 2004). A total of 61 EBSAs have been identified within the five marine biogeographic regions in the Canadian Arctic (Figure 2). As new scientific information and local

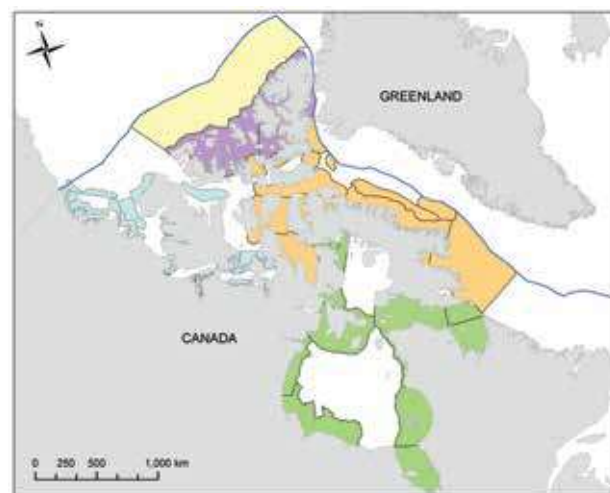


FIGURE 2. EBSAs identified within the five Arctic biogeographic regions (from DFO 2011, 2014a, 2014b). The blue dashed line represents Canada's Exclusive Economic Zone. See Table 1 for list of EBSAs.

knowledge comes available, revisions may be made to the current EBSAs and/or more may be added or removed from this list (e.g., DFO 2015).

Twenty-nine EBSAs from Hudson Bay Complex, Eastern Arctic, Arctic Basin and Arctic Archipelago are present in the IRIS 2 region (Table 1). Some EBSAs were given greater priority due to their national and/or global ecological/biological significance (DFO 2011); we present the main characteristics of these EBSAs below.

TABLE 1. Ecologically and Biologically Significant Areas identified by DFO (2011, 2014a) in the Eastern Canadian Arctic.

Hudson Bay Complex	Eastern Arctic
1.1 Fury and Hecla Strait	2.1 Eclipse Sound/Navy Board Inlet
1.2 Igloolik Island	2.2 Admiralty Inlet
1.3 Rowley Island	2.3 Prince Regent Inlet
1.4 Repulse Bay/Frozen Strait	2.4 Gulf of Boothia
1.5 Southampton Island	2.5 Peel Sound
1.11 Western Hudson Strait	2.6 Lancaster Sound
1.12 Eastern Hudson Strait	2.7 Wellington Channel
	2.8 Hatton Basin-Labrador Sea-Davis Strait
Arctic Archipelago	2.9 Cumberland Sound
4.1 Multi-year Pack Ice	2.10 Baffin Island Coastline
	2.11 Baffin Bay Shelf Break
Arctic Archipelago	2.12 Southern Baffin Bay
5.1 Ellesmere Island Ice Shelves	2.13 Northern Baffin Bay
5.2 Nansen-Eureka-Greely Fiord	2.14 North Water Polynya
5.3 Archipelago Multi-year Pack Ice	2.15 Eastern Jones Sound
5.4 Norwegian Bay	2.16 Cardigan Strait/Hell Gate
5.5 Princess Maria Bay	

17.2.1 Western (EBSA 1.11) and Eastern Hudson Strait (EBSA 1.12)

The key physical feature of Hudson Strait (Figure 3) is its strong currents, acting as a conduit for Arctic waters via Foxe Basin. As the West and central Hudson Strait region is a unique body of water, the Eastern Hudson Strait is heavily influenced by Atlantic waters (Cobb 2011). In comparison to Hudson Bay or Foxe Basin, productivity in Hudson Strait

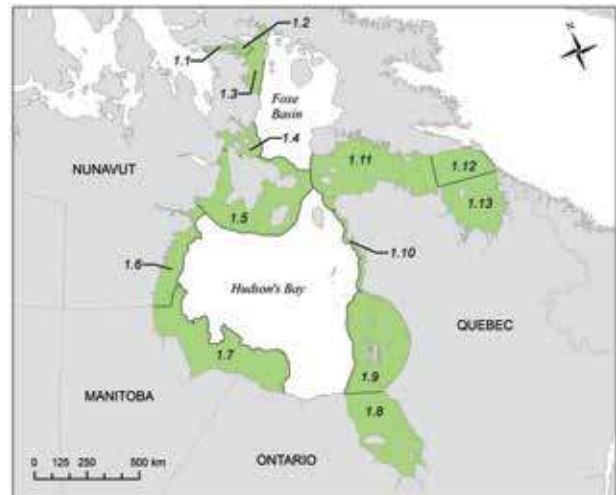


FIGURE 3. EBSAs identified within the Hudson Bay Complex biogeographic region (DFO 2014a, DFO 2011). EBSAs (1.1) Fury and Hecla Strait, (1.2) Igloolik Island, (1.3) Rowley Island, (1.4) Repulse Bay/Frozen Strait, (1.5) Southampton Island, (1.11) Western Hudson Strait, and (1.12) Eastern Hudson Strait are within the IRIS 2 area. See Table 1 for complete list of EBSA names.

is high. Barber and Massom (2007) report a major shore-lead polynya extending along the northern coast of Hudson Strait. Hudson Strait is a major seasonal migration route for marine mammals such as beluga, narwhal and bowhead. This area includes walrus haul-out sites, killer whales, overwintering bowhead and beluga and is critically important for marine mammal feeding and rearing. In addition, there are many seabirds nesting and feeding areas on the northern and southern shores.

17.2.2 Hatton Basin-Labrador Sea-Davis Strait (EBSA 2.8)

Hatton Basin and the entrance to Hudson Strait (Figure 4) are the major outflows of water exiting the Canadian Arctic Shelf seas into the Labrador Sea. The high currents and associated high productivity (Chapter 5) help sustain high populations of invertebrates, fishes, and marine mammals. Compared to other regions within their respect NAFO fishing zones, the southern and western boundaries of Hatton Basin are very heavily fished for shrimp, and the northeastern margin is

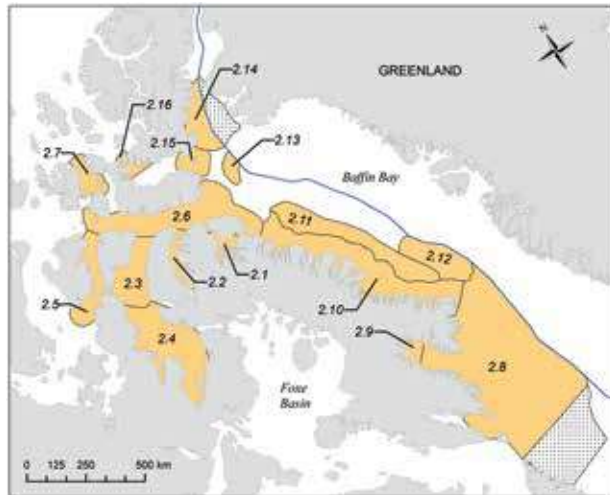


FIGURE 4. EBSAs identified within the Eastern Arctic biogeographic region. The Davis Strait EBSA (2.8) is defined by the biogeographic region boundary, however, the ecological and biological feature(s) extend beyond into the Labrador-Shelf's biogeographic region (identified by the red stippled area adjacent). This is also the case for the North Water Polynya EBSA (2.14), where the ecological and biological features extend into Greenlandic waters to the East. The blue line represents Canada's international boundary. All EBSAs shown are within the IRIS 2 region. (DFO 2011). See Table 1 for list of EBSA names.

heavily fished for Greenland halibut. The central and eastern parts of Hatton Basin are not generally fished due to gear damage caused by its rough bottom and a voluntary closure (Edinger et al. 2007a).

The eastern edge of the Hatton Basin and the northeast edge of Saglek Bank, near the eastern exit from Hudson Strait, are the most important sites for deep-sea corals and sponges in the Eastern Canadian Arctic, for combined high biomass and high biodiversity (Edinger et al. 2007a, Kenchington et al. 2011, Knudby et al. 2013, Kenchington et al. 2016). This area has the highest rate of coral bycatch in standardized survey trawls of any site in the Canadian Arctic or the Newfoundland and Labrador shelf regions (Edinger et al. 2007b), indicating high abundances of large, long-lived corals. The coral fauna on the south side of Hatton Basin and NE Saglek Bank is dominated by hard-substrate-dependent corals such as popcorn coral (*Primnoa*

resedaeformis) and bubblegum corals (*Paragorgia arbor-
ea*), while the north side of Hatton Basin and SE Baffin Shelf are dominated by soft-substrate corals such as sea pens, black corals (antipatharians) and the bottlebrush coral *Acanella arbuscula* (Edinger et al. 2007a). Possible cold-seep-related mounds have been identified in the Hatton Basin EBSA (Jauer and Budkewitsch 2010).

In 2007, the central part of Hatton Basin was given some protection from fishing impacts through the establishment of a 12 500 km² voluntary closure (Figure 5) sponsored by three fishing industry groups. This voluntary closure adopts a “freeze-the-footprint” approach, where fishing skippers agreed not to fish in an area they already avoided due to gear damage (MPA News 2007). Because some scientists think this area is too small (DFO 2017, Gilkinson and Edinger 2009, Kenchington et al. 2016), this area will

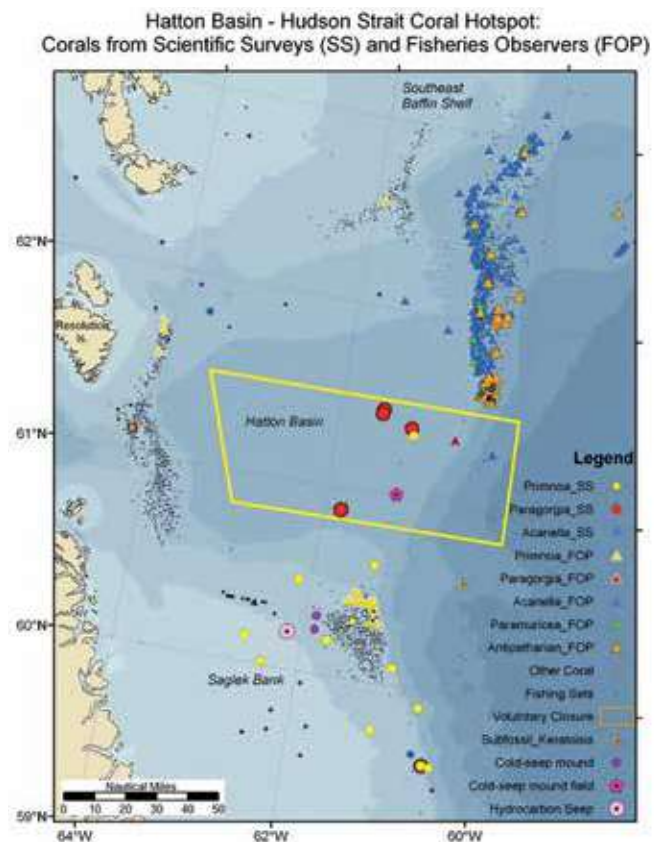


FIGURE 5. Coral distributions surrounding the voluntary closure in Hatton Basin and Entrance to Hudson Strait. Based on data in Edinger et al. (2007) and Wareham (2009). SS refers to scientific survey trawls, while FOP refers to data from the Fisheries Observer Program.

likely be enlarged and converted to a DFO fishery closure. In addition to the importance of this area for commercial fisheries, corals and sponges, its productive waters support a variety of marine mammals and seabirds (DFO 2011).

17.2.3 South Baffin Bay narwhal overwintering area (EBSA 2.12)

At the southern end of Baffin Bay, just north of the sill separating Baffin Bay from the rest of the Labrador Sea (Figure 4), is the more southerly of two overwintering areas for narwhals. This location coincides with deep-sea coral aggregations; large fisheries bycatches of bamboo corals *Keratoisis grayi* were recorded in this area and abundant other coral species, such as black corals sea pens (DFO 2007, Wareham 2009). An ArcticNet Remotely Operated Vehicle (ROV) dive on this site in 2013 found dense stands of *Keratoisis*, and showed devastating impacts of a single trawl pass (Neves et al. 2014). This area had been fished for Greenland Halibut using gillnets, but now has protection under a *Fisheries Act* closure (DFO 2007).

17.2.4 Lancaster Sound (EBSA 2.6)

Lancaster Sound (Figure 4) is one of the Arctic's most biologically productive marine areas (Chapter 5). It is characterised by polynyas, which are areas kept open from ice by wind and currents, and associated sea-ice-edges. Two polynyas are located in this area, one is along the northern coast of Lancaster Sound and the other at the eastern outflow (Barber and Massom 2007). Lancaster Sound is a major migratory corridor for many marine species, and generates a high productivity and a high export of sea-ice algae, providing a high-quality food supply for benthos (Chapter 5). Kenchington et al. (2011) highlighted that the Lancaster Sound and Barrow Strait area supports high benthic abundance, biomass and diversity. The high diversity and production found in this area also induce high benthic remineralization (Link et al. 2013).

Moreover, Lancaster Sound is used as a feeding area for the highest density of polar bears anywhere in the Arctic and as a walrus haul-out site. Finally, over 1 000 000 seabirds

and seabirds use this area as a nesting, feeding and breeding area (DFO 2011).

17.2.5 North Water Polynya (EBSA 2.14)

The North Water Polynya is one of the Arctic's largest open-water areas and the most biologically productive polynya in the Arctic (Figure 4) (Chapter 5). The IUCN has identified the North Water Polynya and Lancaster Sound as a super EBSA following the CBD criteria (Speer and Laughlin 2011). While thin ice does form in some areas, the polynya is kept open by wind, tides and an ice bridge on its northern edge. This physical feature allows an unusually early spring plankton bloom, providing food for many other species. This high-quality food supply is consumed by benthic communities and increases the remineralization at the bottom (Link et al. 2013). This rich polynya also provides shelter for a large concentration of marine mammals, from walrus to seals and polar bears, which feed at the ice edge until spring break-up. Finally, this habitat provides vital feeding grounds for millions of seabirds, including most of the Canadian population of Ivory gull (DFO 2011).

17.3 MPAs

MPAs are one of the principal approaches to protecting biodiversity in the oceans, as they form a broad collection of marine areas in which human activities are regulated by some form of legal system. Most of them are zoned, such that some human activities are permitted in some locations, and other activities are restricted or prohibited. Some MPAs include no-take zones (NTZs), in which all fishing and other resource extraction activities are prohibited. Nevertheless, in Canada, traditional cultural uses of marine renewable resources are permitted in MPAs.

On the whole, protecting an area of the sea from resource extraction, including fishing, protects both the habitat and the populations of organisms that would normally be exploited. Fishing, particularly modern industrial-scale fishing can cause damage to habitats, especially to plants and animals that create or structure habitat for other marine plants and animals (Norse and Crowder 2013). Examples of such

habitat-forming plants and animals in the Eastern Canadian Arctic include seaweeds, calcareous red algae, cold-water corals, sponges, and bryozoans (Buhl-Mortensen et al. 2010).

Although MPAs cannot prevent climate change, they have positive effects on biological communities. Scientists have studied more than 124 marine reserves around the world and monitored biological changes inside them. A synthesis of these studies has shown that fishes, invertebrates, and seaweeds typically have grown bigger and have become more abundant inside marine reserves (Lester et al. 2009). Moreover, biodiversity is also considerably higher within marine reserves. Eastern Arctic reserves have not been specifically considered in this synthesis, but both temperate and tropical marine reserves have been shown to be effective (Lester et al. 2009).

17.4 Indirect benefits

An often underestimated benefit of marine protected habitats is the positive effects of conservation on terrestrial species. When it is covered by ice, the marine environment indeed becomes an important habitat for some tundra wildlife predators. The Arctic fox provides such an example. The fox population of Bylot Island has been intensively studied over the last 10 years, especially since 2007 when some individuals have started to be fitted with Argos satellite collars. Tracking of individuals revealed that some of them ranged long distances and spent considerable time foraging and traveling on the sea ice (Tarroux et al. 2010), as shown in Figure 6. It is very likely that the density of Arctic foxes in the tundra would be much lower if they had no seasonal access to the productive marine ecosystem.

Polar bears are also a sea-ice-dependent species and will be affected directly by climate change threats to the marine ecosystem (Stirling and Derocher 2012). Polar bears require sea-ice habitat for foraging, mating and in some regions for denning. The timing of key events in their life history is coupled with that of their primary prey, the ringed seal, which emerges from dens with cubs of the year and spring seal pupping. Loss of sea-ice habitat, caused by climate change, is the greatest threat to polar bear populations.

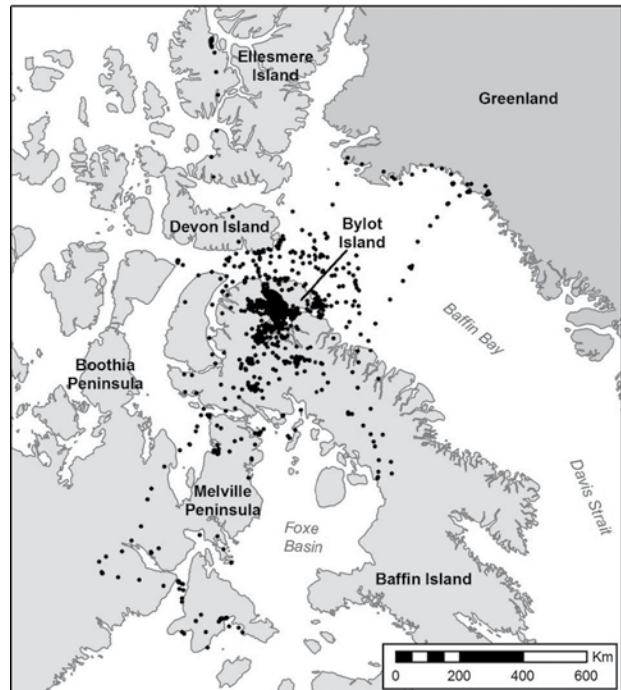


FIGURE 6. Map of the Eastern Canadian Arctic showing movements of 80 Arctic foxes tracked for various periods of time from 19 July 2007 to 31 May 2012. Black dots represent fox locations. Only one location per day is shown for each individual, for a total of 26,700 locations shown on this map. All foxes were captured and fitted with satellite collars on the southwest plain of Bylot Island. Note the heavy use of Eclipse Sound and Navy Board Inlet (between Bylot and Baffin) and the regular use of Lancaster Sound. Also note some long travels to Greenland or Southampton Island.

Therefore, locating seasonal or permanent protected areas in key locations could minimize disturbance to polar bears when sea-ice habitat is in short supply during late spring and summer. This would permit polar bears and other ice-dependent species undisturbed time to maximize foraging and enhance adult and offspring survival. Polar bears come onshore when there is no sea ice and to den. While polar bears can occur anywhere on land within their range, there are known summer retreat areas in the seasonal sea-ice ecozone (e.g., Cape Churchill, NE Bylot Island). MPA designation should take into account retreat areas when boundaries are designated. This would permit enhanced protection of polar bears during the summer season when

they need to conserve energy during this period of fasting. Additional research is required on polar bear den habitat and distribution. Polar bears are known to den in concentrated areas (e.g., northeastern Southampton Island) and individually, dispersed over the landscape (Ferguson et al. 2000, Harington 1968). Where denning areas are known it is important to ensure safe access and egress from the den sites to the spring sea ice.

17.5 Resource exploitation

Studies on the effects of closing an area to fishing have been done in tropical and subtropical environments, especially coral reefs, but also in temperate environments (see reviews by Mora et al. 2006, Stewart et al. 2009). When an area is closed to fishing, the populations of the target species generally rebound; the strength of this rebound is strongest in species that do not migrate. As large predatory fish populations recover, they may cause a decrease in the abundances of some smaller fish species, but fish diversity generally increases (Norse and Crowder 2013). The few studies of fishery closures in polar latitudes have found similar rebound effects on target species, although recovery is usually slower than in tropical reef fishes, which are generally small and non-migratory. Please see Chapter 18, Section 19.3 for more information on resource exploitation related to fisheries in the Eastern Canadian Arctic.

17.6 MPAs in the Eastern Canadian Arctic

Within the Canadian federal government, Environment and Climate Change Canada, Parks Canada and Fisheries and Oceans Canada have the mandate to protect significant nature areas and habitats by managing complementary parks and protected area programs.

17.6.1 National wildlife areas and migratory bird sanctuaries

Environment and Climate Change Canada, directly and/or through partnership arrangements, establishes and manages National Wildlife Areas (NWA) and Migratory Bird Sanctuaries (MBS) for the conservation of significant

marine and/or terrestrial areas that protect migratory birds, species at risk and other species of national importance and their habitat. There are sixteen Environment and Climate Change Canada protected areas in Nunavut (Figure 7), each site protecting both marine and terrestrial areas; it represents approximately 23.4 million hectares (10% of the territory as of 2010). Of these, five NWAs and seven MBSs are located in the Eastern Canadian Arctic (Table 2).

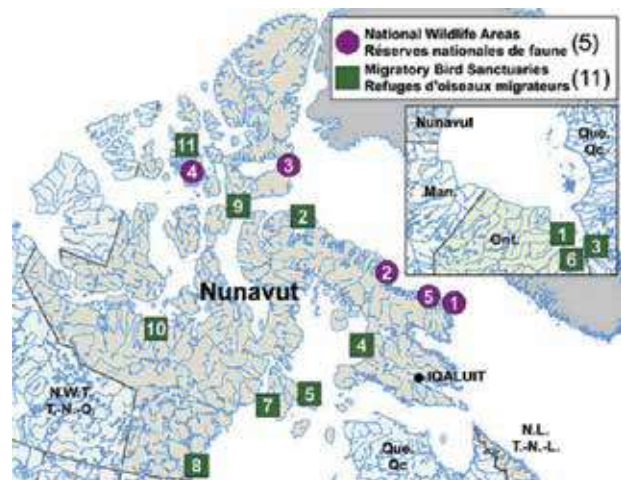


FIGURE 7. Environment and Climate Change Canada's protected areas in Nunavut (www.ec.gc.ca)

TABLE 2. Environment and Climate Change Canada's protected areas in Eastern Canadian Arctic: National wildlife Areas (NWAs) and Migratory Bird Sanctuaries (MBSs).

NWAs	MBSs
1 Akpait National Wildlife Area	2 Bylot Island
2 Ninginganiq National Wildlife Area	4 Dewey Soper
3 Nirjutiqavvik National Wildlife Area (Coburg Island)	5 East Bay
4 Polar Bear Pass National Wildlife Area	7 Harry Gibbons
5 Qaulluit National Wildlife Area	8 McConnell River
	9 Prince Leopold Island
	11 Seymour Island

Co-management of these protected areas between the Inuit of the Nunavut Settlement Area and the Government of Canada ensures that both traditional knowledge and expertise of the Inuit and the best scientific data are combined effectively in all decision-making processes. Covering 30 324 km², these nine conservation areas protect 9280 km² of marine habitat that is important to both marine wildlife and marine-foraging species, including:

- One of the largest bowhead whale concentrations in Canada at Isabella Bay, a species of special concern (Ninginganiq National Wildlife Area);
- One of Canada’s largest thick-billed murre colonies (at Akpait Fiord), and habitat for polar bears and other marine animals (Akpait National Wildlife Area); and

- Canada’s largest colony of Northern fulmars (at Cape Searle), and habitat for marine mammals such as walrus and ringed seals (Qaulluit National Wildlife Area).

17.6.2 National marine conservation areas

Parks Canada is responsible for developing a system of MPAs called the National Marine Conservation Areas (NMCA). The NMCA system divides Canada’s Pacific, Arctic and Atlantic Oceans and Great Lakes into 29 marine regions (Figure 8). Parks Canada’s goal is to represent each of these distinct marine regions with an NMCA.

NMCAs are established to protect, conserve and present examples of Canada’s marine areas for the benefit of present



FIGURE 8. National marine conservation areas are established to protect, conserve and present Canada’s most valuable and unique marine environments for the benefit, education and enjoyment of current and future generations. Parks Canada’s National Marine Conservation Areas System.

and future generations. An NMCA is managed and used in an ecologically sustainable way. Activities such as commercial and recreational fishing, shipping, transportation, and recreation and tourism can continue, however with an increased focus on habitat protection and sustainable use best practices. Each NMCA must also include zones which fully protect special features and sensitive elements of ecosystems. NMCAs will be managed in a way that respects traditional cultural uses and responds to the needs of local communities. Oil and gas exploration development, as well as seabed mining, are not permitted.

The Canadian Eastern Arctic overlaps with five of Parks Canada marine regions: Arctic Archipelago, Lancaster Sound, Baffin Island Shelf, Foxe Basin, and Hudson Strait. Since 2009, Parks Canada, the Government of Nunavut, and the Qikiqtani Inuit Association (QIA) have been actively working together to gather information and consult on the creation of a national marine conservation area (NMCA) in Lancaster Sound (or Tallurutiup Tariunga, as it is called in Inuktitut).

The establishment process follows the phases described in Figure 9, with the identification and selection phases completed a number of years ago. Studies and consultations were included as part of the feasibility assessment phase. The feasibility assessment, led by Parks Canada, the Government of Nunavut, and the Qikiqtani Inuit Association, recommended the current boundary of 109,000 km² in size, announced by all parties through a memorandum of understanding (MOU) in 2017. Public consultations, particularly in the local Inuit communities, played a key role in this feasibility assessment and final boundary recommendation. There was strong support by Inuit for the conservation and protection of Tallurutiup Imanga National Marine Conservation Area in Lancaster Sound. The boundary will be finalized through the Inuit



FIGURE 9. National Marine Conservation Areas establishment process.

Impact and Benefit Agreement, the next step in the establishment process.

The 2017 MOU commits the three parties to the protection of Tallurutiup Imanga as a national marine conservation area. It confirms their agreement to a boundary subject to minor modifications; confirms interim protection for the area; commits Parks Canada and the QIA to begin negotiation of the Inuit Impact and Benefit Agreement; commits the parties to develop an interim management plan with public consultations; and states that once these steps are completed, Canada will move to formally protect the area under the Canada National Marine Conservation Areas Act.

Once established, NMCAs are monitored using a series of indicators to assess the effectiveness of management plans through the development of “state of the NMCA” reports. These reports are produced periodically to provide directions concerning future management actions.

17.6.3 Fisheries and Oceans’s marine conservation tools

The Department of Fisheries and Oceans Canada (DFO) establishes MPAs to protect and conserve important fish and marine mammal habitats, endangered marine species, unique features and areas of high biological productivity or biodiversity. To date, no *Oceans Act* MPAs have been established in the Eastern Canadian Arctic. DFO has other marine conservation tools which may contribute to an MPA network, such as some *Fisheries Act* closures and marine mammal management areas. DFO along with Parks Canada and Environment and Climate Change Canada also protect critical habitat under the *Species at Risk Act* (SARA). The narwhal-coral closure in Davis Strait is an example of a fishery closure to protect habitat.

However, a recent review by Hutchings et al. (2012) highlighted that Canadian’s policy has not been operationalised adequately, leaving many national and international obligations unfulfilled in some important areas, such as the establishment of MPAs. These authors recommend innovative and new approaches to sustain marine biodiversity in oceans surrounding Canada and new research initiatives to support

scientific advice to decision-makers. They concluded that the most effective strategy is to protect existing marine biodiversity which will help to restore the natural resilience of Canada's ocean ecosystems and especially to adapt to global change and anthropogenic activities.

17.6.4 The Last Ice Area

The World Wildlife Fund (WWF) has initiated the “Last Ice Area” project which is an effort to encourage collaborative, multi-party marine conservation planning for the high Arctic regions of Canada and Greenland. In the Canadian Arctic Archipelago, WWF is working with many partners to understand how changes in sea-ice habitats may affect polar bears and marine mammals. They are also mapping the locations of polynyas, tracking wildlife movement and working to bring together scientific research and traditional knowledge. For more information on the project see <http://www.wwf.ca/conservation/arctic/lia/>.

17.7 Conclusion

Six Arctic coastal nations, including Canada, have recently agreed to coordinate efforts to detect and understand long-term change in Arctic marine ecosystems. They produced the Circumpolar Biodiversity Monitoring Program-Marine Plan (CBMP-MP, Gill et al. 2011), assessing the high need to have long-term monitoring (both for physical and biological features), to really understand changes in Arctic ecosystems. Given the substantial increase in natural resource development projects in Canada's North in recent years (Gavrilchuk and Lesage 2014), these long-term monitoring programs will be extremely useful. Gavrilchuk and Lesage (2014) highlighted the larger number of planned developments that will overlap with Ecologically and Biologically Significant Areas in the Canadian Arctic. The projects are diverse (e.g., infrastructure, oil and gas rights, subsea fibre optic telecommunication cable, etc.) but all these projects are going to drastically increase shipping activities in the Arctic. In this context, we need the development of monitoring programs for all ecosystems (see Gill et al. 2011). Funding needs to be secure, recurrent, and not only based on individual initiatives to fulfill these monitoring programs. Furthermore,

traditional knowledge needs to be incorporated in a more systematic way in research and monitoring programs. The involvement of northern communities could be increased in shallow coastal monitoring programs (e.g., intertidal) which will positively increase the spatial and temporal coverage of any monitoring program in specific areas.

In 2017, the governments of Canada and Nunavut and the Qikiqtani Inuit Association announced a boundary for Tallurutiup Imanga National Marine Conservation Area in Lancaster Sound (Figure 10). The boundary for the proposed NMCA, subject to concluding an agreement with the Inuit, is approximately 109 000 square kilometres in size, covering 1.9 percent of Canada's total marine estate, making it Canada's largest protected area, terrestrial or marine. This area, often referred to as the Serengeti of the Arctic, covers critical Ecologically and Biologically Significant Areas for marine mammals, such as seals, narwhal, beluga and bowhead whales, walrus and polar bears. It is also bordered by some of the most important seabird breeding colonies in the Arctic. However, many other areas need attention such as Hatton Bassin and most of the shallow coastal areas, to better understand their role in the ecosystem functioning especially for fisheries resources but also in the context of increased anthropogenic activities in the Eastern Canadian Arctic.

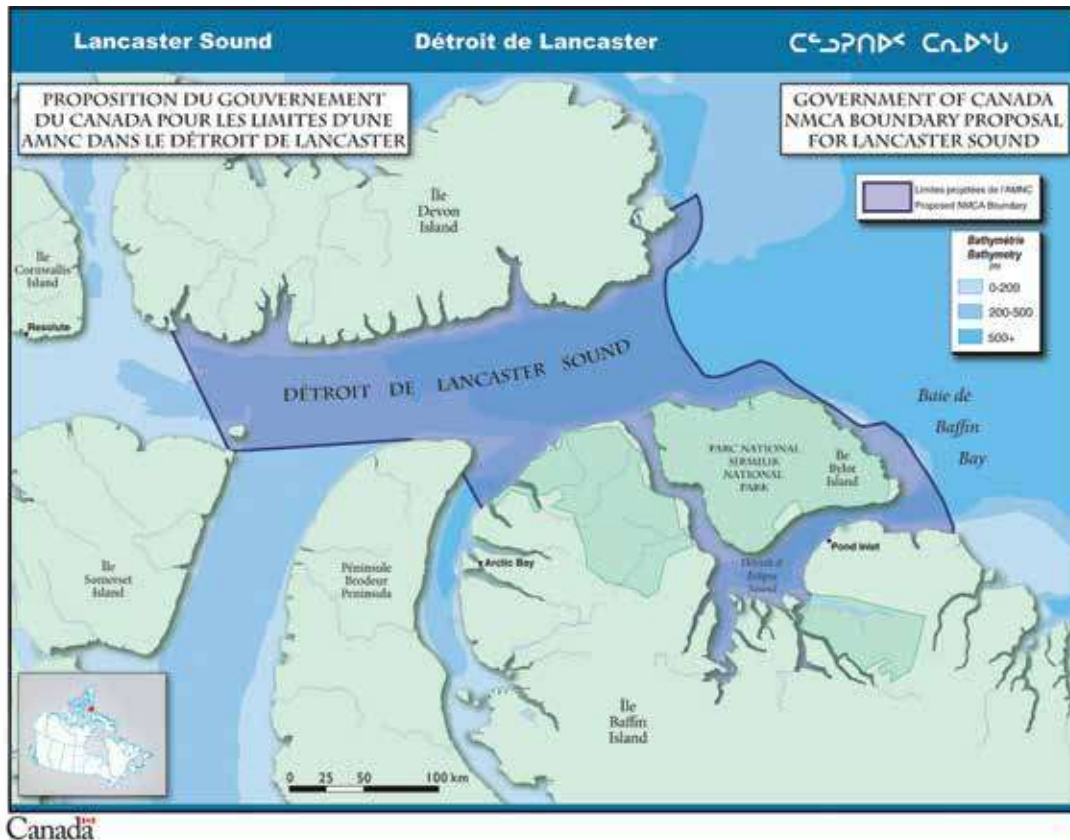


FIGURE 10. Boundary announced in 2017 for Tallurutiup Imanga National Marine Conservation Areas in Lancaster Sound.

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Chapter 18 Commercial Fisheries

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Key implications for decision makers

- Rapid warming of the Canadian Arctic is expected to increase fisheries yields by increasing productivity in existing fisheries, and permitting the emergence of new fisheries. However, there is a possibility that increased export of ice and freshened water into the Eastern Canadian Arctic will increase stratification and limit biological productivity by restricting the supply of nutrients. Even in a best case scenario, the productivity of Eastern Canadian Arctic marine ecosystems will remain modest on a global scale due to cold temperatures and the availability of light, especially during winter.
- Forage fishes (capelin, sandlance and Arctic cod) play a critical role in transferring energy from plankton to commercially harvested species. The scarcity of knowledge about their abundance and distribution constitutes a major impediment to predicting future states of commercial fisheries in the Eastern Canadian Arctic.
- Additional knowledge is needed on the biology of harvested species, such as growth potential and position in local food webs, to facilitate the sustainable management of fisheries resources.
- Fisheries surveys should continue to expand into inshore areas to identify resources that are most accessible to northern communities, and to increase the knowledge of biodiversity in Arctic waters.
- Characterized by low biological productivity and slow growth rates, Arctic waters are susceptible to overfishing and habitat disruptions. Gear restrictions and modifications will be necessary to limit the ecological impact of expanding fishing efforts in the North.
- The sustainability of Eastern Canadian Arctic fisheries can be facilitated by basing management actions on scientific evidence and advice.

Abstract

Fisheries are an important industry in the Eastern Canadian Arctic, primarily targeting Greenland halibut and Northern and Striped shrimp resources in offshore areas of the Baffin Bay-Davis Strait and Hudson Strait regions. An inshore sector, which consists of both subsistence and smaller-scale commercial fisheries, includes an Arctic Char fishery operating throughout Nunavut, and a successful winter fishery for Greenland halibut in Cumberland Sound. Interest exists in expanding fisheries in the Eastern Canadian Arctic into new areas and to target new species, such as urchin and whelk. However, survey limitations have led to a lack of adequate information on the distribution and abundance of potential fisheries resources in much of Canada's North, and the habitat that support these resources.

There is also a need for information on pelagic forage fishes, which play a key role in transferring energy through the ecosystem. Warming waters may permit the northward expansion of fishes and other marine organisms, and increase ecosystem productivity. However, the potential for increased productivity may be limited by increased freshening and stratification of water from melting ice. Continued expansion of commercial fisheries in the Eastern Canadian Arctic will need to consider the impact of fishing activities on the ecosystem; gear impacts, bycatch and overharvesting are known to negatively affect sensitive marine ecosystems. A science-based ecosystem approach to fisheries management will be vital to secure and maintain sustainable fisheries development in the North.

18.1 Introduction

As with most sectors of the Arctic Ocean, rapidly increasing air temperatures are resulting in the lengthening of the ice-free season in the Eastern Canadian Arctic (Xia et al. 2014). In the Baffin Bay-Davis Strait region (Figure 1), decreasing seasonal ice cover is expected to result in warming and freshening of the surface layer, paralleled by an overall increase in water column stratification (Steiner et al. 2015). This also contributes to increased CO₂ absorption, resulting in an undersaturation of aragonite (Fabry et al. 2009). These changes will affect the current equilibrium in marine biogeochemical fluxes and ecosystem services, including fisheries resources (Fossheim et al. 2015, Kortsch et al. 2015). The productivity of marine fauna and harvestable living resources ultimately depends on the availability of light and nutrients in the surface layer. This dictates microalgal photosynthesis that supplies organic carbon to the pelagic food web from lower trophic levels to top predators (Darnis et al. 2012, Tremblay et al. 2012). (see Chapter 5 for further discussion on marine productivity.)

Global projections predict that maximum fisheries catch potential will generally increase over the next 40 years in the Eastern Canadian Arctic (Cheung et al. 2010, Cheung et al. 2016). Based on reports for other regions, it is suggested that fisheries yield could even double in Baffin Bay with existing resources moving northwards as subarctic and boreal seas warm (Perry et al. 2005, Hollowed et al. 2013, Christiansen et al. 2016). While these projections could be viewed as conservative given the possibility that additional fisheries may emerge targeting new species, they also do not take into account factors that could increase stratification and disrupt nutrient replenishment in productive surface waters, strongly limiting potential gains in fisheries productivity.

Over the past 15 years, commercial fisheries, mostly driven by Greenland halibut (*Reinhardtius hippoglossoides*) – commonly referred to as turbot in Atlantic Canada and the Eastern Canadian Arctic – and Northern and Striped shrimp (*Pandalus borealis*, *P. montagui*), have rapidly developed in Nunavut waters, with an increase in total value from \$38 million to \$86 million during the period

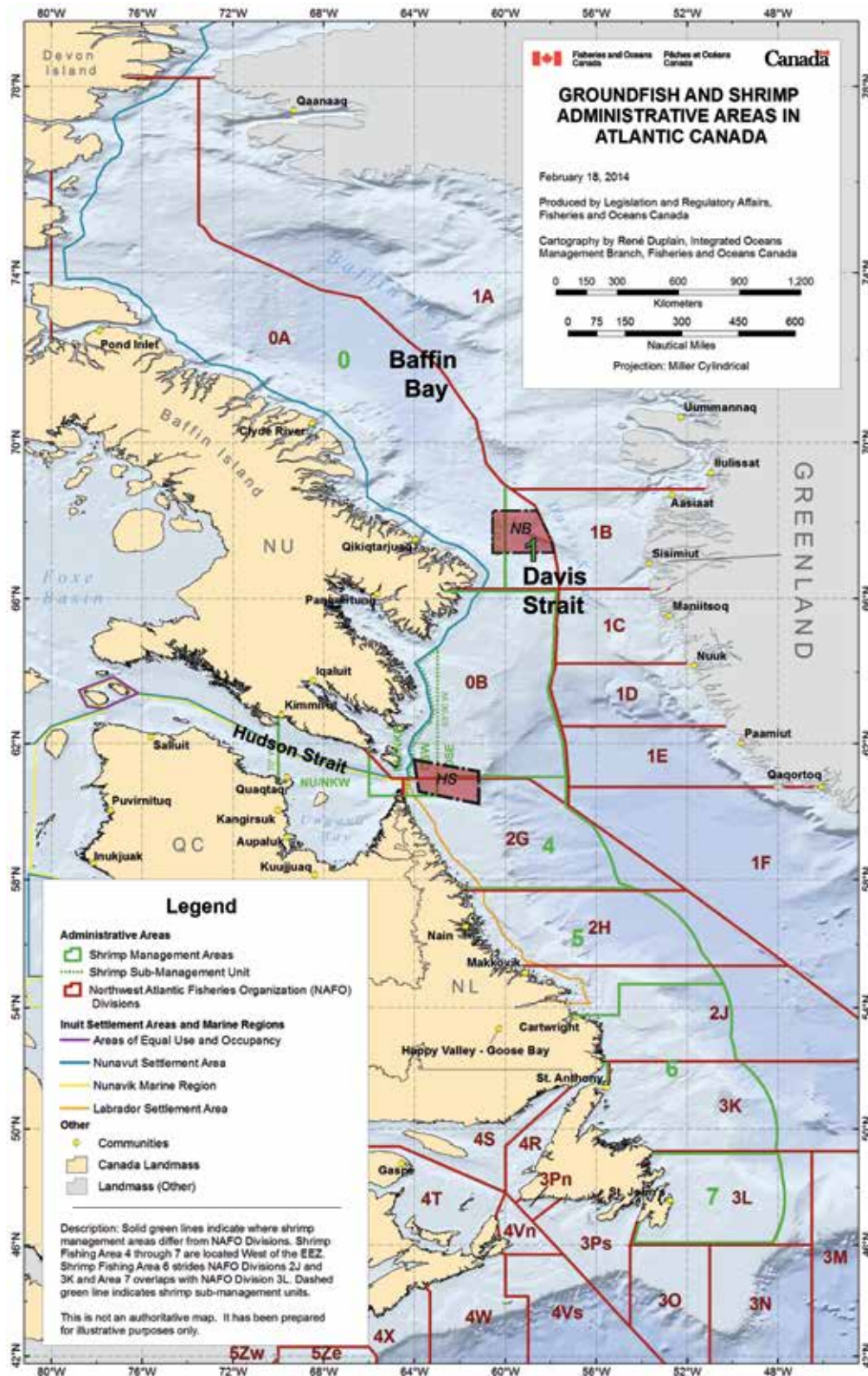


FIGURE 1. Administrative boundaries for fisheries in Eastern Canada. Red boxes correspond to the Hudson Strait CAPP/GEAC voluntary fishery closure (HS) and Narwhal-Coral box Greenland halibut fishery closure (NB). Canada's portion of shrimp fishing area 1 is noted with a 1, while 1B-F constitute the portion of this area within the Greenlandic EEZ. Adapted from Legislation and Regulatory Affairs, Fisheries and Oceans Canada. © Government of Canada.

2006-2014 (Senate Standing Committee on Fisheries and Oceans 2009, Canadian Northern Economic Development Agency, 2015). In 2012, Greenland halibut ranked as the third most important export good for Nunavut (Lambert-Racine 2013). The opening of Nunavut waters under a warming climate is expected to result in new fishing opportunities in the Baffin Bay-Davis Strait Region, as well as within areas of the eastern Canadian Arctic Archipelago (CAA), where exploratory fishing licenses have recently been issued. Sustainable fisheries resources that will benefit future generations of Nunavut communities are a central element of the Nunavut Fisheries Strategy. Given the vulnerability of Arctic marine ecosystems, the further development of the fisheries sector in the Eastern Canadian Arctic should rely on parallel increases in research and monitoring capacity to maintain both economic and ecosystem sustainability (Christiansen et al. 2014).

18.2 Traditional and subsistence fisheries

The people of Canada’s Eastern Arctic rely heavily on resources harvested from the land and the sea; inland and coastal fisheries are an inherent part of the culture and livelihood in the North. Subsistence harvests target

a wide range of resources, from seaweeds to large finfish. These are used primarily for local consumption but serve other uses, such as for cultural practices and as dog food. Sharing networks exist within and among communities, where hunters and fishers give or trade portions of their harvest to others within the territory (Nunavut Tunngavik Incorporated 2011, Statham 2012). Seventeen fishes and two groups of marine bivalves have been identified as being harvested for subsistence purposes in Nunavut, of which 11 are particularly relevant to the Eastern Canadian Arctic (Table 1) (Priest and Usher 2004). Arctic char harvesting is the most prevalent subsistence fishery, with harvests occurring throughout this region (Figure 2), and a mean annual harvest in Nunavut of nearly 199 000 fish (Priest and Usher 2004).

Communities throughout many parts of the Eastern Canadian Arctic have expressed interest in expanding their current fish harvests, looking for new species to target, experimenting with new gear technologies, and expanding fishing efforts into deeper waters. The search for Greenland halibut has been of particular interest along the eastern coast of Baffin Island and into Jones Sound, where exploratory longline fisheries have been developing adjacent to

TABLE 1. Species harvested during subsistence fisheries in the Eastern Canadian Arctic, as reported during the Nunavut Wildlife Harvest Study (Priest and Usher 2004).

Common Name	Scientific Name	Mean Annual Harvest (#) throughout Nunavut (1996-2001)
Arctic char	<i>Salvelinus alpinus</i>	198 611
Capelin	<i>Mallotus villosus</i>	
Clams	<i>Mya</i> spp.	49 169
Cod		6905
Arctic cod	<i>Boreogadus saida</i>	
Atlantic cod	<i>Gadus morhua</i>	
Greenland cod	<i>Gadus ogac</i>	
“Flounder”	n/a	
Greenland halibut (Turbot)	<i>Reinhardtius hippoglossoides</i>	5404
Herring	<i>Clupea</i> sp.	
Mussels	<i>Mytilus edulis</i>	25 509
Sculpin	<i>Myoxocephalus</i> spp.	2806



FIGURE 2. Locations of Arctic Char subsistence harvests reported during the NWHS (1996-2001).

several communities (Hathaway 1993, Walsh 2006a, 2006b, 2008, Wheeland et al. 2015). There is also interest in harvesting invertebrates, with community members diving for clams (Siferd 2005) or potting inshore shrimp and whelk (AFA 2015). This interest and growth in community-based fisheries is expected to continue, as communities adapt to shifts in environmental conditions and look to increase food security.

Harvests for community use account for a large proportion of removals from local ecosystems. It is estimated that in the Cambridge Bay region the annual Arctic char subsistence harvest is approximately half the size of the commercial harvest (Day and Harris 2013). Moreover, subsistence harvests take place over a larger proportion of the species

distribution than do commercial efforts. Despite this, no reporting requirements exist for subsistence fisheries. As such, beyond a few harvest studies, there is little available data on the target species, or the timing, locations, or quantities of subsistence fisheries (e.g., Priest and Usher 2004). The Nunavut Wildlife Harvest Study was a targeted effort over a five-year period (1996-2001), and provides the most recent estimates of subsistence harvests in this area.

18.3 Commercial fisheries

18.3.1 Greenland halibut

Greenland halibut are commercially fished in the Eastern Canadian Arctic both inshore and offshore. Since the early 1980s, a number of communities along the east coast of Baffin Island have explored the potential for inshore Greenland halibut fisheries. The inshore commercial fishery primarily takes place within the Cumberland Sound Turbot Management Area, which has an annual quota of 500 t. An additional allocation of 100 t has been reserved from quotas in Northwest Atlantic Fisheries Organization (NAFO) Division 0A (Figure 1) for further exploratory efforts in the portion of this Division that falls within the boundary of the Nunavut Settlement Area (DFO 2014a). The Cumberland Sound fishery uses longlines, and occurs primarily in the winter through the ice. However, fishing also occurred during the open water season in 2009, 2010 and 2011 (Government of Nunavut 2011). This inshore fishery is co-managed by DFO, the Pangnirtung Hunters and Trappers Organization (HTO) and the Nunavut Wildlife Management Board (NWMB) (NLCA 1993).

The offshore Greenland halibut fishery takes place in Baffin Bay and Davis Strait within NAFO Divisions 0A and 0B (Table 2). This fishery has been ongoing since the mid-1960s in Division 0B, and expanded north into Division 0A in 1996 (DFO 2014a). It is managed by DFO, however, input from NWMB is requested prior to implementing management measures. The quota in Division 0A is allocated to Nunavut interests, whereas Division 0B is fished by vessels from Nunavut, Nunavik and Atlantic Canada. A combination of fixed (mainly gillnets, some longline) and mobile

TABLE 2. Summary of the offshore turbot fishery in Baffin Bay/Davis Strait (data from DFO 2014a).

Year	NAFO Division 0A			NAFO Division 0B		
	Quota (t)	Catch (t)	Value (\$000)	Quota (t)	Catch (t)	Value (\$000)
2006	6500	6634	28 859	5500	5592	19 794
2007	6500	6173	26 369	5500	5334	17 718
2008	6500	4964	20 467	5500	5424	15 869
2009	6500	6496	24 343	5500	5547	24 541
2010	6500	6394	26 663	7000	6989	36 691
2011	6500	6262	31 586	7000	6985	41 146

(otter trawl) gear is used in the offshore harvest, with fishing concentrated at depths of 800-1300 m.

Offshore Greenland halibut stocks are assessed through the NAFO Scientific Council, using data from DFO and Greenland Institute of Natural Resources (GINR) multispecies trawl surveys. Data on the recruitment of Greenland halibut are obtained from GINR shrimp surveys. Reliable ageing methods are not available and movements of fish inshore and offshore are not well understood. However, given current trends in the survey indices, these fisheries are considered to be sustainable at current harvest levels (Jørgensen and Treble 2015).

18.3.2 Shrimp

Shrimp fisheries operate within Baffin Bay, Davis Strait, Hudson Strait and Ungava Bay (Figure 1). Additional delineations are made within the primary shrimp fishing grounds of Davis Strait, Nunavut, Nunavik, and Nunatsiavut areas (Figure 3). Quota also exists for Northern shrimp in SFA1 and SFA 0 (Figure 1). However, no catch has been reported against the SFA0 quota beyond initial exploratory trials (DFO 2010). The Northern Shrimp Advisory Committee (NSAC) was formed to review assessments and make management recommendations to the Minister of Fisheries and Oceans Canada. This advisory committee is comprised of representatives from DFO, Nunavut, Nunavik, Nunatsiavut, and industry. The Minister forwards NSAC recommendations to the NWMB and Nunavik Marine Region Wildlife Board for approval.

The shrimp fishery targets two species: *Pandalus borealis* and *P. montagui*. All fishing occurs through the use of single and twin bottom trawls, and harvest levels are managed based on a system of Total Allowable Catch (TAC) currently allocated amongst 17 offshore license holders (DFO 2015a). The shrimp fishery in SFA 1 is shared with Greenland, with Canada receiving a quota of 8500 t in 2015 – 17% of the overall TAC of 60 000 t (DFO 2015b). Canadian catches in SFA 1 declined substantially in this area, from approximately 7000 t annually from 2003 to 2005, to just 5 t in 2012 (Hammeken Arboe and Kingsley 2013). Catches in the other management areas have remained stable or increased in recent years (DFO 2015a). Currently, harvests of *P. borealis* are greatest in the Davis Strait West and Nunavut/Nunavik East areas, with catches near 5000 t. The *P. montagui* harvest is most prevalent in the Nunavut/Nunavik West area (Table 3, Figure 3).

Shrimp stocks are assessed within Eastern and Western Assessment Zones (EAZ, WAZ) from data collected during surveys run jointly by DFO and the Northern Shrimp Research Foundation (NSRF) in the EAZ. DFO conducted biennial surveys in the WAZ between 2007 and 2013, but starting in 2014 surveys have been conducted on an annual basis in both the WAZ and EAZ in collaboration with the NSRF. Currently, the *P. borealis* resource within the EAZ is considered to be healthy within a precautionary framework (DFO 2015a). However, the status of *P. borealis* in the WAZ, and all *P. montagui* resources in Nunavut-adjacent waters is uncertain due to data limitations and fluctuations in spawning stock biomass (SSB) indices.

TABLE 3. Northern Shrimp quota and catch (2013/14) within Nunavut-adjacent waters. Areas are identified on Figure 3: Nunavut West (NU-W), Nunavut East (NU-E), Nunavik West (NK-W), Nunavik East (NK-E), Davis Strait West (DS-W), and Davis Strait East (DS-E). Adapted from Siferd (2015). © Government of Canada.

		DS-E	DS-W + NU-E + NK-E	NU-W + NK-W
<i>P. borealis</i>	Quota (t)	3157	6166	1500
	Catch (t)	978	5042	2080
<i>P. montagui</i>	Quota (t)	971	1150	5000
	Catch (t)	79	871	4775

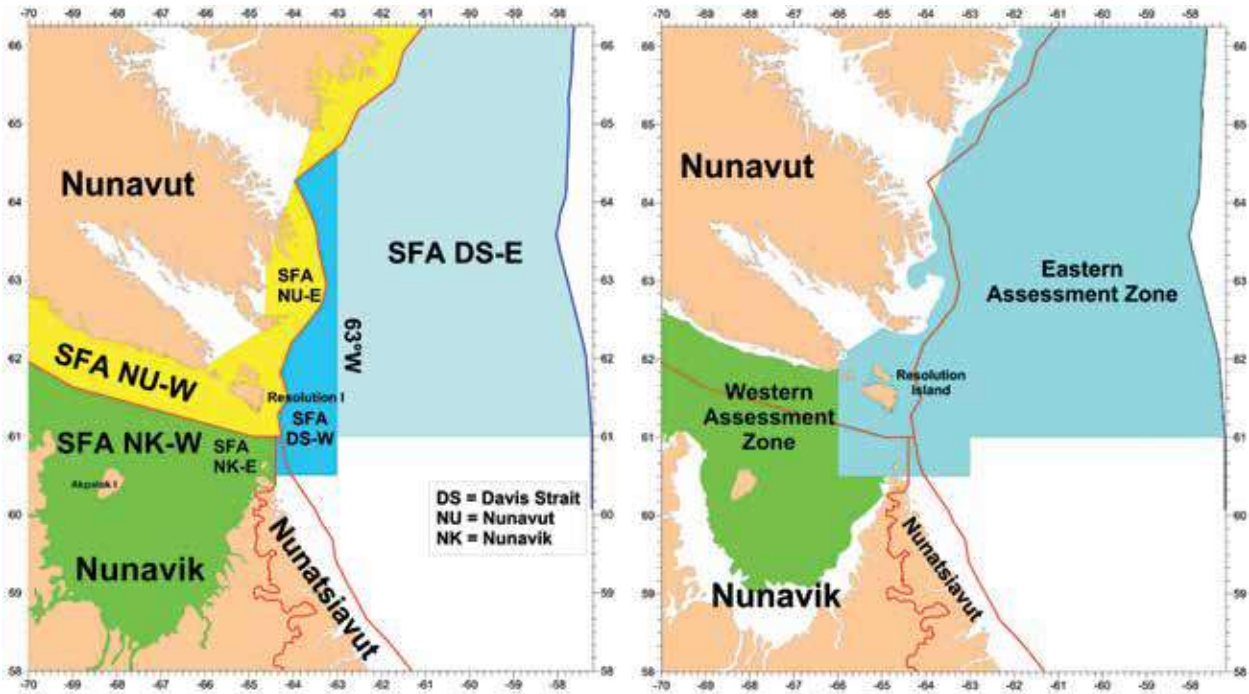


FIGURE 3. Shrimp management (left) and assessment (right) areas in Nunavut-adjacent waters: Nunavut West (NU-W), Nunavut East (NU-E), Nunavik West (NK-W), Nunavik East (NK-E), Davis Strait West (DS-W), and Davis Strait East (DS-E). Adapted from Siferd (2015). © Government of Canada.

18.3.3 Arctic char

Arctic char have been commercially harvested in Nunavut since 1960, with current fisheries operating in all three regions of the territory. Char fisheries are co-managed by DFO, the local HTOs and the NWMB. The largest fishery occurs outside of the Eastern Canadian Arctic, in the area of Cambridge Bay, which accounts for approximately half of Nunavut's commercial harvest (DFO 2013a). In the IRIS 2 region, commercial char fisheries occur in Cumberland Sound and near Qikiqtarjuaq. Iglookik, Baker Lake and Whale Cove also have occasional commercial harvests. Char are captured primarily with gill nets as the fish move upstream (autumn migration into freshwater for over-wintering) and downstream (spring out-migration to marine waters for summer feeding). Gillnet fisheries during the summer also target char during long-shore movements, though this is largely for subsistence use. In many cases, both commercial and subsistence fisheries target the same char populations in the same areas. In 2013, Nunavut's Arctic char had a landed value of over \$200 000 (DFO 2015c). Data limitations with regard to stock structure and distribution, and the size and location of harvests, greatly affect the management of char fisheries in the North. In many areas, accurate estimates of stock size and, in turn, sustainable harvest levels cannot be obtained (VanGerwen-Toyne and Tallman 2010). A number of char stocks in Nunavut have shown signs of overfishing, leading to closures and the implementation of gear restrictions (DFO 2013a, DFO 2013b, DFO 2014b, Day and Harris 2013).

18.4 Environmental impact of commercial fisheries

Fisheries can have broad impacts on the ecosystems in which they operate. Overfishing leads to significant declines in targeted fish stocks or other organisms caught as bycatch; declines that can alter trophic relationships and shift the balance of aquatic ecosystems. Fishing gear can also disrupt the environments where fisheries operate, through ghost fishing (wherein lost gear continues to fish as it drifts) and disturbing benthic habitats and communities. The type of gear used is a significant factor in determining

the impacts that a fishery will have on the ecosystem in which it operates. A variety of gear types are currently used in the Eastern Canadian Arctic (Figure 4). Bottom otter trawl, longline, and gill nets have all been used in the offshore Greenland halibut fishery (Treble and Stewart 2009, Jørgensen and Arboe 2013), with inshore fishing using primarily longlines (DFO 2008a). The offshore shrimp fishery in Nunavut-adjacent waters is trawl-based (DFO 2007, DFO 2015a), whereas gillnets, angling, weirs and snagging are used for commercial and subsistence char fishing (DFO 2008b, DFO 2013a, DFO 2013b).

Bycatch is a concern when considering the impacts of fisheries. The use of gillnets in the inshore Greenland halibut fishery is not advised due to concerns over the potential for marine mammal entanglement, bycatch, effects on large female Greenland halibut (through gear selectivity), and ghost fishing (Treble and Stewart 2009). A number of marine mammal entanglements have been reported from fisheries in the waters around Baffin Bay and Davis Strait, including narwhal entangled in lines, and seals, sperm whales and bowhead whales caught in gill nets (Hathaway 1993, Treble and Stewart 2009). Longline

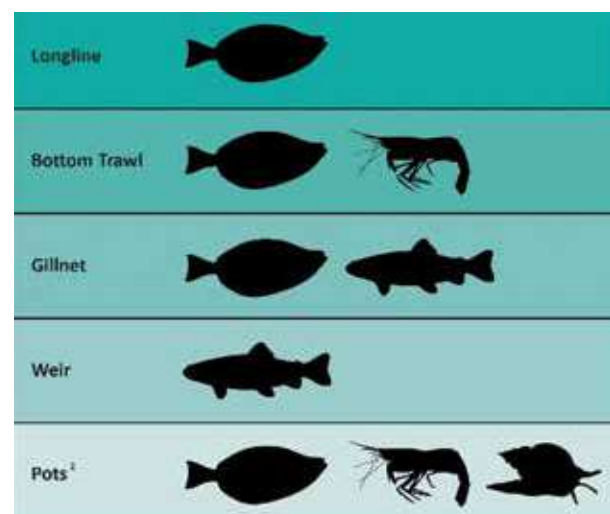


FIGURE 4. Gear types currently used to target commercial species (Greenland halibut, Northern shrimp, Arctic char, Whelk) in the Eastern Canadian Arctic. ¹Note that pot fisheries are currently only used in an exploratory/experimental manner.



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fisheries in Nunavut result in significant Greenland shark (*Somniosus microcephalus*) bycatch, as reported from commercial fisheries in Cumberland Sound (DFO 2008a) and exploratory fisheries around Baffin Island (Walsh 2006a, Walsh 2008), and as far north as Jones Sound (Wheeland et al. 2015). Shark bycatch has also been noted in previous gill net fisheries (Hathaway 1993). Increased bycatch of Greenland sharks was noted during initial exploration into expanding the Cumberland Sound Greenland halibut fishery into the summer open water period (Dennard et al. 2010, DFO 2008a). If interest in expanding this open water fishery is increased, necessitated by warmer temperatures and more unstable ice conditions, it will be important to consider gear modifications that will help to reduce this

bycatch (Grant et al. 2014). Similar consideration will need to be given in other exploratory fisheries. Other finfish – including Arctic skate (*Amblyraja hyperborea*), grenadiers (Macrouridae), eelpouts (Zoarcidae), sculpin (Cottidae), and American plaice (*Hippoglossoides platessoides*) – and a variety of benthic invertebrates have also been reported as bycatch during exploratory fisheries (e.g., Hathaway 1993, Walsh 2008, 2006a, Grant et al. 2014, Wheeland et al. 2015) throughout the Eastern Canadian Arctic. In addition, there is concern over potential seabird bycatch as fisheries expand in the Arctic, as high bycatch rates have been reported from both longline and gillnet fisheries located in the Baffin Bay-Davis Strait region where fisheries operate near breeding colonies (Hedd et al. 2015).

Gear loss can also be a significant issue in fisheries in the North given shifting ice conditions and distribution (e.g., Hathaway 1993) (Figure 5), increasing the potential for ghost fishing in these areas. Between 2004 and 2008, 739 gillnets, with a total length of more than 73 km, were lost during the Greenland halibut fishery in NAFO Division 0A (Treble and Stewart 2009).

Gear modifications can reduce many of the impacts of fishing on non-target species. The use of monofilament gangions on longline gear, rather than traditional braided nylon, can effectively decrease catch rates of non-target species



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FIGURE 5. Hauling pots during exploratory fisheries in the Lancaster Sound Region. Encroaching sea ice can endanger gear and lead to gear loss and subsequent ghost fishing.

while maintaining or increasing catch rates of Greenland halibut (Grant et al. 2014). Pot fisheries have less impact on benthos than active fishing gears, and bycatch is largely brought aboard the ship in good condition, allowing for live release. In addition, the use of pots over longlines has the potential to reduce Greenland shark bycatch in Nunavut Greenland halibut fisheries (Grant et al. 2014). Modifications can also be made to pots (Figure 6a), by adding escape mechanisms to reduce the bycatch of finfish and invertebrates (Winger and Walsh 2007), and biodegradable panels to limit ghost fishing if a pot is lost (e.g., Smolowitz 1978, Winger et al. 2015) (Figure 6b). Trawl gear can be modified to reduce bottom contact and, therefore, impacts on fished areas (Munden 2013), and by outfitting gear with bycatch reduction devices, such as the Nordmøre grid that is mandated in shrimp trawl fisheries (Richards and Hendrickson 2006, DFO 2007).

Bottom trawls can be destructive when they are towed across hard bottoms and areas inhabited by corals (Figure 7). This may be of particular concern in the Eastern Canadian Arctic, where deep-water fishing for Greenland halibut along the shelf slopes is likely to intersect with areas of high coral diversity and abundance (Gilkinson and Edinger 2009). Corals have a widespread distribution throughout the Baffin Bay-Davis Strait Region (Wareham 2009), and provide habitat complexity for bottom-dwelling

a



b



FIGURE 6. Modifications to pots for (a) bycatch reduction using an escape mechanism for small finfish and invertebrates, and (b) ghost fishing by the use of biodegradable panels limiting ghost fishing when gear is lost. Photos: Paul Winger



HARRY MERCER, FROM DFO

FIGURE 7. Corals are caught as bycatch in a commercial Greenland halibut trawl.

organisms (Buhl-Mortensen et al. 2010). Corals and sponges may also act as nursery areas for deep-water fishes (Baillon et al. 2012, Chernova 2014). Two fishing closures are currently in place to help protect deep-water corals: the Narwhal-Coral Box Greenland Halibut fishing closure in Baffin Bay and an industry-sponsored voluntary closure in Hudson Strait (Figure 1). Benthic video from Baffin Bay has demonstrated that more than a decade after trawling ceased, there is little visible evidence of recovery in areas once occupied by hard corals (Neves et al. 2014).

Over soft bottoms, such as those areas targeted by Northern shrimp fisheries, trawls resuspend sediments, disturb benthos, and can eliminate microstructures in the benthic habitat (Jones 1992, Løkkeborg 2005). In high latitude areas such as the Bering Sea, trawled soft-bottom areas have been associated with lower overall species diversity, with impacts most pronounced in long living and sessile organisms (McConnaughey et al. 2000).

18.5 Impact of environmental change on commercial fisheries

Temperature drives change in Arctic marine ecosystems. Warmer temperature are associated with sea-ice melt, longer open water periods, increased stratification, acidification and the freshening of surface waters (Chapter 5).

The cumulative effects of changes in these environmental factors associated with increasing temperatures are likely to impact commercial fisheries.

The magnitude of future temperature increases linked to climate change remains uncertain in the Eastern Canadian Arctic. If temperatures in the region increase following global trends, warming waters and decreasing seasonal ice cover could be expected to result in increased maximum fisheries catch potential through the higher productivity of established fisheries and/or the emergence of new fisheries based on boreal species expanding northward (Cheung et al. 2010). However, another possibility exists that biological productivity will remain strongly limited by high stratification of the water column resulting from increased sea ice and freshened Arctic water inflows to the Eastern Canadian Arctic via Nares Strait and the CAA (Chapter 5).

18.5.1 Scenario 1: Increased productivity under a warming regime

Under a scenario of increasing temperatures in the region following global trends, higher growth and productivity rates can be expected for the existing Greenland halibut and Northern shrimp fisheries given that Baffin Bay corresponds to the northern edge of the distributions of both species. Individual and population growth rates of fishes and marine invertebrates are strongly temperature dependent (e.g., Myers et al. 1997); additional warming of Eastern Canadian Arctic waters is likely to increase growth and reduce age at maturity in species that are currently exploited. Unfortunately, baselines of individual and population growth rates for these species do not exist for stocks found in Nunavut waters, as methods to obtain reliable estimates of age have not yet been developed (Treble et al. 2008, ICES 2011).

Even though data is poor regarding fisheries in the Eastern Canadian Arctic, strongly limiting our capacity to forecast future states of current fisheries under a warming regime, an examination of the dynamics of adjacent southern fisheries ecosystems may provide insight on future states of Eastern Canadian Arctic marine ecosystems. In most areas of the

Northwest Atlantic, including the Eastern Canadian Arctic and reaching as far south as the Flemish Cap (Figure 2), the abundance of pandalid shrimp rapidly increased during a cold period in the late 1980s and early 1990s, with parallel collapses of numerous groundfish stocks. The Flemish Cap (NAFO division 3M) provides an extreme example of temperature-driven shifts between fish and shrimp populations. Following the Flemish Cap cod stock collapse in the early 1990s (NAFO 2014), a local Northern shrimp population rapidly increased to harvestable levels and supported a lucrative fishery until the mid-2000s (Casas 2013). After the onset of the warm regime observed throughout the Northwest Atlantic in the mid-2000s, the flourishing Flemish Cap shrimp population rapidly collapsed over a 4-year period, while the cod population fully recovered over a 7-year period (Casas 2013, NAFO 2014). Similar observations were made on the northeast coast of Newfoundland (NAFO divisions 2J3KL) in which a current decline of shrimp biomass is being paralleled by indications that the Northern cod stock and other fish populations are rebuilding (DFO 2014c). In the Pacific sector, the rapid warming of the Gulf of Alaska in the late 1970s and 1980s also resulted in a regime shift from a dominance of shrimp to one of finfish (Anderson 2000).

Given the shifting dynamics in these adjacent or similar systems, continuous warming of Eastern Canadian Arctic waters is expected to favour the productivity of groundfish populations to the detriment of shrimp populations. The Striped shrimp *Pandalus montagui*, which prefers temperatures ranging between -1 to 2°C, may be more susceptible to range restrictions and declining abundance relative to the Northern shrimp *P. borealis*, which typically prefers waters ranging between 0 to 4°C (DFO 2015a). Research surveys in NAFO Divisions 0AB have indicated the occurrence of a deepwater redfish (*Sebastes mentella*), population biomass of approximately 150 000 t (DFO 2014d). This modest stock has never been subjected to a commercial fishery; however, conditions favouring groundfish productivity could potentially result in new fishing opportunities for this species.

In addition to shifts in productivity of species endemic to the Eastern Canadian Arctic, a warming regime could facilitate the northward expansion of species that are

currently limited to boreal waters. Fisheries resources in the Northeast Atlantic have already exhibited dramatic changes in distribution. In the Barents Sea, Atlantic cod and Atlantic herring have extended the northern limit of their range (Loeng and Drinkwater 2007). The most striking change in distribution related to climate warming might be that of the Northeast Atlantic mackerel (*Scomber scombrus*) stock. Until the early 2000s, the northern limit of that population corresponded to the coastal waters off Norway. As the North Atlantic warmed up, mackerel gradually extended their feeding migration westwards and have now invaded coastal waters off Iceland and Greenland (Jansen et al. 2012).

Boreal pelagic forage fish such as capelin (*Mallotus villosus*), herring (*Clupea harengus*), mackerel, and sandlance (*Ammodytes sp.*) are relatively mobile species that are often characterized by rapid, dramatic changes in distribution following thermal changes in marine ecosystems. Recent studies suggest that capelin (Gaston and Elliott 2014) and sandlance (Falardeau et al. 2014) show a high potential for expanding into Arctic seas as the duration of seasonal ice cover shrinks. Even though these species are currently of limited commercial interest, they play an important role in the ecosystem by channelling energy from plankton to some of the large predators targeted by commercial fisheries. A change in the equilibrium between the endemic Arctic cod and the boreal capelin and sandlance could have major consequences on energy pathways within the ecosystem and on the distribution and productivity of harvested species (Litzow et al. 2006).

18.5.2 Scenario 2: Productivity remains limited by increased water column stratification

Decreases in seasonal ice cover are expected to result in increased annual primary production in multiple regions of the Eastern Canadian Arctic due to the generation of a secondary peak in autumn primary production, as observed in boreal and temperate systems (Ardyna et al. 2014). However, such an increase in primary production will be limited to sectors characterized by limited freshening and stratification of the surface layer (Ardyna et al.

2014, Bergeron and Tremblay 2014). Increased stratification resulting from the freshening and warming of surface waters may prevent wind action from replenishing nutrients in the surface layer, and limit potential increases in primary production (Bergeron and Tremblay 2014).

Given water circulation patterns in the Baffin Bay-Davis Strait region, the increased export of sea ice from the Arctic Ocean via Nares Strait, as well as from Greenland and Ellesmere glaciers and ice caps, is likely to entrain cold waters from the eastern side of Baffin Bay into its western side (Tang et al. 2004). Moreover, increased export of cold freshened waters from the CAA due to the dissolution of the multiyear pack ice (Wang and Overland 2009), melt from glaciers and ice caps (Rignot and Kanagaratnam 2006), and overall increased river outputs (Déry et al. 2009) may result in a parallel increase in water column stratification on the western side of Davis Strait. This would in turn result in a cooling of surface waters and reduce nutrient transport between water masses, with consequent effects on local primary production.

There is evidence of a freshening trend on the Baffin Island shelf since 1980 as well as warming of mid-depth waters of Baffin Bay due to the increased input of water from the melting Greenland Ice Sheet (Hamilton and Yu 2013). Under this scenario of increased stratification, potential increases in maximum fisheries catch potential would be largely limited to the eastern Baffin Bay-Davis Strait region, where a temperature increase is predicted from warming Atlantic water transported via the West Greenland Current and the West Greenland Slope Current (Tang et al. 2004). During a recent warming pulse in the area during the early 20th century (Dunbar 1982), increased biological productivity was largely limited to the west coast of Greenland, where a northward expansion of the distribution of Atlantic cod and Atlantic salmon was noted (Drinkwater 2006).

Decreasing sea ice has also been linked to increased absorption of CO_2 leading to acidification of surface waters and a resulting undersaturation of aragonite, a form of calcium carbonate found in plankton and marine invertebrates (Yamamoto-Kawai et al. 2009). This undersaturation has

been observed at depths to 150 m in CAA (AMAP 2013); this undersaturation is expected to spread throughout the water column. However, uncertainty remains in the predicted magnitude, extent, and pace of future acidification in Arctic waters (e.g., Cai et al. 2010, Yamamoto et al. 2012). Acidification is suggested to have a negative impact on phytoplankton, crustaceans, molluscs and echinoderms (AMAP 2013). The response of Arctic fishes, and impact acidification may have on overall ecosystem structure is currently unknown. For further reading on ocean acidification, see Chapter 5, Section 5.4.4.

While future levels of biological productivity in the Eastern Canadian Arctic remain difficult to predict, it is expected that even under scenario 1, potential increases will remain modest at a global scale (Figure 8). Overall, we predict that prospects for the emergence of large-scale fisheries, similar to those in adjacent boreal ecosystems, will remain limited by low light availability, cold temperatures, and high stratification resulting in low nutrient availability.

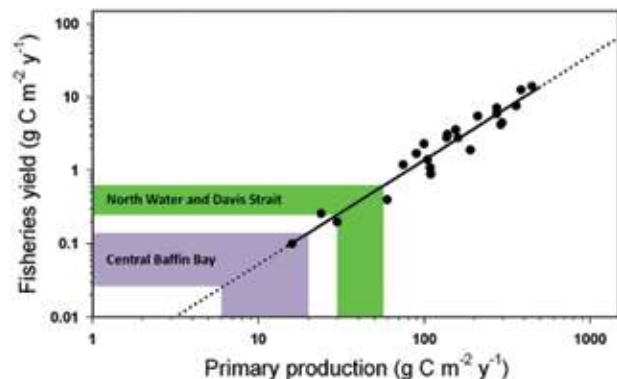


FIGURE 8. Global relationship between fisheries yield, measured as fish landing, and annual primary production in large marine ecosystems. Adapted from Nixon and Thomas (2001). Range in annual primary production during the period 1998-2014 (AMAP 2017) and predicted fisheries yield for Central Baffin Bay as well as the North Water Polynya and Davis Strait (similar ranges) are overlaid on the global relationship.

18.6 Challenges and recommendations for future fisheries in the Arctic

The development of fisheries in Canada's Eastern Arctic faces a number of challenges due largely to the remoteness of the area. Vessel access is limited by sea ice, leaving a short open-water season during which fishing grounds can be accessed. Inshore, ice conditions are becoming less predictable, restricting the extent to which fisheries can safely occur through the ice. A lack of infrastructure in Nunavut presents barriers to landing and processing fisheries catches, obtaining reliable fuel supplies, and transporting products to markets in the South.

Currently, assessments of commercially exploited species are limited by gaps in the understanding of their biology and role within the ecosystem. For example, a lack of age information limits the choice of models available for stock assessment. A promising ageing methodology has recently been developed for shrimp and other crustaceans (Kilada et al. 2012); however, this has yet to be validated in Arctic waters. More biological information will be needed to predict the responses of Greenland halibut and shrimp populations to warming conditions. In addition, information on the distribution of species' habitat in the Eastern Canadian Arctic is limited, with bathymetric data available at very low resolution for much of the area. Recent efforts have focused on inshore seabed mapping in the Baffin region of Nunavut (e.g., Hughes Clarke et al. 2015, Mate et al. 2015).

There is a danger in expanding commercial fisheries too rapidly. Marine resources can become overexploited, and the removal of large fishes can rapidly alter ecosystem structure. So far, fisheries stock assessments in the Eastern Canadian Arctic are largely limited to Baffin Bay and Davis Strait using data from multispecies trawl surveys conducted since 1999 in NAFO Divisions 0AB. Current surveys cover depths of 400-1500 m (Treble 2015) in Div. 0A (south of 72° N) and Div. 0B while previous surveys have been conducted in depths of 100-800 m in Div. 0A in 2006 and 2008 (Treble 2007). The biennial nature of the surveys in the main index area (0A-south) has resulted in a relatively short index series with which to determine trends over time

for the Greenland halibut stock. Shrimp Fishing Area 3 was also surveyed in alternate years between 2007 and 2013 and the NSRF has conducted surveys in Div. 0B since 2007 with the Western Assessment Zone included since 2014.

Currently, there is a lack of information on biodiversity and potential fishery resources in inshore waters, the areas that are most accessible for community-based fishery development. Inshore hook and line and trawl surveys, including an annual fishery-independent survey in Cumberland Sound, have been completed aboard the Government of Nunavut's research vessel *Nuliajuk* at locations along the eastern coast of Baffin Island since 2011, but other areas remain largely unsampled. Increased investigation into species diversity and abundance of marine resources in Nunavut's inshore waters was identified as a priority by DFO and the Government of Nunavut in 2009 with the development of the Nunavut Fisheries Science and Research Agenda, supported with funding from CanNor and industry.

Expanding exploratory fishing efforts provides an opportunity for cooperation between industry, government, managers, and academia to gain insight into these systems before wide-scale commercial exploitation begins. The New Emerging Fisheries Policy (DFO 2008a) and protocols for the exploration of Arctic char fisheries (DFO 2010) – both of which prioritize conservation and science-based management – require the collection of biological information and catch per unit effort data during an exploratory period before commercial development of a stock can be approved. Information should continue to be collected on the biological condition of fishes and bycatch composition, as should the examination of other environmental variables mandated during exploratory fisheries. The RV *Nuliajuk* and other charter vessels can serve as platforms for further research partnerships.

The consideration of Inuit Qaujimajatuqangit in assessment, and inclusion of community involvement in ecosystem monitoring will be key to the success of fisheries management in the Eastern Canadian Arctic. This consideration of traditional knowledge in the decision-making process was identified as a guiding principle of the Nunavut Fisheries Strategy (2005), and is recognized in DFO's New Emerging Fisheries Policy (2008).

Fishery resources in the North may have potential for further commercial development, but they also represent subsistence resources that are important for food security for northern communities. An examination of the diversity in these areas will also help in assessing the impacts of a changing climate by providing a baseline from which to track species expansions with continued warming (e.g., Piepenburg et al. 2010, Link et al. 2013). It is difficult to predict how fisheries resources, and ecosystems as a whole, will respond in the face of changing environmental conditions. This issue is amplified in the North where changes are expected to be most rapid and most pronounced (IPCC 2014), but where little is known about current or past states of the marine environment.

The Arctic marine ecosystem is largely driven by the abundance of Arctic cod, a pivotal species that transfers the bulk of energy from lower trophic levels to large predators, including harvested species (Darnis et al. 2012). However, little is known about the abundance and distribution of this pelagic schooling fish within the Eastern Canadian Arctic as current survey methods provide no information on pelagic fishes. The introduction of hydroacoustic methods in surveys of the waters surrounding Nunavut could provide important information on pelagic forage fishes, including the distribution of their early life stages (Geoffroy et al. 2015, 2011). Previous research has shown that the spatio-temporal match between the emergence of Arctic cod larvae and production of their preferred prey is an important determinant of survival during the larval stage (Michaud et al. 1996, Thanassekos et al. 2012). A recent study conducted in the Beaufort Sea and the CAA also linked variability in early life survival to the timing of ice breakup and sea-surface temperatures in spring (Geoffroy 2016). High survival occurred in years characterized by relatively early ice break-up and warm temperatures. This combination of environmental factors may play an important role in driving variability in early life survival and subsequent abundance of Arctic cod stocks.

While community and industry interests are leading to new fishing opportunities in the North, fisheries yields in the Eastern Canadian Arctic will likely never reach the levels experienced in adjacent southern areas. Even if increased

temperatures result from ongoing climatic changes, the Eastern Canadian Arctic will remain a cold environment with highly seasonal primary production rates (Tremblay et al. 2012). All decisions about fisheries development should be made cautiously, especially given the limited data available in the North, and the precautionary principle should prevail. Management actions should be based strictly on scientific advice to ensure the sustainability of Eastern Canadian Arctic fisheries.

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Chapter 19 Mining and Communities

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Key implications for decision makers

- Recent volatility in global commodity prices has significantly reduced mineral exploration and development since 2011.
- Mineral exploration and development will see benefits and challenges associated with climatic and environmental change.
- Large-scale developments may stimulate community opposition due to concerns over environmental and socio-cultural impacts.
- Northern governments and land claim organizations are focused on maximizing benefits while minimizing or mitigating the negative impacts of mineral development.

Abstract

Mining has become a complex and still poorly understood driver of both economic and socio-cultural change in the Eastern Canadian Arctic. Mineral development history in the region dates to the late 1950s, but by the early 2000s, there were no active mines in the territory. A period of record investments in mineral exploration and development in the territory has been followed by a steep decline, due to low global commodity prices. Two major mines, Agnico-Eagle Mines Limited's Meadowbank gold mine near Baker Lake and Baffinland's Mary River project (iron ore) on north Baffin Island, are currently in operation, while a third, the Tahera Diamond Corporation's Jericho diamond mine, was recently abandoned. Several other major projects are in development. The particular climatic and environmental conditions of the Arctic impose infrastructural, logistical and construction challenges that constrain the economic viability of Arctic operations. Increasingly, climate change is a significant factor for operating and future mines and mine infrastructure. Positive and unanticipated benefits of climatic change include the migration of new plants and animals, warmer winters, and extended access to waterways. Although the outlook for mining remains uncertain given shifting political-economic conditions and commodity prices, the pace of anticipated development underscores the need for appropriate governance and monitoring at the local, regional and territorial scales to ensure effective management of associated environmental and socio-cultural impacts.

19.1 Introduction

Mining has become a complex and still poorly understood driver of both economic and socio-cultural change in the Eastern Canadian Arctic. From a low in the early-2000s (after the closure of Nunavut's two operating mines), the mining industry now constitutes a growing proportion of the territorial economy. From 2003 to 2011, Nunavut saw spending on mineral exploration and development increase six-fold. However, the recent decrease of global commodity prices has slowed the rate of exploration and mining in the territory (NRCan 2014a). As a result, between 2011 and 2014, mineral exploration and development expenditures decreased dramatically from \$536 million to \$148.1 million (see Figure 1) (NRCan 2014b). As of 2014, there were 47 on-going exploration projects in Nunavut, down from 140 in 2008 (NRCan 2014b, Nunavut Overview 2008).

Since the establishment of Nunavut in 1999 and the implementation of the Nunavut Land Claims Agreement (NLCA), the nature of mining in the region has changed. Increasing territorial control over the mineral development process means mining companies are subject to territorial regulations and, where mining occurs on Inuit Owned Lands, companies must conclude an Inuit Impact and Benefit Agreement (IIBA) with Nunavut Tunngavik Incorporated (NTI), which collects royalties on behalf of beneficiaries of the NLCA (Bowman 2011). NTI also administers mineral exploration agreements on Inuit Owned Lands, and nearly all the advanced exploration projects in the territory are on these lands. Mineral exploration and development is promoted in part by NTI, the Government of Nunavut (GN), and Indigenous and Northern Affairs Canada (INAC), which seek to improve Nunavut's economic standing and standard of living through the expansion of mineral extractive industries in the region (Nunavut, Department of Economic Development and Transportation 2009). In general, mining companies increasingly seek to acquire a "social license to operate" and contribute economic and employment benefits to communities (Prno 2013). Mineral extraction is therefore becoming an increasingly complex negotiation between the interests of corporations, governments and Indigenous organizations (Gibson et. al. 2011).

Mineral development has the potential to create benefits for individuals, communities and the territories through employment, infrastructure development and royalties (Rhéaume and Vuotari 2013). IIBAs present opportunities for communities and regional Land Claim Organizations (LCOs) to negotiate these benefits. To capture these benefits, mining employment and training programs have been created, such as the Nunavut Mine Training Fund and the Kivalliq Mine Training Society, located in Rankin Inlet. IIBAs also permit the capture of resource revenues by regional LCOs, although until full devolution the Government of Nunavut relies on the federal transfers of resource rents (Cameron and Campbell 2009).

Mining activities have at times met with criticism at a local level, as large scale developments have the potential to rapidly alter Inuit culture, land use, demographics, and delicate environmental systems that support traditional harvesting. Certain grassroots organizations, which feel local needs and perspectives are not represented by territorial regulators, have formed to oppose large scale industrial activities (Makita 2015, Scobie and Rodgers 2013). Thus the presence of mining may increase tensions within mixed economies, based on traditional and wage labour practices, and create conflict over changing cultural values. In addition, the social and economic changes brought by large-scale mineral development in the Eastern Canadian Arctic will likely interact in complex ways with climate-related environmental changes.

19.2 Historical and political background

Mineral extraction has a long if intermittent history as a driver of Indigenous and non-Indigenous relations in the Eastern Canadian Arctic. Returning to England from a failed search for the Northwest Passage in 1576, Martin Frobisher brought back what he thought was high-grade gold ore. Subsequent expeditions to Frobisher Bay in 1577-78 mined about 1400 tons of what turned out to be worthless ore, as well as generating early encounters with Baffin Island Inuit (Ehrenrieck 1998). Until the 20th century, however, exploration of the Arctic emphasized "inventory science" and mapping, rather than mineral prospecting.

Surface coal seams were worked seasonally in the 1950s by Pond Inlet Inuit for local trade and fuel supplies but otherwise, Arctic mineral resources remained largely unexploited.

The Rankin Inlet Nickel Mine, which operated from 1957-1962, inaugurated modern mineral development in the Arctic, and was notable for its employment of significant numbers of Inuit workers. The community itself was established around the mine, and Inuit from across the Kivalliq (then Keewatin) region relocated to Rankin Inlet seeking wage labour opportunities. While federal Northern Affairs officials encouraged wage labour as a route to the “modernization” of Inuit, both the government and the community struggled to cope with the sudden closure of the mine and the plight of displaced workers, most of whom were unable or unwilling to return to full-time subsistence practices (Rodon et. al. 2013, Keeling and Boulter 2015). The mine was considered a success as an experiment in Arctic mining logistics, but it also exemplified the unstable and transient nature of mining economies in resource-dependent regions. The mine left a significant legacy in the Rankin Inlet community, with community members suggesting that while the North Rankin Nickel Mine operated for a short period of time, it remains a landmark, both in the positive association of providing opportunities and encouraging migration to the area, as well as a reminder of the environmental impacts caused by the mine, including seafood contamination and faulty remediation efforts (Cater and Keeling 2013).

Expanded prospecting activities (facilitated by aviation and government surveying) and booming commodity markets led to further large-scale mine development, at Nanisivik on north Baffin Island (opened in 1976, Canada’s first High Arctic mine) and Polaris on Little Cornwallis Island (opened in 1982), both lead-zinc operations. These mines, which closed in 2002, operated under agreements with the federal and territorial governments regarding economic and social benefits, but failed to meet Inuit employment and training objectives (Bowes-Lyon et. al. 2009). In particular, some Inuit workers struggled with separation from families while working at these remote commute-mine sites, and

with combining rotation work with traditional activities and community obligations (Hobart 1982, Wenzel 1983, Bowes-Lyon et. al. 2009). The community of Resolute acted as a staging area for the Polaris mine, some 100 km away, but was otherwise largely bypassed by both the impacts and the benefits. Arctic Bay, connected by a 21 km road to Nanisivik, was more directly affected by the economic and environmental changes associated with mine development and subsequent closure. Ten years on from closure, community-based research found ambivalence in local experiences with Nanisivik, and extensive disappointment, in some cases resentment, over the handling of mine closure, including discontent with the company and government’s disposal of valuable equipment and infrastructure (Tester et al. 2013, Midgley 2015).

Mineral and energy resource exploration influenced political change in the Arctic. Controversy over a proposed uranium development near Baker Lake in the 1970s and 80s spurred court action by the community and Inuit Tapirisat Canada (now Inuit Tapirisat Kanitami), and reinforced the agitation for Inuit control over development and resources in the Eastern Canadian Arctic (McPherson 2003). The NLCA, signed in 1993, transferred title including mineral rights to approximately 2% of Nunavut Territory, lands that were selected for high mineral potential. The land claim also created Inuit co-management and licensing boards, and required that major developments on Inuit-Owned Lands include an IIBA. These provisions, along with federal environmental assessment requirements, now regulate most of the exploration and development activity in Nunavut (Bowman 2011). In spite of the increasing role of the territorial government and Inuit land-claim organizations in mining regulation, considerable controversy has followed recent development proposals such as the Kiggavik uranium development near Baker Lake and the Baffinland Iron Mines Mary River project. Local communities and activists have expressed frustration at the speed, complexity and inaccessibility of the development process (Bernauer 2012, Kunuk 2012).

19.3 Current activities

After a boom in activity in the early 2010s, forecasts indicate decreasing mineral exploration activity in Nunavut (Nunatsiaq News 2015). In 2013, the global metal and mineral prices declined by 16% and are at rates not seen since 2009. As a result, mineral exploration and development has slowed significantly since 2011 (Figure 1), before recovering somewhat in 2015. Even the Qikiqtani and Kivalliq regions in Nunavut, areas that are particularly rich in gold, diamonds, silver, uranium, nickel, copper, platinum, iron, and oil deposits, are experiencing a reduction in prospecting and geological surveying. From 2012 to 2014, these two regions saw a plunge from 50 to 27 sites being explored (NRCan 2014b). However, there are few sites that are scheduled to go into production in the near future.

The territory’s first gold mine, the Meadowbank mine near Baker Lake, began producing gold in 2010. Forecast to remain open for a decade, Agnico-Eagle Mines Ltd. has announced the mine would close in 2018. Permits are still

pending for the Amaruq deposit, a satellite deposit of the existing Meadowbank mine, located about 60 kilometres away from the Meadowbank mine site. If approved, the Amaruq project is expected to open in 2019 (Greens 2017). Other major mineral developments at or near the production stage include the Agnico-Eagle’s Meliadine gold mine near Rankin Inlet and Baffinland Iron Mines’ Mary River project, on northern Baffin Island. While production began at Mary River in 2014, the Meliadine gold mine is still under construction, and is expected to open in the fall of 2019 (a year earlier than anticipated). A third major development, AREVA’s Kiggavik uranium project near Baker Lake, was denied approval from the Nunavut Impact Review Board (NIRB) in 2015, in part due to the company not having a firm start date or development schedule (LeTourneau 2015). Other sites, however, have struggled to reach or maintain production, including the TMAC Resources Inc.’s Hope Bay gold project near Cambridge Bay, and the Tahera Diamond Corporation’s Jericho diamond mine on Contwoyto Lake, abandoned by its owner in 2012.

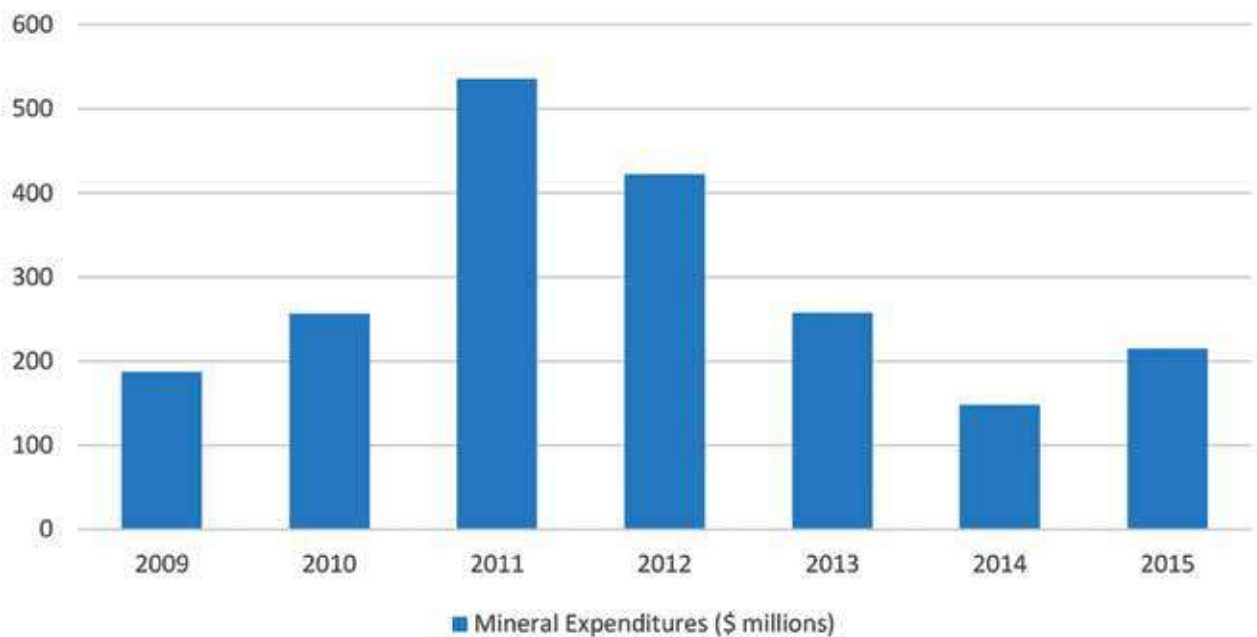


FIGURE 1. Mineral Exploration Expenditures in Nunavut (2009-2015) [Sources: NRCan 2014b, 2016]

Baffinland Iron Mines' Mary River project, one of the world's most northerly mines, is perhaps the more ambitious mining venture of the two operational sites. The iron ore mine received the Project Certificate from the Nunavut Impact Review Board (NIRB) on December 28, 2012 (Baffinland Iron Mines Co. 2015). A month later, Baffinland Iron Mines Co. significantly reduced the scope of its project, creating an "Early Revenue Phase", which decreased the amount of ore mined and shipped from 18 million tonnes to 4.2 million tonnes per year and delayed the construction of a railway and port on Steensby Inlet (Nunatsiaq News 2014). The Mary River Project went into production in 2014, costing \$740 million to construct, as opposed to the initially projected construction cost of \$4 billion (Jordan 2013). Until global markets improve the prices of iron ore, Baffinland will ship a reduced amount of iron ore out of Milne Inlet strictly during open water season (Nunatsiaq News 2014). Ultimately, the project's estimated lifespan is 21 years and includes the construction of a 143 km railway (projected to cost \$10-million per km) and a port at Steensby Inlet to permit year-round shipping (Braden 2012, Baffinland Mines Ore Co. 2015).

On September 6, 2013, the Qikiqtani Inuit Association signed an IIBA with Baffinland Iron Mines. While the project is hailed by some as a major economic windfall for the entire territory, the lengthy impact review process has seen significant criticism. Many Inuit in the region, still practicing a mixed wage and land-based lifestyle, are worried about how the mine will affect their environment and culture (Nunatsiaq News 2012). Igloolik-based filmmaker Zacharias Kunuk has criticized the environmental assessment process, saying it fails to engage Inuit in a meaningful dialogue about the benefits and risks of such a transformative project (Kunuk 2012). There are also questions around how climate change will affect the operating costs and logistics of such an ambitious and large-scale project (Canadian Mining Journal 2012).

The AREVA Resources Canada Kiggavik uranium mine was denied approval by the NIRB in 2015. Initially the project was projected to be both an open pit and underground



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operation, and was scheduled to go into production in 2017. The site was predicted to have a 14-year lifespan and cost approximately \$2.1 billion to build over 4 years. While it was expected that the site would create nearly 700 jobs, many Inuit were concerned about how the mine would impact local caribou herds and groundwater supplies (Rohner 2015). This controversy dates back to the 1980s, when prospecting for uranium was first undertaken in the Baker Lake region by the German company Urangesellschaft. In 1990, the community voted 90% against the original mine proposal (McPherson 2003). In 2007, however, NTI reversed its stance on uranium mining, instead adopting a new policy that supported the "sustainable" extraction of uranium in Nunavut, and in 2012 the Government of Nunavut issued a policy statement supporting exploration and mining of uranium, under certain conditions (Government of Nunavut, 2012). During the AREVA environmental assessment process, a grassroots organization, Makita, formed to intervene in regulatory hearings and promote public dialogue on the impacts of uranium mining (Makita 2015, Bernauer 2012; Kneen 2011). In October 2014, AREVA submitted its final environmental impact statement to the Nunavut Impact Review Board (NIRB) for the Kiggavik Project, but the review process was marked by delays and controversy (Forum Uranium Corp. 2014). The final NIRB community hearing on the Kiggavik Project was held in 2015 in Baker Lake and ultimately resulted in approval being denied for the project (Rohner 2015).



ARN KEELING

Along with the resurgence of mining in Nunavut, considerable social-scientific research effort is being focused on understanding the community impacts and benefits of contemporary mineral development (Rodon and Lévesque 2015, Rodon et al. 2013, Knotsch et al. 2011, Petersen 2012). The picture of the social outcomes and changes initiated by large-scale developments and their associated IIBAs, however, remains far from clear, in spite of ongoing research into social indicators of development impacts (cf. Czyzewski et al. 2014, Angell and Parkins 2011, Haley et al. 2011). Community monitoring accompanying IIBAs, through bodies such as the Nunavut regional Socio-economic Monitoring Committees (Nunavut Socio-Economic

Monitoring Committees 2007), may provide useful information on short- and long-term changes to community conditions related to mineral development, as well as building capacity within northern communities to monitor environmental and social changes occurring over periods of rapid industrial development. However, it is important to note that this community-based monitoring has been inconsistent in its coverage (see Jones and Bradshaw 2015).

19.4 Mining and environmental change

Mineral extraction, in addition to inducing environmental change, is affected by the particular climatic and

environmental conditions of the Arctic. These conditions impose infrastructural, logistical and construction challenges that constrain the economic viability of Arctic operations (cf. MacDonald and Miller 2014). “Pioneering” mining operations like Polaris and Nanisivik adapted their surface and underground operations, as well as shipping and logistical arrangements, to accommodate extreme Arctic conditions. Upon closure in 2002, these mines also faced challenges of closure and reclamation planning, including considering the effects of climate variability and change on tailings management facilities and soil remediation requirements (Midgley 2015).

In general, mines have been designed with the assumption that climate conditions will be stable (Pearce et al. 2011). Increasingly, climate change is a significant factor for operating and future mines and mine infrastructure. Recent research (Pearce et al. 2009, Nunavut RAC 2012, Prowse et al. 2009) suggests significant climate change risk exposure in mining operations, including:

- Transport infrastructure: effects of permafrost thaw on road beds and impacts of warming on winter ice roads; impacts of sea-level change and changing sea-ice conditions on port infrastructure and shipping routes.
- Mine buildings and sites: effects of permafrost thaw on structural stability; impacts of extreme weather events on site access and infrastructure (such as snow fences).
- Mineral processing operations: effects of changing water availability on production rates and effluent disposal practices; effects of permafrost thaw and extreme weather events on berms, slopes and pit walls of mines; effects of climate change on design of tailings management facilities (erosion, permafrost thaw).
- Environmental management: effects of warming air and ground temperatures and changing precipitation patterns on potential acid rock drainage and contaminant mobilization; closure planning and reclamation challenges, particularly of tailings management facilities.

Changing permafrost conditions, for example, will likely affect all aspects of mine operations and infrastructure,

as increasing Arctic air temperatures reduce the extent of permafrost, increase the depth of the active layer, and affect the zones of transition between continuous and discontinuous permafrost areas. For example, land-based tailings management facilities (TMFs) in the Arctic have typically been designed to take advantage of permafrost conditions to freeze tailings, inhibiting contaminant mobilization and potential acid rock drainage formation (Nunavut RAC 2012). Tailings caps at the Rankin Inlet, Nanisivik, and Meadowbank mines, for instance, are engineered to promote freezing of tailings and to act as the active (thaw) layer. Changing permafrost conditions have the potential to affect these practices, as well as groundwater and surface water flows in and around TMFs, increasing the possibilities of contaminant seepage, settlement, and structural problems such as erosion and slumping (a significant vulnerability that extends to the post-operational phase of mining). Similarly, Instanes et al. (2005) suggest that areas of active mine construction, particularly open pit, may be susceptible to slumping or collapse due to long-term exposure of permafrost overburden. In these ways, climatic changes may interact with or exacerbate localized human-induced environmental changes resulting from infrastructure and mine development.

Changing permafrost regimes may also significantly affect infrastructure for mineral and hydrocarbon development. But only recently has the mining industry integrated climate assessment into development and infrastructure planning, and begun to consider measures to mitigate or adapt to climate-related hazards (Pearce et al. 2009). Doing so is critical in Nunavut, where most infrastructure is purpose-built for resource developments. For instance, in its Draft Environmental Impact Statement, Baffinland Iron Mines predicted that the area around its Mary River project will see increases in active layer depth of up to 50% over the life of the mine, increasing risks to shoreline infrastructure and road or railway embankments. The construction of port facilities, such as those planned for Milne and Steensby inlets on north Baffin Island, must also account for sea level change (rising or falling), changes in sea-ice thickness, extent and duration, and changing frequency and intensity of storm events (Nunavut RAC 2012).

Changing environmental conditions may in some cases provide opportunities along with challenges. In particular, reductions in the duration and extent of sea-ice cover, particularly multi-year ice, has the potential to facilitate marine transport in the Arctic by extending shipping seasons and reducing navigational hazards and costs (Prowse et. al. 2009, see Chapter 20). In combination with rising commodity prices, reduced shipping costs (a critical consideration for bulky commodities such as minerals) may improve the viability of Arctic mineral operations (Têtu et al. 2015). Climate change, combined with the construction of new transportation infrastructure, could potentially open new areas of the Eastern Canadian Arctic for mineral exploration and development.

Climate-related risks and opportunities directly affecting the mining sector are likely to interact in complex ways

with the wider social, economic and environmental dimensions of climatic change. However, research to date on these connections remains inconclusive (Southcott 2013). With climate change expected to induce changes to vegetation, wildlife habitats and migration patterns, and traditional harvesting practices, such changes (and their uncertainties) must be incorporated into environmental assessment and management plans for mineral and infrastructure developments. Indeed, the question of exposure and adaptation to the effects of climate change cannot be decoupled from wider social and economic conditions affecting the mining industry, such as global economic conditions, resource governance, and political change in the Arctic (Prno et al. 2011). Although the vulnerability and adaptive capacity of northern communities to climatic change has been extensively studied in recent years, the intervening importance of resource extraction and shipping has not



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been thoroughly assessed (Cameron 2012). These factors include the ongoing transition of Arctic communities to a mixed wage and land-based economy, the social impact of large influxes of cash and workers associated with major developments, the volatility of resource-based economies and the impact of mine closure, as well as the ongoing process of regulatory devolution to territorial authorities.

19.5 Outlook for mining

Mineral development in the Eastern Canadian Arctic has the potential to significantly transform the social and economic landscape of the region. Managing and better understanding these changes has become a central concern of territorial authorities, as witnessed by the extensive social impact assessment and monitoring procedures—and public debates—associated with major developments. These changes are likely to interact in complex ways with climate, socio-cultural, and environmental change in the region, and the cumulative impacts of these changes will test the resilience of already stressed Arctic communities. The encounter between small, geographically dispersed Inuit communities and national and transnational mining capital is of increasing interest to social scientists examining cultural and economic change in the Arctic (Bernauer 2011, Cameron 2012). Mineral development raises challenges for Inuit communities in particular, due to impacts on: food security and health; culture and language; rising income disparity; and family and social life (Gibson and Klinck 2005, Angell and Parkins 2011). Although many Inuit communities have found avenues for greater participation in the economic benefits of mining through IIBAs, the pace of anticipated development underscores the need for appropriate governance and monitoring at the local, regional and territorial scales to ensure economic change does not undermine community adaptability and resilience (Bowman 2011, Caine and Krogman 2010).

Important questions also remain about the sustainability of mineral resource-dependent economies such as that emerging in Nunavut. Minerals, as finite resources, are inherently unsustainable and, as evidenced by the recent downturn, mining economies are subject to externally



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generated shocks due to regulatory changes, market conditions or the discovery of more economically viable deposits elsewhere (Waye et al. 2009, Bradbury 1979, Bridge and McManus 2000). While the Nunavut Government and the Government of Canada are committed to creating a “conveyor belt” system that would bring new mines into production as old ones are phased out, local authorities’ ability to manage these external factors is limited (Rhéaume and Caron-Vuotari 2013, Nunavut, Department of Economic Development and Transportation 2009).

Considerable debate surrounds the perils of reliance on non-renewable resources for economic development and the so-called “resource curse” (cf. Bridge 2004, Ali, 2003, Bebbington et al. 2008, Crowson 2009, McAllister 2007). Important long-term planning challenges associated with mine closure and the transition to post-mining economies remain in the Eastern Canadian Arctic (Rixen and Blangy 2016). Some of the forecast projects may never actually go into full production, just as Newmont’s Hope Bay gold mine in western Nunavut suddenly halted its pre-production phase in early 2012 leaving many Inuit out of employment (George 2012). Moreover, as recent trends have shown, operating mines are not necessarily economically secure, given global economic conditions and the cost of extracting ore in Arctic environments. Forecasts prepared for the

Kiggavik Environmental Impact Assessment indicate that, of nine major mining projects expected to begin construction between 2010 and 2017, one-third are expected to end operations by 2025, and only one operation (Mary River) will extend beyond 2035. Although industry watchers expect further resources to be delineated and developed, managing the transition to a post-mining economy will present sustainability challenges to the region as significant as those associated with climate change. There have been important new developments in recent years, but the outlook for mining in the territory remains uncertain given shifting political economic conditions and commodity prices. There is great need for appropriate governance and monitoring at the local, regional and territorial scales to ensure economic change does not undermine community adaptability and resilience.

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Chapter 20 Arctic Shipping Traffic: More Ships Will Come, but not for Transit

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Key implications for decision makers

- Destinal traffic (i.e., ships that go to the Canadian Arctic to perform economic activities there and then return to another destination) has already expanded significantly (nearly 2.8-fold from 2005 to 2016) in the Canadian Arctic.
- Shipping can be a strong development tool if service expands to local communities and there is infrastructure construction.
- Traffic is mainly driven by local economic activities, which include local communities, and natural resources.
- Transit traffic is likely to remain limited.

Abstract

Sea ice is melting fast but this evolution did not trigger a fast expansion of transit shipping. What is observed is a steady expansion of destinal or local traffic, ships that go to the Canadian Arctic to perform economic activities there, and then return to another destination, as opposed to transit shipping where ships merely go by without stopping over. This reality of shipping in the Canadian Arctic is no different from what can be seen elsewhere in the Arctic, even along the Northern Sea Route where destinal shipping is expanding fast along with natural resources extraction, but where transit shipping has plummeted since 2013. Shipowners see local market possibilities and thus favor destinal shipping, while transit conditions are still perceived as too hazardous from a commercial point of view.

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20.1 Introduction

The melting of sea ice in the Arctic Ocean is widely documented and is fuelling narratives around the renewal of a “cold war,” or even an armed conflict in the Arctic for the control of both its natural resources and sea routes (Lasserre 2010a, 2017). These doomsday scenarios run against the history of cooperation that characterize interstate relations in the Arctic (Lasserre 2017).

A look at the map shows the savings in distance that can be achieved with the Arctic routes: for example, a trip between London and Yokohama through the Northwest Passage is 15 700 km and 13 841 km through the Northeast Passage, which is significantly shorter than the route through Suez (21 200 km) or Panama (23 300 km). These findings fuel the idea that these Arctic routes, because they are shorter, are bound to attract abundant through traffic, and consequently will become a major political issue. Amid the media widespread image of a future maritime highway across Arctic seas, even some scientists yield to the popular image and assert, without proof, that Arctic traffic is set to increase rapidly. Beyond the seemingly decisive advantage of Arctic routes, however, there remain many obstacles to navigation. In addition, these scenarios for the development of marine traffic in the Arctic remain highly speculative and are not based on an analysis of shipowners’ perceptions.

This chapter presents the results of an empirical survey conducted among shipping companies to determine their interest in developing activities in the Arctic. Besides examining the potential development of shipping in Arctic routes, this research must be placed in the context of intense competition between shippers, competition that makes both service reliability and costs of transport paramount. In this competition structure, the benefits of established routes between major hubs seem to prevail, so that new routes have difficulty being developed.

20.2 The question of sovereignty over Arctic passages

Few analysts question the common belief that it is only a matter of time before new sea lanes will be operational in the Arctic. This prospect is at the very heart of the ongoing debate on security in the Canadian Arctic, and raises the issue of control of such navigation, and therefore of Canadian sovereignty over the Northwest Passage and the Canadian Arctic waters. This debate on control of navigation triggered the Canadian House of Commons to vote a highly debatable resolution, in December 2009, renaming the Northwest Passage to the Canadian Northwest Passage, a move unlikely to attract any sympathy elsewhere in the world.

The potential opening up of shipping routes through the Northwest Passage, across the Canadian Archipelago, as well as along the Northeast Passage, north of Siberia, has raised security concerns as it implies a potential surge in navigation of all sorts of ships (Byers 2009, Grant 2010, Lasserre 2010a). Analysts have speculated about potential threats to the environment should an oil tanker run aground or sink; to military security should terrorists try to infiltrate North America through the back door of a sparsely populated and poorly monitored area; or to human security should a passenger ship hit a growler and sink, as happened to the *M/S Explorer* in Antarctica in November 2007. Further, several accidents took place in the summer 2010 in the Arctic: the tanker *Mokami* ran aground near Pangnirtung on August 12th, the cruise ship *Clipper Adventurer* ran aground on August 27th in the Coronation Gulf due to the poor accuracy of nautical maps, and the fuel tanker *Nanny* ran aground near Gjoa Haven on September 2 due to an uncharted sand bar. The question of sovereignty over the Northwest Passage (claimed as internal waters by Canada) and the Northeast Passage, crossing areas claimed by Russia as internal waters, boils down to who controls shipping along them. But this whole debate assumes there will be more traffic, whereas this is, so far, speculation, at best an educated guess: shipping, if increasing presently, is still far from active in these Arctic waters. To what extent is traffic going to expand in these waters, given shipping interests?

20.3 Little research on the economics of Arctic shipping

Most of the research on Arctic shipping is based on the hypothesis that a shorter route would result in the growth of marine traffic. While no studies to our knowledge have looked at the shipping sector's plans to expand and / or develop business opportunities on Arctic sea routes, several studies have been conducted to determine the potential cost advantages of Arctic transit routes (see Table 1) over other routes. The simulations used in these cost advantage studies incorporate a number of variables such as, average transit speed taking account of ice cover, building and operation costs for a vessel, how many rotations a vessel can carry out given its average speed; the bunker fuel cost; freight rates, etc.

Borgerson (2008) states that Arctic transit could enable shipping firms to save \$3.5 million per transit. Banking on the shorter distances (a fact), he postulates that average speed will not be an issue and gives no information regarding his sources or the basis for his calculation. Unless verification is provided, it is prudent to question his figure. Aker Arctic Technology (2006) calculated a cost of \$354 per container for the route from northern Iceland to the Aleutians along the Northern Sea Route (NSR); when combining this cost with the two transshipments Europe-Iceland and Aleutians-Asia (no data), the study concludes with a marginal but real profitability of the route. Guy (2006) presented several scenarios based on variables such as ship chartering, transit time, potential toll fees and insurance, and showed that transit across the NWP can be profitable, but only with optimal conditions that are seldom met. Similarly, Mejl ander-Larsen (2009) concludes that ice conditions remain too difficult and unpredictable for profitability. Liu and Kronbak (2010) stress the fact that costs induced by polar shipping make transit poorly profitable, except with very expensive fuel cost hypotheses. VERNY and Grigentin (2009) conclude transit costs will be much higher on Arctic sea routes than through Suez. DNV (2010) concludes transit can be profitable for the Northern Sea Route only, especially if fuel prices reach the \$900/t limit (Table 1).

While these scenarios do suggest a potential advantage of Arctic routes in the form of lower business costs, they also show that, contrary to popular belief, this theoretical advantage remains highly uncertain given the investments and special equipment required for Arctic navigation, the variable transit time and the cost of insurance.

Furthermore, these cost analyses, by definition, do not take account of the issues involved in marketing the proposed services. While managing business costs is one dimension of operating a business, it certainly is not the only one. The positioning of the service offering, the nature of the service and its operational constraints are also decisive factors in choosing a route.

Few studies have been conducted that look at the intent of ship owners and ocean carriers to develop business opportunities along Arctic sea routes, in the context of melting sea ice, and none before the first survey we published in 2011 (Lasserre and Pelletier 2011).

20.4 A survey of shipping firms shows a lack of enthusiasm for Arctic shipping

For the present chapter we surveyed 142 shipping companies that directly operate their own ships or charter vessels. Companies leasing their ships to carriers (service providers) were excluded since the purpose of the study was to interview companies that make the decisions on which sea routes their ships will take and whether or not they own the vessels involved.

The present study was also limited to shipping line operators in the Northern Hemisphere, since the advantage in distance disappears when both the origin and destination are in the Southern Hemisphere. From February 2008 to March 2010, heads and executives of these companies were contacted, first by questionnaire, and then directly by phone. Companies were invited to answer the following questions: "Are you considering developing operations in the Arctic? Why?" A total of 98 answers were compiled. The companies that were included operate a total of 8 148 ships; firms in the container business accounted for 84.5%

TABLE 1. Summary of studies on cost advantages of transit Arctic routes, 2006-2014.

Aspect studied	Position	Study
NWP summer transit	Potential profitability is uncertain given uncertainty on routes and higher costs.	Guy (2006)
Container shuttle service between Iceland and Aleutians	Marginal but real profitability.	Aker Arctic Technology (2006)
Arctic transit in general	Very profitable because of shorter distances.	Borgerson (2008)
Transit using the NWP compared with Panama between Asia and the N-E coast of North America	Present profitability is negative or marginal. Could change if fuel costs reach high levels and if ice keeps receding significantly.	Somanathan et al. (2009)
Container transit using NSR compared with Suez	Potential profitability but not in the near future.	Mejlænder-Larsen (2009)
Container transit using NSR compared with Suez	NSR is technically feasible. Costs are about twice as high on the Northern Sea Route as on the Suez route.	Verny and Grigentin (2009)
Container transit using NSR compared with Suez	The NSR is not economically feasible at all if the ice-breaking fee remains at the current level.	Liu and Kronbak (2010)
Europe-Asia transit year-round	NWP not profitable Year-round transit not profitable unless very high fuel prices. NSR competitive for northern Asian hubs in summertime in 2030.	DNV (2010)
Commercial transit along the NWP	More costly by \$75 000 to \$175 000 per trip to use NWP.	Paterson (2011)
Commercial transit along the NSR	Transit can be profitable for direct costs.	Falck (2012)
Europe-Asia transit along the NSR	Cost per container is higher along the NSR because large ships cannot use NSR for now; besides, the reliability of the route is too low.	Carmel (2012)
Commercial transit along the NSR and the NWP	Direct costs can be lower for shorter Arctic transit routes if optimal conditions are met. Commercial factors for container are a severe obstacle.	Lasserre (2014)

of the market share as of September 2010, according to the Alphaliner Top 100 rankings (www.alphaliner.com/top100/index.php), which makes their opinions fairly representative of the container transport sector.

The relatively small sample did not lend itself to statistical analysis and all quantitative statistical approaches were rejected in favour of a qualitative approach, the only legitimate one, which was used to analyze the data.

The responding firms were broken down according to their home region (Europe, North America or Asia) and sector of activity: container, roll-on roll-off (RoRo), bulk (dry and liquid), general cargo or special project cargo. Transport logistics for roll-on roll-off ships are similar to those for container ships with respect to time management and tight schedules to meet, which allowed for them to be grouped together. Whereas special project cargo are generally used in construction

projects and call for customized services which, in general, are exempt from scheduling constraints. Companies with a mixed fleet were classified according to their dominant sector of activity. A distinct category was created for fleets consisting of numerous container ships and bulk freighters. When the ratio of bulk ships to container carriers was greater than or equal to 0.6, the company was classified in the mixed (Container and Bulk) category. Responses to the first question, “Are you considering developing operations in the Arctic?” were divided into three categories: yes, no and maybe.

Among the companies expressing an interest in the Arctic, eight are already present on the Arctic shipping market,

three in the bulk sector and five in the general cargo sector. These companies are active in servicing local communities as well as mining and hydrocarbon development operations in the Canadian or Russian Arctic. All these companies indicated their intention to expand their service offerings in the Arctic shipping market.

For all sectors combined, a vast majority of respondents indicated their company’s lack of interest in Arctic routes (Table 2). However, a breakdown of these data by sector of activity immediately highlights the widely different approaches taken by carriers in this respect.

TABLE 2. Overview of responses according to company’s home region and main sector of activity.

	Sector of Activity						Total
	Container	RoRo	Container and Bulk	Bulk	General Cargo	Special Project	
Yes	0	0	2	9	5	1	17
No	35	2	5	25	4	0	71
Maybe	3		1	6	0	0	10
Total	38	2	8	40	9	1	98

	Home Region			Total
	Europe	Asia	North America	
Yes	10	0	7	17
No	32	25	14	71
Maybe	5	3	2	10
Total	47	28	23	98

Container ships: carry boxes or containers used to transport consumer goods. Container lines work on a just-in-time basis embodied in scheduled service with stopovers at several ports.

RoRo: roll on, roll off: ships that transport vehicles.

Bulk ships are designed to transport unpackaged cargo, such as grains, coal, ore, and cement loaded directly its cargo holds and not in unitized boxes.

General cargo ships are designed to transport containers but can also load some bulk cargo and a variety of goods.

Special project ships are designed to carry oversized elements, usually for large construction projects.

In the general cargo sector, many companies in the sample are already active in the Arctic and this sector seems to be the one with the greatest proportion of companies showing a desire to develop Arctic shipping services. Five companies said that they intend to increase their services, while four showed no interest in doing so. The special project shipping firm Beluga (now bankrupt), based in Bremen (Germany), also responded positively, which makes sense since, in the summer of 2009, it began providing special service to a Siberian community (Yamburg) to deliver construction goods. This interest does not rest on potential transits, but on local destination shipping.

In the bulk sector, responses were generally negative, although six companies were undecided and nine said they were interested.

In the mixed container and bulk sector, responses were also rather negative: five “no” responses against only two “yes” responses.

In the roll-on roll-off and container segments, however, there was no ambiguity: the response was a resounding no.

Recent traffic figures seem to attest to this very limited interest for transit along Arctic sea-lanes. If a growing number of ships do come to the Canadian Arctic (Table 3), few do so to cross the Northwest Passage (Table 4): traffic is mainly destination, not for transit (Lasserre 2010b, Lasserre and Pelletier 2011). That does not mean it is safer, for accidents with cruise ships could prove dramatic, as well with tankers loaded with oil for instance. Interesting to note is the stabilization of the cruise shipping figures, contrary to what was expected and to the evolution of the Arctic cruise traffic in Greenland and Svalbard notably.

Regarding the Northeast Passage, data is more difficult to get from Russian authorities. The most common figures indicate there were between two transits of the Northeast Passage in 2009; five in 2010, 34 in 2011, 46 in 2012, 71 in 2013, but 31 in 2014, 18 in 2015 and 19 in 2016 (Data Center for High North Logistics). Destination traffic is much more significant: in 2015, transit tonnage was 39 586 metric tons but destination traffic amounted to 5 392 414



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tons. Partial transit is thus growing, which has been the case already in Soviet times, a traffic which has been driven by natural resources economics. As mentioned, when one looks closer to the partial list we could find, the transits the Russians put forth stem from the fact Moscow considers traffic for the Northern Sea Route (NSR), which officially begins in the west at the Kara Gate: traffic originating from Murmansk, for instance, will be considered as originating from beyond the NSR. And precisely, most ships that are considered as having transited the NSR in 2011 started their journey in Murmansk, Vitino, Arkhangelsk (Arctic Russia), Honningsvåg or Kirkenes in Finnmark (Norway), with a few exceptions: one ship left Onsan (South Korea) with kerosene bound for Le Havre (France); three left Petropavlovsk in Kamchatka to St. Petersburg and one from Vladivostok to St. Petersburg with frozen fish; one delivered oil equipment to Kholmsk in Sakhalin Island from Larvik in southern Norway; and a seismic vessel stationed

TABLE 3. Number of ship voyages to the Canadian Arctic, 2005-2016.

	2005	2007	2009	2010	2012	2014	2015	2016
Number of ship voyages of which:	123	201	210	309	322	301	315	346
Fishing vessels	22	51	65	123	114	119	129	131
Cruise ships	12	17	18	18	23	11	18	20
Cargo ships or barges of which:	65	101	100	124	122	108	120	147
General cargo	16	28	23	35	32	32	34	36
Tanker	17	24	23	28	31	25	27	23
Bulk	21	26	27	27	24	33	36	53

TABLE 4. Transit traffic in the Northwest Passage.

Ship type	2005	2007	2009	2010	2012	2014	2015	2016
Icebreaker	2	2	2	2	2	4	6	3
Cruise ship or touristic icebreaker	2	3	3	4	2	2	2	3
Cruise ship or touristic icebreaker, partial transit	0	0	0	2	4	0	6	10
Pleasure craft	0	2	10	12	22	10	19	15
Tug	0	0	2	1	2	0	0	0
Commercial ship	0	0	0	0	1	1	0	1
Commercial ship, partial transit (destinational)	0	0	1	4	6	8	10	12
Research ship	3	0	0	0	1	0	0	0
Total complete transit	7	7	17	19	30	17	27	23
Total partial transit	0	0	1	6	10	11	16	24

in Hammerfest transited the NSR to join New Zealand. Overall, there were seven known real transits. Traffic is indeed growing, like in the Canadian Arctic, but most of the Northeast Passage traffic is from the Arctic, linked to the exploitation of Arctic natural resources, and therefore is destinational too: ships come, load in an Arctic port and then deliver the goods along the NSR.

The following conclusions can be drawn from these figures:

- Navigation in the Canadian Arctic has increased, but remains essentially destinational rather than transit traffic.
- Especially since 2006, there has been a general upsurge in total traffic in the Canadian Arctic, which reflects an increase not only in fishing activities and tourism, but also in commercial shipping, consisting of service to local communities and natural resource exploitation operations. The region can expect that traffic driven by fishing and natural resources exploration/exploitation will keep increasing.
- Although there has been a real increase in transit traffic through the Northwest Passage, mainly driven by pleasure craft, such traffic is still at a very low level: 26 transits in 2010, only three of which were commercial. In contrast, Panama saw 13 000 transits in 2008, Malacca, 70 700 transits in 2007 and the Suez Canal, 21 000 in 2008 .

20.5 Analysis: a sharp contrast between transit and destination traffic

An examination of the responses received to the second question—“Why are you considering, or not, developing operations in the Arctic?”—allows us to comment on their distribution and confirm the picture thus obtained accurately reflecting the strategies of the carriers.

20.5.1 Arctic routes are likely to remain risky for a long time

The persistence of risk and uncertainty on these routes is a commonly mentioned factor among shipping companies: problems due to drifting ice or extreme cold; inter-annual

variability in ice extent despite the trend in melting; the scarcity of port facilities and navigation aids, especially on the Canadian side; the inaccuracy of nautical charts, isolation and, as a corollary of all this, the policies of insurers (cited 18 times). For example, the lack of infrastructure as a risk factor was underlined by shipping operators during the Polar Shipping Summit in Montreal, May 5-6, 2010 (Nunatsiaq Online 2010). With respect to the inaccuracy of nautical charts, between 1996 and 2009, before the three accidents in the summer 2010, four cruise ships had run aground in the Arctic.

Risks posed by drifting multi-year ice (Howell et al. 2013), but increasingly too by growlers and small icebergs which are very difficult to detect, force ships to greatly reduce their speed as the possibility of encountering such blocks of ice increases. When that happens, transit times are longer, which reduces the benefits of Arctic transits (mentioned six times). The frequency of small icebergs in Baffin Bay is likely to increase as the Greenland cap shows definite signs of melting (Lasserre 2010c). Fog, poor visibility and difficult ice conditions are likely to increase the risk of accidents, as testified by the collision of two Russian tankers along the Northeast Passage in July 2010 (Nilsen 2010).

To meet insurance requirements, businesses wishing to operate these routes must still buy expensive ice strengthened ships (class 1A at least) well equipped to navigate in these polar areas (de-icing system, two drive shafts, etc.). It is unclear from the interviews whether all companies considering transiting through Arctic routes think ice-strengthened ships are still a necessity, but firms considering destinational traffic are fully aware that a class 1A (Baltic or Lloyds classification) is a minimum standard. Insurance firms are still bracing with actuarial calculations for Arctic shipping, but it is likely they will be extremely reluctant to insure ships not designed for navigation in potentially iced waters.

Ships must also be temperature-controlled to protect goods from freezing, especially for the container sector (three mentions), and equipped to face icing. Such ships are more expensive to build (capital costs) and operate (less



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hydrodynamic and heavier, therefore with a higher fuel consumption per km) (cited 13 times). Ragner (2008) and DNV (2010) attest to the fact that fuel consumption is less efficient with ice-strengthened ships. The fuel consumption difference may not be as significant as between old and new ships or as between faring at full speed and a slower pace (Stopford 2009, Wijnolst and Wergeland 2009). However, even if the differential is to the order of a few percent, combined with a much higher investment cost and the fact that the increased steel structure reduces somewhat cargo capacity, in a very competitive business environment, this fuel margin must be relevant for shipping companies (Guy 2011).

20.5.2 Reduced costs? A common sense assertion that needs to be questioned

Cost considerations (potential savings) were of interest to businesses considering using Arctic transit routes between Europe and Asia or between Asia and North America's Eastern Seaboard. Potential savings and/or shorter routes is the main factor set forth by companies interested in transit, not destination traffic, but these are not numerous: only six companies answering "Yes" or "Maybe" have transit in mind. This point is highly significant, since it shows that, contrary to the images widely circulated in the media, many marine carriers are far from being won over by the prospect of significantly less expensive transit

opportunities. Furthermore, many of the businesses that considered going to the Arctic or showing an interest in Arctic routes are well aware of their potential difficulties, spontaneously mentioning the need to invest in costly ice strengthened ships, the inherent risk in Arctic navigation due to drifting ice, the scheduling challenges due to seasonal variations and the scarcity of infrastructures and services in the Arctic region should an accident occur. One company even cited the possibility of the transpolar route becoming navigable over the long term, which would make the routes passing through Arctic straits obsolete.

20.5.3 The transit segment is not structured to benefit from Arctic routes

The container shipping industry—like the car shipping industry, which uses roll on roll off ships—operates in a just-in-time mode, and this operational constraint is being reinforced as shipping operations are more and more integrated in a broader logistics chain (Terrassier 1997, Clarkson Research Studies 2004, Lorange 2008, Damien 2008). This industry is therefore not driven by the transport cost per twenty foot equivalent unit (TEU) alone, but by other factors such as transit time, marketing advantages of faster delivery, but also the reliability of delivery schedules and the value of markets along the way. Container shipping firms do not merely sell the shipping of goods, but also

guarantee on-time delivery according to a fixed schedule. Drifting ice, an increasing number of icebergs and thick fog banks, however, make it difficult to meet these tight schedules. Drifting ice can temporarily block some straits, making them very tricky to navigate, which could cause delays in delivery or perhaps even force the ship to turn around and transit by the Panama Canal, resulting in disastrous delays both in terms of financial penalties and reduced credibility (cited 23 times).

- The ice will reform every winter under polar conditions, which include severe cold, total darkness (the polar night) and complete isolation. Therefore, potential transit routes will not operate during winter, which means that ship owners will have to change their schedules twice a year, a situation that not only is costly but also increases the risk of errors, and hence of delays as well (cited 22 times). Accurately predicting freeze-up and breakup dates is still very difficult. Since schedules are fixed several weeks in advance, there is a risk of launching summer routes before some straits are ice free or, inversely, of missing a number of days when navigation is possible (cited eight times).
- Given the costs of operating ice strengthened ships (as discussed earlier), the possibility of a toll (already in place in the Northeast Passage due to a mandatory escort though Russia) and the significantly higher insurance premiums, one cannot say if the real cost of transiting via Arctic routes would be that attractive (cited ten times).
- Along Arctic routes, there are no intermediate market (stopovers) and no port adequately equipped to receive the containers to be unloaded/offloaded at potential rotations, which reduces the commercial interest of these routes, compared with the multiple loading/unloading opportunities along traditional routes such as Suez or Panama (cited 14 times). This is in line with the literature that underlines the restructuring of the shipping industry along the “main line” of major port hubs (Rotterdam, Felixstowe, Algeciras, Marsaxlokk, Suez, Dubai, Mumbai, Singapore, Hongkong, Shanghai, Busan, Kobe and Long Beach) from which transshipment is operated to service regional ports (Comtois and Rimmer 2004, Damien 2008, Renault 2010).
- Poor perceived security included the scant infrastructures to regulate traffic (buoys) or to shelter ships should they suffer from mechanical problems (cited nine times). The Canadian Coast Guard operates, in the whole NORDREG area, 242 buoys, beacons and racons (radar transponders used to mark navigational hazards), a very small number given the size of the territory. There are only three wharves in the Canadian Arctic: one in Churchill, south of Hudson’s Bay; a private one in Deception Bay, in northern Quebec; and one in Nanisivik, formerly used by the mine that shut down there (Lehnert 2012). One wharf will be built in Steensby Inlet, on Baffin Island in Foxe Basin, to service the Mary River mine, and new installations will be built for the Navy in Nanisivik. This is therefore the only wharf along the Northwest Passage for ships to stop should they need it.
- The container sector is a very competitive market: carriers try to optimize their rotations and write off their ships faster by plying their trade on busy routes with good cargo potential. Consequently, experiments like Arctic routes look more like theoretical options than profitable solutions. The company has not given it much thought (cited 26 times).

20.5.4 Local traffic is set to be the growth engine of Arctic traffic

Among companies that foresee an increase of business opportunities in the Arctic, and that do consider developing their activities there (answer ‘Yes’) or at least are thinking about it (answer ‘Maybe’), most do not have transit in mind, but rather destination traffic.

Local shipping services, whether involving the delivery of goods to local communities or the servicing of local resource exploitation operations, prompted a significantly higher number of businesses to express a real interest in Arctic shipping. Fifteen businesses cited this rationale for their interest in Arctic shipping, all with an unequivocal “yes.” There seems to be a real potential for destination short sea shipping in the Arctic. The local shipping services market, particularly the servicing of mining and oil

and gas operations, seems promising and it is clearly this market niche that is attracting shipowners who have made up their mind about the Arctic market.

- With the extension of the relatively navigable season, local communities are eager to develop shipping as this vital link enables them to greatly reduce the cost of their consumer goods, otherwise delivered mostly by plane.
- Natural resource exploration and exploitation is experiencing a boom cycle, both with the prospect of declining ice cover and increasing world market prices. Although the size of the reserves should not be overestimated, nor the technical difficulties to exploit them be minimized (Offerdal 2009), the interest of mining and oil firms for the area is certain. Their production will need to be shipped to final markets and their mines serviced (mentioned six times).
- A few ports can be used as gateways to hinterland markets: Churchill for North America, Murmansk and Archangelsk for Russia. Servicing these ports could represent a niche market (mentioned three times).

One interesting point that should be noted, which is consistent with shipowners' motivations, is that in this subgroup, eight out of fifteen businesses stated that they favor the Northeast Passage (Northern Sea Route), which has better infrastructures, more local ports to service and more mining and oil and gas operations.

However, the main drawback of the Arctic bulk shipping market, either for local service or transit traffic, is its small size.

- For local general cargo service, the volumes of goods to be carried are limited and the competition is already very fierce (cited four times).
- Natural resource exploitation creates traffic, but a relatively small number of ships will be enough to service oil and gas deposits for a long time. The case of the Mary River iron mine, on Baffin Island, comes to mind with its huge deposits of 365 million tons of ore. To be exploited, it would only require eight ships from the Fednav shipping company (Lasserre 2010c). It is also estimated that in 2020, about 20 million tonnes of LNG

will be transported from Russian Arctic gas fields to North America. Transportation of such a large volume would nevertheless require only about 20 new ice-class LNG tankers (Wheater 2007). The market is therefore not a major one for the years to come, although it is growing rapidly (cited nine times).

- Besides, in the bulk segment, whether liquid bulk for oil or gas, or dry bulk for mineral ore, the relatively small market size for the years to come makes it difficult to write off the investment for ice-strengthened ships in a shipping segment where earnings are volatile and the investment process risky (Clarkson Research Studies 2004). As ice-strengthened ships are more costly to operate (they are heavier and less hydrodynamic), using them in warmer waters is financially inefficient. For the cost of a major investment to be fully written off, such as a more expensive to build and operate ice strengthened ship, the ship must be used in Arctic waters, otherwise there would be little or no hope of a return on the investment. However, the bulk market operates on spot contracts (tramp) rather than regular liner shipping, and regular services (shuttle tankers) are the exception; besides, the ship owner is not the only actor in defining the itinerary (Terrassier 2001, Lacoste 2004). Before getting involved in the Arctic niche market, several ship owners would like to have a bit of a financial guarantee—in other words, that they would be able to find shuttle contracts or enough cargo to ship in Arctic waters for a number of years, which is not easy to achieve due to the way this market operates (cited seven times). This kind of long-term relationship can be seen with Frontline's chartered ships to British Petroleum, or, in the Arctic, with Fednav and Baffinland Iron Mines (Mary River Project).
- These routes will remain too risky—especially when considering the nature of the cargo, potentially very polluting—and therefore too expensive to insure (cited three times).
- Given the evolution of markets and the geography of the operating and consumption areas, trying to develop such routes does not seem worthwhile (cited eight times).

To sum up, an examination of the reasons cited by shipowners for their interest or lack of interest in Arctic sea routes reveals the following basic points in the strategies of shipping companies:

- The container industry is not interested at all in Arctic shipping. The constraints of just-in-time planning, schedule creation and risks are too great, in comparison with what are perceived as relatively modest profits.
- Niche markets prefer to supply to local communities, offer a high potential for growth, and the companies already involved have a firm intention of expanding their service offerings.
- Reaction from bulk shippers is mixed. Using Arctic transit routes could be a worthwhile strategy, but was cited by few respondents. It is more the possibility of capturing a share of the highly expanding market for servicing mining and oil and gas activities that seems to be attracting shipowners' attention.
- The potential savings in transit time and costs, emphasized widely in the media, do not seem to have won over many companies. Firms either are not interested in Arctic transit routes or play down the advantage of the shorter distances because of the higher capital and insurance costs to be incurred, or the fact that transit time is not much different from other routes anyway because of reduced speed. This observation is in line with the review of the literature on cost simulations discussed earlier.

20.6 Conclusion

Arctic seaways provide a definitely shorter route between Europe and Asia than routes through Panama or the Suez. The summer melting of sea ice has fuelled scenarios of an impending explosion in transit traffic through the Northeast and Northwest passages, as shipowners desperately try to reduce fuel costs and increase their rotations.

However, an analysis of shipowners' intentions, based on a sample of 98 companies, reveals a totally different, and much more restrained, picture. Although marine traffic in the Russian or Canadian Arctic seems to be definitely on the rise, this is far from being an explosion. In addition,

although a few voyages in the Northeast Passage have recently attracted a lot of media coverage, the increase is not in transit traffic but rather in destination traffic, the growth being fuelled by vessels servicing local communities and natural resource exploitation activities. The bulk sector remains cautious about Arctic routes, while the container segment is definitely not nurturing interest in these routes. The conclusions of this research were confirmed in another sample test carried out in 2014-2015 (Lasserre et al. 2016).

To sum up, Arctic passages will not become the new Panama of the 21st Century. This empirical evidence from the survey of shipping firms and the analysis of traffic data is in line with traffic scenarios set up by the Arctic Council in its Arctic Marine Shipping Assessment 2009 Report: "Arctic voyages will be overwhelmingly destinational, not trans-Arctic" (Arctic Council 2009). However, this increase in destinational traffic still means control must be exercised on traffic, for many ships will transport potentially hazardous cargo, especially oil or concentrated minerals.

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Chapter 21 Cruise Tourism

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Key implications for decision makers

- A substantial decline in the extent of ice coverage has resulted in a greater accessibility for passenger vessels; their number doubled between 2007 and 2014 but this is far from a boom.
- There is an apparent discrepancy in the size of the market between the Canadian Arctic and other Arctic regions that witnessed sustained marine tourism traffic.
- The lack of available polar class vessels constitutes a major constraint to cruise shipping that limits the diversification of itineraries.
- A significant increase in cruise shipping is likely to not occur without significant development of marine infrastructure and a revision of the regulation and permit process.
- Maritime infrastructure is poor or inadequate in most Eastern Canadian Arctic communities which represents a challenge for communities, but not so far for cruise operators.

Abstract

Melting of sea ice has increased opportunities for marine tourism development in the Canadian Arctic Archipelago, leading to increased pressures on the environment and on local communities. This, together with the Canadian Coast Guard's Northern Marine Transportation Corridor Initiative (NMTCI) underscores the need for guidelines pertaining to tourism-related transportation, as well as monitoring of priority sites used by cruise and pleasure craft operators. Based on semi-structured interviews with cruise ship operators and Hot Spot Analysis performed in ArcGIS (10.1), this chapter examines the spatial patterns of the cruise tourism industry in the Eastern Canadian Arctic waters between 2001 and 2016 and evaluates the challenges faced by cruise ship operators in these remote locations. The discussion is focused on the importance this study represents as a first step towards the identification of priority conservation areas to regulate marine tourism in the Canadian Arctic.

21.1 Introduction

Since 1995, melting of sea in the Arctic has increased opportunities for marine tourism development in many parts of the region and particularly in the Eastern Canadian Arctic (Lasserre and Têtu 2015). In this context, a substantial decline in the extent of ice coverage has resulted in greater accessibility for passenger vessels and pleasure crafts that have increased rapidly over the past decade (Tivy et al. 2011, Stewart et al. 2013, Pizzolato et al. 2014). For instance, the number of pleasure craft and passenger vessels, respectively quadrupled and doubled between 2007 and 2014 (Pizzolato et al. 2014, Dawson et al. 2016, Johnston et al. 2017). This rapid evolution and the rise in the number of locations visited by a cruise ship caused for some concern from the scientific community on the impacts on the environment and on communities (Stewart et al. 2007, Marquez and Eagles 2007, Stewart and Draper 2009, Lamers and Amelung 2010, Fay and Karlsdottir 2011, Stewart et al. 2011, Stewart and Dawson 2011, Grenier and Müller 2011, Lemelin et al. 2012, Dawson et al. 2014, de la Barre et al. 2016, Johnston et al. 2017, Têtu 2017).

In reaction to this rapid development of marine tourism, the Canadian Coast Guard (CCG) began to address some of the deficiencies in Canada's Arctic shipping policy by launching the Northern Marine Transportation Corridor Initiative (NMTCI) (CCG 2015, Porta et al. 2017, Dawson et al. 2017). This initiative aims to ensure that the appropriate maritime services and systems are in place to support safe navigation in the Arctic. Highly related to this initiative is the need for guideline creation and monitoring of prioritized sites used by cruise and pleasure craft operators (Blangy et al. 2010, Dawson et al. 2014, Johnston et al. 2017, Têtu 2017). The purpose of the guidelines is to support visitation through information, controlled impacts, and to ensure visitation occurs within the existing governance framework. Environmental degradation increases stress on populations, creates insecurity and can erode collective identities (Graeger 1996). Thus the monitoring of environmental degradation linked to marine tourism is required. Moreover, while the question of the development of the

marine tourism industry in the Canadian Arctic remains controversial as expert's analysis do not converge (Howell and Yackel 2004, Lasserre and Têtu 2015), the NMTC initiative underlines the lack of reliable analysis on historical patterns and spatial trends of the marine tourism industry in Canadian Arctic waters.

The objective of this chapter is to understand the dynamics of the cruise tourism industry in Eastern Canadian Arctic waters. Firstly, we draw on a historical and more contemporary spatial portrait of passenger vessels in the Eastern Canadian Arctic between 2001 and 2016, as well as the most visited locations. Secondly, we present the main challenges faced by the operators in the Canadian Arctic, based on previous analysis (Têtu 2012, Lasserre and Têtu 2015). Lastly, we discuss the originality this study represents as a first step in the creation of site guidelines for marine tourism-related transportation in the Canadian Arctic.

21.2 Assessing cruise tourism in Arctic Canada: methodology

21.2.1 Survey on cruise tourism operators

In 2012, a survey was sent to 66 cruise ship operators that operate either their own ships or chartered ships; 67% (44 operators) responded to our survey questions. There are four categories: those already present in the Canadian Arctic (nine operators); operators in the European and Russian Arctic (Arctic Expedition Cruise Operators - AECO – 12 operators); operators in Antarctica (International Association of Antarctica Tour Operators – 19 members); members of the Cruise Line International Association (CLIA (21 members) and independent operators (others), mainly British companies (5 members). The AECO and International Association of Antarctica (IAATO) represented the two main organisations present in Polar Regions, the AECO in the Russian and European Arctic and IAATO in Antarctica. On the other hand, the CLIA were selected because their members are the biggest players in terms of ships and loading capacity in the World, and are potential operators that could have been interested in a diversification of their activities, as well

they bring new players and more passengers in the Arctic. From December 2011 to March 2012, directors and executives of cruise tourism companies were solicited. Through semi-structured interviews, companies already present in the Canadian Arctic were asked to answer the following questions: 'Do you intend to expand your business activities in the Canadian Arctic and why? Nine companies answered the survey. Marine Tourism companies active in other locations than the Canadian Arctic were invited to answer the following questions: 'Do you intend to enter the cruise tourism market of the Canadian Arctic and why? Thirty-seven companies completed the survey. A more thorough but similar study was set up by Têtu (University of Ottawa) and Lasserre (Laval University) in January 2017. Interviews are ongoing but the results are not yet available.

21.2.2 Monitoring the cruise tourism in Arctic Canada through GIS

The list of Cruise operators and their movements in Canadian Arctic waters from 2001 to 2016 have been obtained from a comprehensive source of ship track information available in Arctic Canada, namely the Canadian Coast Guard's (CCG) NORDREG (Northern Canada Vessel Traffic Monitoring Services) annual datasets. These datasets includes position data upon entry and exit of the NORDREG zone (north of the 60th parallel), daily positions at 1600 Coordinated Universal Time (UTC), in addition to vessel name, call signal, International Maritime Organization (IMO) number, and flag state (Pizzolato et al. 2016). The spatial mapping of cruise ship operators in the Eastern Canadian Arctic as well as the most visited locations is the result of the conversion of the daily position coordinates into an ArcGIS supported format. Manipulations on the dataset with the Optimized Hot Spot Analysis tool in ArcGIS allowed us to identify statistically significant spatial clusters (1 square kilometres cells) of high values (hot spots) and low values (cold spots) (ESRI 2017) as well as to create thematic maps.

21.3 Cruise tourism in the Arctic: a global overview

Cruise tourism in the polar arctic region differs substantially from cruises in warmer waters like the Caribbean or the Mediterranean Sea, which are presently the two most famous cruise destinations in the world. Despite the average prices for Polar cruises which are much higher than for classical cruises, sometimes 7-fold greater, cruise tourism has experienced a steady growth in all polar markets, both Arctic and Antarctic (Lasserre and Têtu 2015). However, there is an apparent discrepancy in the size of the market between the Canadian Arctic and other Arctic regions that witnessed sustained marine tourism traffic, as it is the case for Greenland, Spitsbergen (Svalbard) and Northern Norway (Ibid.) In contrast, Canada's market share of polar cruise tourism remains very small and differs from other Arctic regions. For example, indigenous people inhabit the Canadian Arctic, Greenland, Russia, Alaska and Norway, whereas Spitsbergen and Iceland they do not. In Spitsbergen and in Iceland, cruise companies focus primarily on fauna and flora, given the absence of indigenous peoples. In Alaska, Canada, Greenland, Norway, and some cruise destinations on Russian Arctic Islands, the cruise destinations focus both on natural environments and indigenous populations. Consequently, these tourist services use established maritime infrastructure and promote economic benefits (Kaae and Rabede 2011). For this purpose, the presence of small towns and villages along the coasts of Greenland and Iceland, and at a smaller scale in Alaska and Norway, favours better economic return.

There are also great disparities between the size of passenger vessels in most Arctic Regions and in the Canadian Arctic. For most Arctic Cruise tourism destinations, except in the Canadian Arctic, the presence of maritime infrastructure allows cruise ship companies to bring large ships (between 1000 and 4000 passengers) for port visits. The presence of these marine infrastructures favours visits and spending in inhabited places (Dupré 2009). In this regard, large cruise vessels are possible in Spitsbergen (Svalbard Archipelago, Norway), Alaska, Norway and Greenland, whereas the Canadian Arctic is reliant on expedition or adventure cruise

vessels and passengers can only come ashore on zodiacs, which is sometimes a logistical constraint (Angell and Parkins 2010). The Russian Arctic coastline, despite the scarcity of settlements and infrastructures, remains a very popular destination (Lamers and Amelung 2010).

The cruises, conducted mainly on ancient Russian icebreakers, promote arctic safaris, promotes natural sites and islands of Russian coastline, as well as visits of local communities in landings sites on Siberia. The Quark's expeditions from Murmansk to the North Pole on the world's most powerful Russian icebreaker 50 years of Victory (Lasserre and Têtu 2015) is also a very popular voyage. The prices of such trips are, however, exorbitant and are on average between \$22 000 to \$33 000 but can reach \$100 000 for a luxury berth (Quark Expedition 2017). Considering the entire Arctic region, a rapid expansion of cruise tourism took place from the beginning in the late 1990s until 2010, for all Arctic destinations (Ibid.).

21.4 Historical and spatial patterns of cruise ships in the Eastern Canadian Arctic waters, 2001-2016

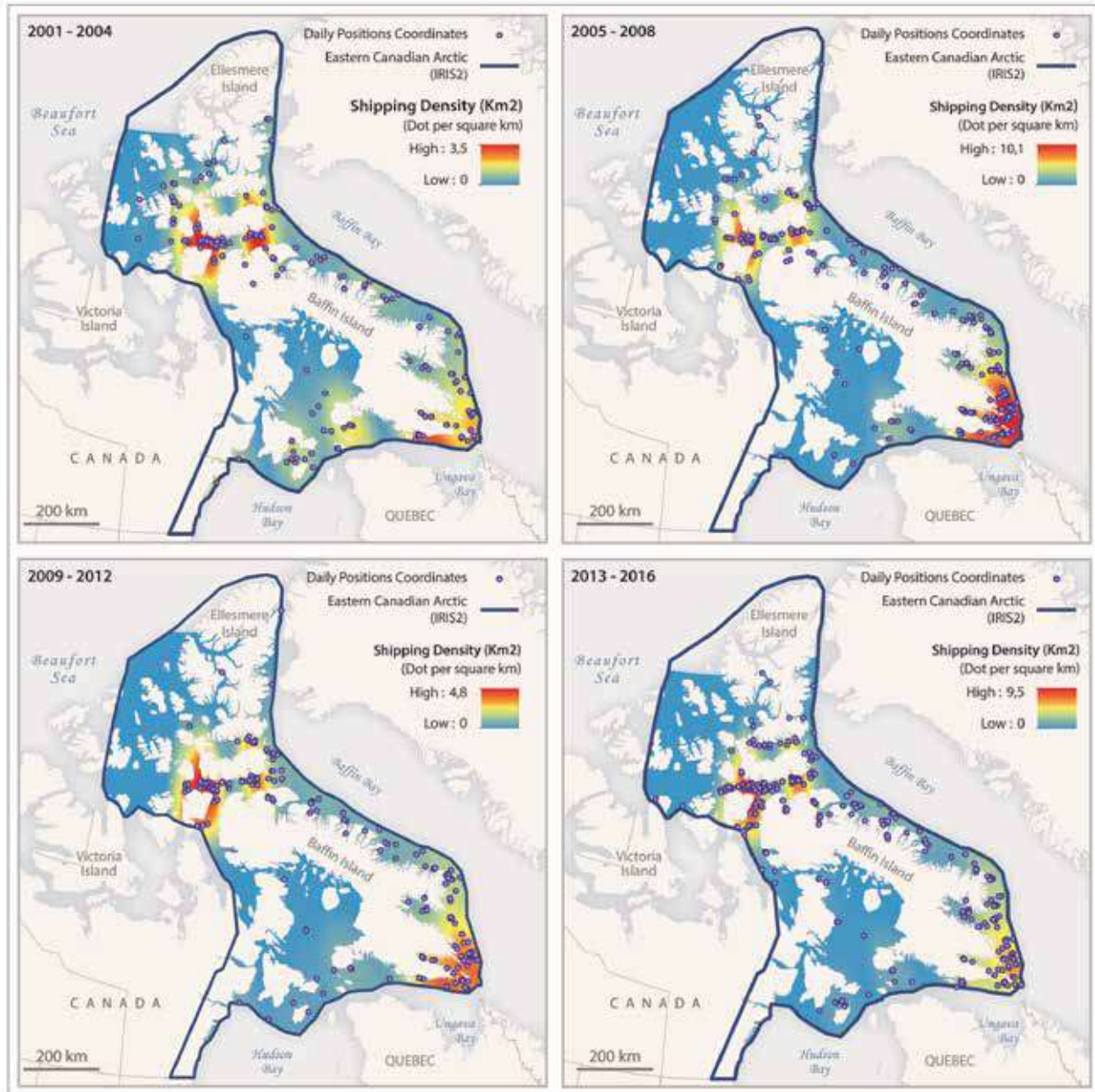
Cruise ships in the Eastern Canadian Arctic waters between 2001 and 2016 were concentrated in the Lancaster Through, south of Ellesmere Island, and in the surrounding area of Monumental Island and Iqaluit, in the Hudson Strait and waters south of Baffin Island and Baffin Bay (Figure 1). Previous studies (Stewart et al. 2007, Dupré 2009, 2010, Stewart and Dawson 2011, Lasserre and Têtu 2015) highlighted a diversified geography of visits in the Canadian Arctic, where stopovers were concentrated in the Eastern (Baffin Island and northern Quebec) and central Arctic (Figure 2). This pattern of stopovers by cruise ships is explained by the fact that most visited sites are those where sea-ice conditions are less of a constraint according to the Arctic Shipping Pollution Prevention Regulations (ASPPR) Zone/Date System (Lasserre and Têtu 2015) that are around Resolute (Zone 13) and near Iqaluit (Zone 15).

Under the ASPPR Zone/Date System, the Canadian Arctic is divided into 16 zones where the sea ice is permanently

analyzed by the Coast Guard: the ice class of the vessels compared with the nature and extent of the ice determines whether the vessels meet the requirements to enter a particular zone. The system is completed by the Arctic Ice Regime Shipping System (AIRSS), which involves comparing the actual ice conditions along a route to the structural capability of the ship (Ibid.).

Between 2001 and 2004, the passenger vessels were highly concentrated in the eastern entrance of the Northwest Passage, around Beechey Island and Dundas Harbour in the Lancaster Through. Beechey Island for instance, is a historical site where members of the 1845 Franklin expedition are buried. Their graves represent an important attraction in the region. On the south coast of Devon Island, the old abandoned RCMP detachment at Dundas Harbour remains an important and regularly visited shore location. There is also a concentration of vessels in the eastern part of Hudson Strait, to a lesser extent along the west coast of Hudson Bay near Arviat, and in the Foxe Channel around the community of Cape Dorset, which recorded a high level of cruise activity during the first years of the 21st century. However, as hypothesized by Stewart et al. (2010), the demise of ice coverage produced a decline in cruise activity in most of Hudson Bay from 2005 until 2016 and as is the case for Cape Dorset as well as Arviat and Rankin Inlet. Because the prevalence of sea ice is an important part of visitor experiences of polar cruises (Stewart et al. 2007), the diminishing ice regime (Pizzolato et al. 2016) that shifted north ice-supported wildlife resulted in a drastic reduction of cruise ships in these communities (Têtu 2017).

Between 2005 and 2008, despite the record of sea-ice melt in the Arctic from June through September 2007, there has been a reduction of cruise tourism activity in the Lancaster Through, but an increase around Iqaluit and the south-east of Baffin Island. For instance, the number of vessels doubled between 2001-2004 and 2005-2008, from six to 13. In this 2005-2008 phase, the icebreaker Kapitan Khlebnikov went further north. This vessel sailed in Eureka Sound and in the Tanquary Fiord three consecutive years (2006, 2007 and 2008), landed at the Quttinirpaaq National Park multiple times and visited the north east side



Directed by : Pierre-Louis Tétu, 2017. Graphic Edition: Department of Geography, Laval University, 2017
Source: Canadian Coast Guard, 2016

FIGURE 1. Spatial densities of daily positions coordinates of Passenger Vessels in the Eastern Canadian Arctic waters, Baseline (2001-2004); Phase 1 (2005-2008); Phase 2 (2009-2012); Phase 3 (2013-2016).

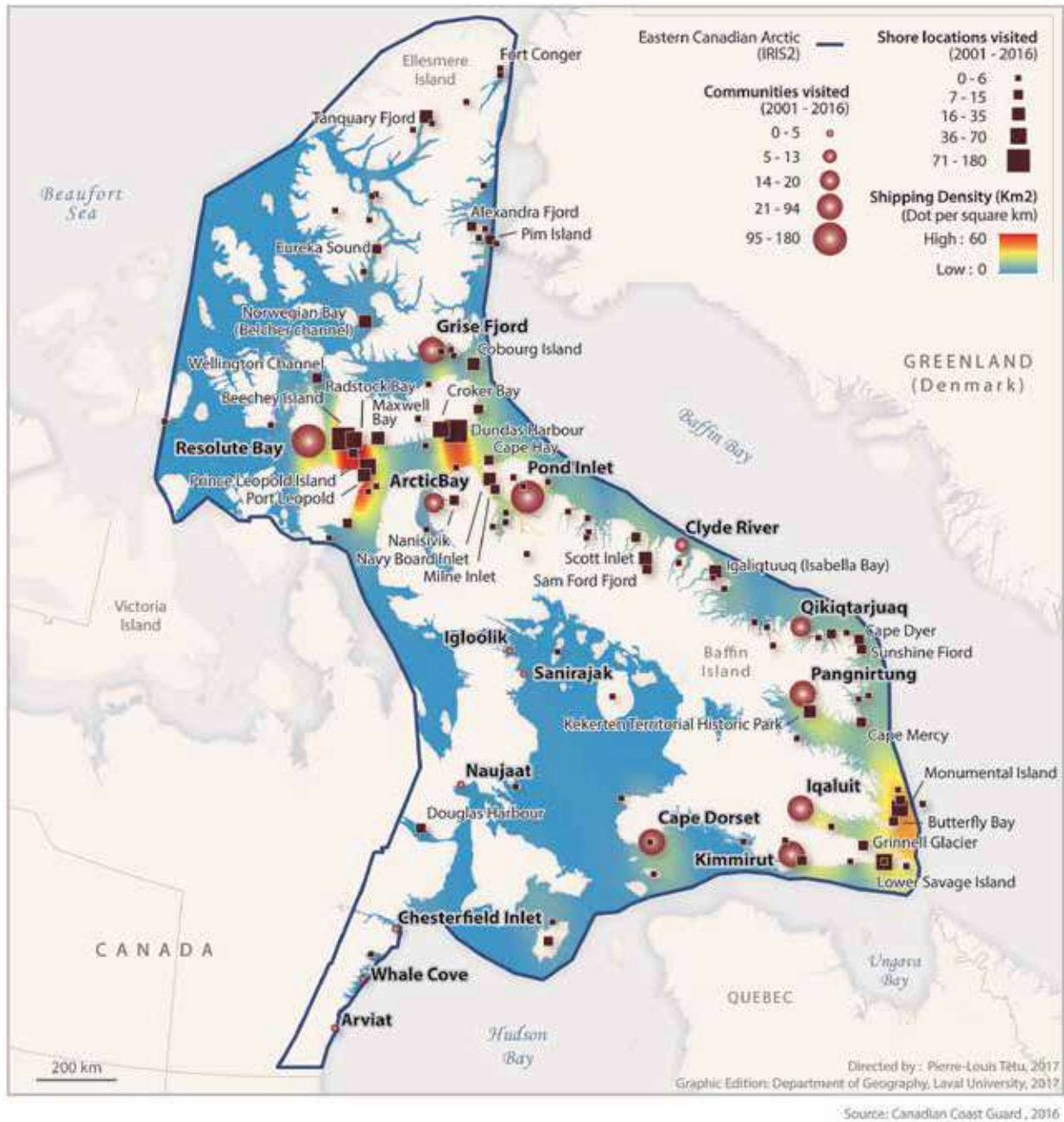


FIGURE 2. Most visited shore locations and communities in the Eastern Canadian Arctic, 2001-2016.

of Ellesmere Island in 2005 and 2008 by landing passengers by zodiacs at the historic site of Fort Conger.

The same high densities of stopovers in the Lancaster Through and in Hudson Strait were observed during both phase 2 (2009-2012) and phase 3 (2013-2016). Despite a decrease in densities in the area of Lancaster Through between 2005 and 2008 in comparison with the baseline (2001-2004), there was an increase during the third phase (2009-2012) in this area and mainly around Beechey Island. In the south-east part of Eastern Canadian Arctic waters there was, however, a decrease in the shipping densities in comparison with the former period. In Hudson Bay and in the High Arctic, the densities remain low during this third phase. The icebreaker *Kapitan Khlebnikov* Polar Class (PC) 3 has been and is still the strongest passenger vessel in Canadian Arctic waters (Table 1). It remains one of the very few vessels to repeatedly sail in these high latitudes around Ellesmere Island. The only other one is the *Akademik Ioffe* (PC7) that offered a voyage in these remote locations in 2010. However, with the melting of sea ice, cruise ships also venture further and further north: in September 2012, *Clipper Adventurer* (PC7) sailed into Nares Strait, a waterway between Ellesmere Island and Greenland where it meets the Lincoln Sea (Lasserre and Têtu 2015).

However, the *Kapitan Khlebnikov* was removed from cruise service in March 2012 for mining purposes (Lasserre and Têtu 2015). During the third phase (2013-2016), there was a continuing concentration of vessels around Beechey Island and at a lesser extent in the south of Baffin Island in the area surrounding Iqaluit and Hudson Strait, which continue to record a decrease in cruise ship activities. However, despite these fluctuations in the number of vessels visiting each community or shore location, it seems that specific locations could be impacted by cruise ships and passengers disembarking onshore. In this regard, a study led by Pierre-Louis Têtu aims to identify the most visited locations in the Canadian Arctic based on past trends and outlines steps for developing site guidelines that are designed to minimize impacts upon shore locations visited by ship-based marine tourism in Polar Regions. The project is in collaboration with Jackie Dawson, holder of the Canada Research Chair in Environment, Society and Policy Group (ESPG) of the University of Ottawa and with Margaret Johnston, professor at Lakehead University.

The analysis of daily position coordinates also reveals that cruise ships operating in the Canadian Arctic are most of all ice-strengthened (at the exception of the *Caledonian Sky* (2012) which is even less than the Baltic System class 1D) and complies with basic Canadian regulation and IMO



PIERRE-LOUIS TÊTU

TABLE 1. Cruise vessels in the Eastern Canadian Arctic waters from 2001 to 2016, according to their Polar Class (PC) notation.

Phases/ Polar Class (PC) Notation	PC3	PC6	PC7	No PC	Others
2001-2004	<i>Kapitan Khlebnikov</i>	<i>Bremen</i> <i>Hanseatic</i>	<i>Akademik Ioffe</i> <i>Clipper Adventurer</i> (now <i>Sea Adventurer</i>) <i>Orion</i>	<i>Lyubov Orlova</i> (1B)	<i>Le Levant</i> (Double-hull reinforced)
2005-2008	<i>Kapitan Khlebnikov</i>	<i>Bremen</i> <i>Hanseatic</i> <i>National Geographic Explorer</i>	<i>Akademik Ioffe</i> <i>Clipper Adventurer</i> (now <i>Sea Adventurer</i>) <i>Explorer</i> (sank in 2007) <i>Prince Albert II</i> (now <i>Silversea Explorer</i>)	<i>Lyubov Orlova</i> (1B) (out of service) <i>Ocean Nova</i> (1B) <i>Akademik Shokalskiy</i> (1D) <i>Alexander Von Humboldt</i> (1D)	<i>Ushuaia</i> (Double-hull reinforced)
2009-2012	<i>Kapitan Khlebnikov</i>	<i>Bremen</i> <i>Hanseatic</i>	<i>Akademik Ioffe</i> <i>Clipper Adventurer</i> (now <i>Sea Adventurer</i>) <i>Polar Star</i> (out of service) <i>Prince Albert II</i> (now <i>Silversea Explorer</i>) <i>Clelia II</i> <i>Hanse Explorer</i> <i>Sea Voyager</i>	<i>Le Boréal</i> (1C) <i>The World</i> (1C) <i>Ocean Nova</i> (1B) <i>Le Diamant</i> (1D) <i>Lyubov Orlova</i> (1B) (out of service)	<i>Caledonian Sky</i> (100A1)
2013-2016	<i>Kapitan Khlebnikov</i> (2015-2016); out of service in 2017	<i>Bremen</i> <i>Hanseatic</i> <i>National Geographic Explorer</i>	<i>Akademik Ioffe</i> <i>Akademik Sergei Vavilov</i> <i>Hanse Explorer</i> <i>Sea Voyager</i> <i>Silversea Explorer</i> <i>Sea Adventurer</i> (former <i>Clipper Adventurer</i>)	<i>Ocean Endeavour</i> (1B) <i>Le Boréal</i> (1C) <i>Le Soléal</i> (1C) <i>L'Austral</i> (1C) <i>Crystal Serenity</i> (1D)	

Source: date obtained from NORDREG System (2001-2016) through public inquiries. Polar Class determined according to Lasserre and Têtu (2015) and Têtu (2012).

guidelines for ships operating in polar waters. The venturing into Canadian Arctic waters of ships with little or no ice-strengthening like the *Caledonian Sky* attests to the flexibility the Canadian legislation offers. The ice-class of most other vessels is however not necessarily strong and this constitutes a serious limitation of their autonomy, as they cannot enter specific zones depending on their ice class and the prevalence of sea ice in a specific area.

For instance, the *Lyubov Orlova*, which is now out of business (Lasserre and Têtu 2015), was only ice-class 1B, *Le Diamant* and *Le Levant* are both 1D; MS *The World*, *Le Boréal* and *Le Soléal*, all ice-class 1C will nevertheless navigate Baffin Bay and the NWP. For instance, between 2001 and 2004, the vessels around Resolute and Dundas Harbour are either PC 7 (*Akademik Ioffe*) or PC 6 (*Hanseatic*, *Bremen*), with the exception of the ice-breaker *Kapitan Khlebnikov* (PC3) that sailed at multiple times in the multiyear-ice areas of Ellesmere Island, in the High Arctic.

21.5 Expansion of cruise tourism in the Canadian Arctic: a lack of interest from worldwide cruise operators

Operators surveyed in 2012 were classified according to their geographic area of activity as explained previously: those already present, AECO, IAATO, CLIA, and those identified as ‘others’. The companies in the Canadian Arctic are quite limited: two companies already present, Silversea Cruise and La Compagnie des Îles du Ponant, and a third, a

yachting operator and member of IAATO, Eyos Expedition, expressed their interest in the Northwest Passage. All three also indicated their intention to expand their activities in the Canadian Arctic in the coming years. Four years later, it seems that Silversea Cruise offers only one trip throughout the Northwest Passage per year. The construction of two new ships – the *Austral* & the *Soleal* – La Compagnie des Îles du Ponant has enabled an increase in their activities in the region (Lasserre and Têtu 2015).

The vast majority of the 44 companies that agreed to participate in our survey in 2012 indicated little interest in the Canadian Arctic cruise market (Table 2). Among the four AECO members interviewed, three companies mentioned a lack of interest for the Canadian Arctic cruise tourism market, and one was undecided. In general, they stated that their customers preferred the Russian and European Arctic, and would thus continue to focus their operations in these areas. Thirteen companies of IAATO were also not interested in cruises in the Canadian Arctic, with the exception of one undecided response and three positive responses. Finally, no company from the CLIA and no company among those classified as ‘others’ was interested in the Canadian Arctic. It seems, however, that after the survey was completed in 2012, the CLIA member Crystal Cruise organized a trip through the Canadian Arctic despite the fact that they mentioned to us that they had no interests in tourism in the region.

The responses to the question “why” provided key information on priorities and divergent interests of cruise operators

TABLE 2. Cruise tourism operator’s interest for the Canadian Arctic: outcome of the 2012 investigation. Question: Do you intend to expand your business activities in the Canadian Arctic?

	Geographic areas of cruise operators				
	Already Present (Canadian Coast Guard Database)	AECO (Arctic Expedition Cruise Operators)	IAATO (International Association of Antarctica Tour Operators)	CLIA (Cruise Line International Association)	Others
No	5	4	13	9	0
Maybe	0	1	2	0	5
Yes	2	0	3	0	0

and their future needs in terms of investment and research and development. Only five operators intended to increase their activities in the Canadian Arctic, with two undecided and three potential new comers from IAATO, namely Aurora Expeditions, Cheesemans Ecology and Travel Dynamics. This contrasts with the optimistic scenarios of a booming Arctic cruise sector in Canada, however these predictions are confirmed by the trends we have previously explored. The three potential new comers from IAATO expressed their interest in the Northwest Passage but do not have enough ships available and must therefore postpone their projects. Indeed, the lack of adequate, ice-strengthened passenger ships appears to be a major constraint for these three operators. Despite growth in the number of vessels and passengers to most Arctic destinations (Lasserre and Têtu 2015), the development of the Canadian Arctic as a major cruise tourist destination is much more modest. The survey of cruise operators showed that only two out of eleven operators already present intended to expand their activities in the Canadian Arctic. With regard to operators present in other regions, only three of nearly 51 surveyed operators intend to enter the Canadian Arctic market. This

lack of enthusiasm is due, in part, to major navigational constraints which stem, mainly, from the sea ice that requires ice-strengthened vessels, unlike other destinations like southern Alaska, southern Greenland or Iceland.

21.5.1 Sea ice and the lack of ice-strengthened vessels available is a major constraint for operators

The lack of available ice-strengthened vessels imposes limits on expansion. Aurora Expeditions, Chessesmans Ecology and Travel Dynamics, three companies that operate cruise itineraries in Antarctica as well as in the Russian and European Arctic, confirmed their interest in developing new itineraries in the NWP but were unable to implement their projects since they could not find adequate ships. In the same vein, the fact that Polar Star Expeditions no longer operates, that Quark Expedition's *Kapitan Khlebnikov* suspended its cruises tourism activities in 2012-2013 and in 2015-2016, and that *Lyubov Orlova* was seized, also decreases the number of vessels cruising in the Canadian Arctic (Figure 3).

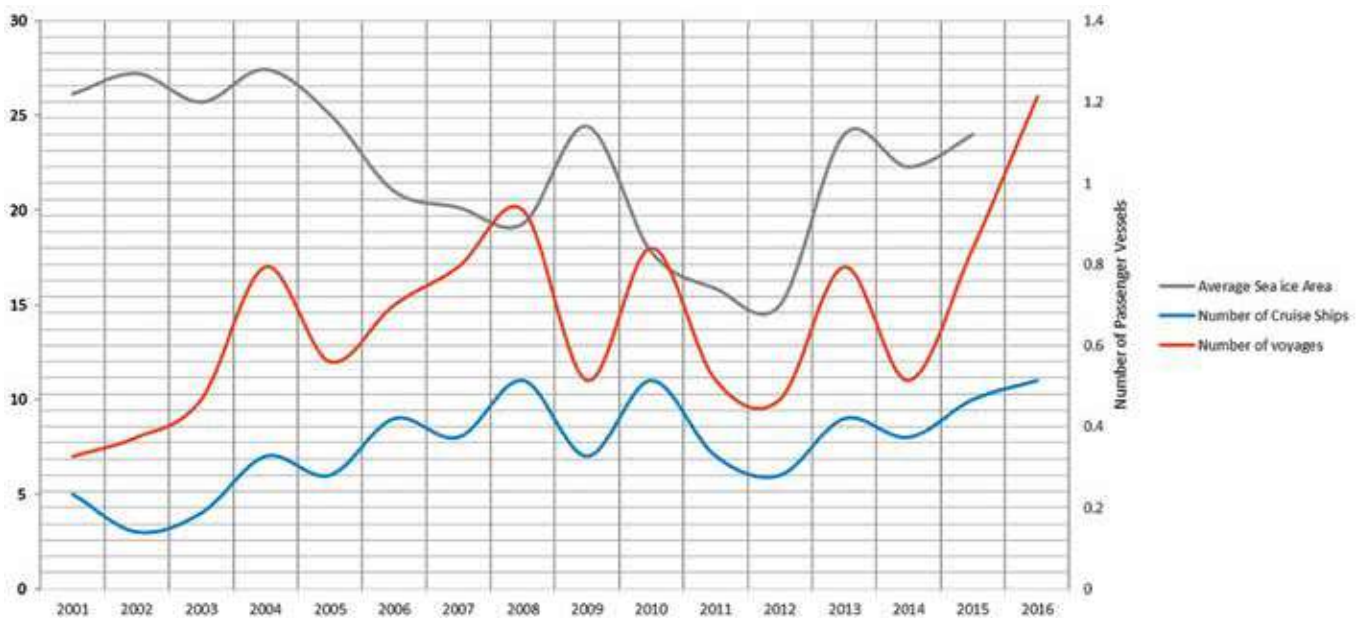


FIGURE 3. Number of cruise ships present in the Eastern Canadian Arctic waters and their number of voyages, 2001-2016.

Operators need to therefore find or order rather small (and thus more costly to operate given the limited economies of scale) and ice-strengthened passenger ships for Canadian Arctic cruises. Cruise tourism is faced with a choice regarding its operating method: either cruises with large ships that can accommodate a large number of tourists, but that will rarely enable them to go ashore; or cruises with smaller ships, at times ice-classed but with limited economies of scales, that can reasonably organise landings on a twice-daily basis if wished. Therefore, the entry into the Canadian Arctic market by players who own large vessels often with a low ice class, like the no-ice class *P&O Aurora* (1975 passengers), *AIDA Aura* (1300 Passengers) or *Costa Deliciosa* (2260) that visited Greenland in recent years, a trend that can also be observed in Iceland or Svalbard, proves more difficult in the Canadian Arctic. However, it seems that the *Crystal Serenity* (1070 passengers) sailed in Arctic Waters in 2016. However, apart from *Kapitan Khlebnikov* (PC3), no ship can sail freely in Canadian Arctic waters in the summer without major regulation constraints justified by the prevalence of sea ice and its erratic distribution from year to year. Vessels without a PC notation, like *Caledonian Sky* (100A1 in Lloyd's System), the *Crystal Serenity* and *Le Diamant* (both 1D class in the Baltic System), *MS The World* and *Le Boréal* (both 1C) and *Lyubov Orlova* (1B), *Le Levant* and *Ushuaia* (Double-hull reinforced) are severely restricted in their activities. The strong shipping regulations and the limitations due to drifting ice make ice strengthened ships mandatory. The lack of PC vessels constitutes a major constraint to cruise shipping in the Canadian Arctic that limits the diversification of itineraries.

21.5.2 The lack of maritime infrastructure: an obstacle for communities, yet not so far for the operators

The lack of port infrastructure in the Eastern Canadian Arctic is obvious. Most of the communities are serviced with barges and provide no facility for ships to dock as we can see in Greenland, in Iceland or elsewhere in the Arctic. For instance, it is expected that the construction of a deep

water port in Iqaluit or Rankin Inlet as well as small craft harbours in other communities are initiatives that, once completed, might increase the attractiveness of certain locations and might promote the development of tourist shipping (Lasserre and Têtu 2015). In addition, improved maritime infrastructure would facilitate cruise ship calls in ports of communities that have received very few ships in the past 16 years. For example, a deep water port in Rankin Inlet would thus increase the potential attractiveness of the Hudson Bay region and neighboring communities and consequently would allow Chesterfield Inlet and Clyde River to expect visits from cruise ships and further develop their touristic services. While the lack of sea ice and icebergs seems to reduce the interest of Hudson Bay for cruise operators, it seems that better marine infrastructure could allow bigger ships to sail in the area. Overall, there is a great need to improve marine infrastructure in the vast majority of communities in the Eastern Canadian Arctic (Figure 4).

It seems, however, that operators disagree on the impact of poor infrastructure on Arctic cruise market growth in Canada. La Compagnie des Îles du Ponant, for instance, does not see the lack of maritime infrastructure in the Canadian Arctic as a major constraint since part of their broader business strategy is to offer a unique experience to their guests through zodiac excursions. On the other hand, Adventure Canada does quote this as another limiting factor for the introduction of larger ships: the logistics of having 100 passengers with zodiacs is feasible, however it is not the case with 2000 passengers as it is more complicated and increases the risk of forgetting a tourist onshore. Other companies such as One Ocean Expedition which are already present in the region see the lack of deep water ports with fuel and water bunkering facilities as a major limitation to the expansion of their activities. A similar opinion has been obtained from CLIA and AECO members Holland America and Silversea. They claim that there is not enough available fuel, that marine infrastructure in the region is inadequate to berth large passenger vessels, as well as the lack of adequate infrastructure for search and rescue operations.



FIGURE 4. The lack of marine infrastructure in Pond Inlet, Eastern Canadian Arctic (right), in comparison to the very small communities of Greenland which are already well equipped (left).

Our data show that many of the cruise operators surveyed suggest that the lack of maritime infrastructure in the Canadian Arctic acts as a barrier for as a barrier to increasing their activities and organising the itineraries of large capacity vessels. Expanded maritime infrastructure in the Canadian Arctic will be necessary to increase the number of vessels and tourist visitors in the area. Indeed, economics tells us that the current cruise prices are limiting the growth of demand for these cruises. The development of marine infrastructure in the Eastern Canadian Arctic could stimulate the interest of companies which own large capacity vessels with reduced exploitation costs per passenger as we see in Greenland or Iceland. On this topic, the literature underlines that the success and development of cruise activity in an area of navigation depends on various factors: attractive ports of departure/arrival, the seasonality of the area concerned, the presence of infrastructure (ports with passenger terminals) and the purchasing power of people living in the area concerned (Lasserre and Têtu 2015). Destinations looking to expand their market share need to consider issues such as, where their potential tourist markets are located and to what extent their location is easily accessible for those markets (Nelson 2013). This is entirely contingent upon the transportation system. In the European Arctic (Greenland, Iceland, Svalbard and Russia), the cruise companies often start their trips from a port that is well connected to air services. In the Eastern Canadian Arctic, there is no public port with berths except

for one located in Churchill. Air connections do exist to most communities, but air fares are very expensive, and can be a limiting factor.

21.5.3 The complexity of Canada's legislation over Arctic waters reduces its attractiveness

The socio-political issues concerning the NWP and the desire of the Canadian government to protect its sovereignty are reflected in the cruise tourism industry. Indeed, several operators have underlined the negative effect of Canadian legislation with respect to navigation in its waters (Lasserre and Têtu 2015). Moreover, the complexity in the permitting and regulatory process represents a major barrier to cruise operators and seems to be limiting development potential and other cultural and educational benefits related to tourism in the region (Dawson et al. 2017).

In this regard, the Director of Expedition of Silversea Cruises emphasises that the Coasting Trade Act, which prohibits foreign vessels to operate from a voyage embarking in one Canadian port and ending that same voyage in Canadian waters without leaving the territory, as a major constraint to the expansion of its activities. With regards to the more sustainable development of local communities, he affirms that he 'would like to offer a series of shorter voyages, which would benefit us as a company and the local communities. Similarly, One Ocean Expedition Company

that operated the Russian icebreaker cruise ship *Akademik Ioffe* emphasized the limitations related to the Canadian Border Service Agency (CBSA) clearances and the constraining costs of inspections, which make the Canadian Arctic a costly place to operate (Dawson et al. 2017). However, while Canadian regulations may be considered severe by cruise operators, Canada is not the only market where regulations are tight, but the high volume of permits needed to sail in Canadian Arctic waters limits the freedom of navigation of cruise operators; in comparison with the permitting systems in Greenland and Svalbard which seem to be more streamlined (Ibid.).

21.6 Conclusion

The summer melting of sea ice has fuelled scenarios of an impending explosion in marine traffic in the Arctic, including cruise shipping. However, although marine traffic in the Russian or Canadian Arctic seem to be increasing, this is far from a boom. Thus it is unlikely that cruise tourism in the Canadian Arctic will experience the rapid growth predicted some years ago. For instance, most of the operators surveyed communicated their disinterest in expanding their business activities or to enter the Canadian cruise tourism market, with only three signalling their interest. In this regard, we consider that a diversification of cruise itineraries and a modest increase in cruise tourism activities in the future will likely be occurring, yet we may not witness a significant increase in cruise shipping without further development of marine infrastructure and a revision of regulation and permit processes in the Canadian Arctic.

In the frame of the Northern Marine Transportation Corridors Initiative (NMTCI), our analysis of spatial and historical trends in the Eastern Canadian Arctic helped to bridge the gap of knowledge and represents a first step towards the identification of priority conservation areas. While growth in cruise activity in the Eastern Canadian Arctic has remained stable in recent years, some shore locations appear to be more visited than others. Further research will need to address the impacts of cruise ships and passengers on the environment. Environmental degradation increases stress on populations and creates insecurity.

Monitoring the impacts of human traffic can contribute to enhanced security and sovereignty in the Arctic. A review of existing site guidelines initiatives in Svalbard (Norway), Antarctica and elsewhere would be a good starting point.

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Chapter 22 *Inuit Qaujimajatuqangit* and the Transformation of High School Education in Nunavut

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Key implications for decision makers

High school education:

- Systemic challenges of disengagement from school, low graduation levels, high levels of staff turnover, and struggles to implement bilingual education limit the ability of Inuit to participate fully in the knowledge economy and prepare for the impact of climate change.
- Through the National Strategy on Inuit Education, the Government of Nunavut and the Inuit Tapiriit Kanatami are working to provide a collaborative vision and framework for change that will foster parental engagement and build a school system rooted in *Inuit Qaujimajatuqangit* (IQ) and lead to success for high school students in Nunavut.

IQ and the transformation of high school education:

- Student engagement improves when parents, teachers, administrators, and District Educational Authority (DEA) members work together to provide personal and academic support as high school students complete their education.
- Grounding education in IQ contributes to a stronger sense of identity and confidence among youth increasing student engagement in high school.
- Strong Inuit leadership in schools and communities provides positive role models for Inuit youth and promotes pride in Inuit culture and identity encouraging students to complete a high school education.
- Including IQ-based curriculum in high schools, as well as improving overall academic standards, will contribute to raising graduation levels in Nunavut.

Abstract

“*Inuit Qaujimaqatunqangit* and the Transformation of High School Education in Nunavut,” was/is a research project that involved researchers from the University of Prince Edward Island (UPEI), Faculty of Education, and Inuit UPEI Master of Education graduates working in partnership with the Nunavut Department of Education and the Coalition of District Education Authorities of Nunavut to identify factors contributing to improved educational outcomes for Inuit students. Case studies of high schools in Pangnirtung, Clyde River, Rankin Inlet, and Kugluktuk provided data related to high school education across Nunavut by analysing interviews with youth, teachers, staff, principals, District Educational Authority (DEA) members, parents, and community members. Findings indicated that high school students want to learn about their language and culture as well as obtain an education that prepares them for post-secondary education. Support from families, including grandparents, as well as Inuit principals, teachers and staff, were named as key influences promoting academic and personal success as students complete their education to the grade 12 level. A ten-year statistical analysis of available data for the four high schools was also completed for the period from 2000 to 2010. Two documentary videos were produced: *Going Places: Preparing Inuit High School Students for a Changing, Wider World*, and *Alluriarniaq Stepping Forward: Youth Perspectives on High School Education in Nunavut*.



KERRI WHEATLEY

22.1 Introduction

The ArcticNet research project “*Inuit Qaujimagatuqangit* (IQ) and the Transformation of High School Education in Nunavut” was led by researchers at the University of Prince Edward Island (UPEI) Faculty of Education, in partnership with the Nunavut Department of Education and the Coalition of District Education Authorities of Nunavut. The goal was to begin addressing gaps in performance data related to high school education in Nunavut and to reveal practices contributing to improvements in student performance, with particular attention to IQ, Inuit ways of knowing and being, and its implementation in high schools. The project documented the leadership of Inuit principals and District Education Authority (DEA) members in two communities, Clyde River and Pangnirtung, and revealed findings primarily based on interviews with Inuit youth in four communities: Clyde River, Pangnirtung, Rankin Inlet, and Kugluktuk. These communities are situated in different regions of Nunavut. Interviews also took place with young people at Nunavut Sivuniksavut, a successful post-secondary transition program in Ottawa. The research included ten-year historical and statistical profiles of the four high schools involved in the study and considered quantitative educational indicators that begin to reveal patterns of educational outcomes in Nunavut high schools (McGregor 2014).

22.2 High schools case studies: What we have learned

The four communities chosen for the research project offer a perspective on high school education in Nunavut. Located across the territory, each community has distinct characteristics and unique historical contexts. The high schools in Pangnirtung and Clyde River were beginning the transition to grounding education in IQ principles and had strong Inuit educational leaders leading this process when the research was conducted. The high school in Rankin Inlet has benefitted from the presence of long-term, dedicated non-Inuit staff and educational leaders as well as Inuit staff and Elders who support the teaching of Inuktitut and Inuit culture. The historical and statistical profiles in these

schools focus on the ten years between 2001 and 2010 and on grades 10 to 12. The high schools involved in the study were Attagoyuk School in Pangnirtung, Quluaq School in Clyde River, Maani Ulujuk Ilinniavik School in Rankin Inlet, and Kugluktuk High School. The following discussion offers an overview of the findings and gaps that are emerging from the research.

22.2.1 Grounding Inuit high school education in IQ – why this foundation is so important

Interviews with Inuit principals, teachers, and youth clearly indicated that having IQ principles and practices as the foundation of education in high schools in Nunavut is very important (see also Chapter 9), although the implementation of IQ happens in different ways in each school and depends largely on leadership and DEA support. Strong Inuit educational leaders in the high schools in Clyde River and Pangnirtung promoted IQ; however, there are very few high schools in Nunavut where consistent, long-term Inuit leadership has been maintained. From 2007 until 2011, Jukeepa Hainnu, a graduate of the UPEI Master of Education (MEd) program, led Quluaq School in Clyde River as the principal. At Attagoyuk School in Pangnirtung, Lena Metuq, the long-term co-principal, also a UPEI MEd graduate, provided Inuit leadership for three years with Cathy Lee, a long-term non-Inuit educational leader. The approaches used by these Inuit and non-Inuit educational leaders positively impacted the students in both schools.

The implementation of IQ as a foundation for education involves daily efforts to use IQ principles as the guiding ethos of schooling, with principals, teachers, and staff consistently working to welcome students, parents, and community members. The Inuit leaders effectively implemented Inuktitut/English bilingual programs in both schools. Inuit values and practices were modelled by both Inuit and non-Inuit teachers and leaders who provided advice to support students facing challenges, and used Inuit methods of addressing conflict. Above all, supporting students through challenges emerged as a critically important element in promoting educational success. At Quluaq School, Jukeepa Hainnu fostered IQ through welcoming:

[I] want it to be welcoming for people, everyone no matter where one comes from. If people visit from outside, or especially for the Elders, I want them comfortable. Because formal schools are foreign to them. The school has to be welcoming because we are proud of Inuit and believe in them. We do not like to be recognised when we have no pride in ourselves. I do not want to see Inuit feel that way, so I want them to feel welcomed here (Hainnu 2010).

The implementation of IQ also occurred through on-the-land or camp experiences, and sewing and shop classes taught by Inuit, as well as the Inuktitut/Inuinnaqtun language teaching, and teaching provided by Elders, language specialists and Inuit teachers. For 20 years, Pangnirtung has offered a consistent annual on-the-land experience for all students, kindergarten to grade 12, through a Spring Camp program provided with support from the local DEA, Elders, and community members. According to Lena Metuq, high school students look forward to this at the beginning of the school year, and it has become an important element in the school's IQ program (McGregor 2014). As Jukeepa Hainnu indicates, programs based on IQ teach students more than they could learn inside the walls of a classroom:

[T]he hunting and sewing programs seem small but the content learning is huge. There is no prescribed curriculum for Inuit Qaujimajatuqangit. Teaching using advice is not a visible element....They are portrayed through IQ [practices], and not by writing. We try to show this in our school (Hainnu 2010).

Students and youth recognized the importance of IQ in grounding their Inuit identity and having a stronger grasp of Inuktitut is important to students' identity. Students and youth indicated that feelings about their identity are negatively affected by the loss of culture and language. Rankin Inlet youth and substitute teacher, Hilary Angidlik states,

[M]y dad is teaching me Inuktitut, so I'm learning a lot more, but they weren't that strong at all. I lost it when I was in, I guess, when I started kindergarten. But before that Inuktitut was all I spoke...I feel ashamed, like not knowing... not knowing it anymore (Angidlik 2012).

Some of the students and youth interviewed also indicated that experiences learning Inuktitut, being with Elders, going to camp, and enjoying traditional practices, such as sewing, provided them with a sense of being grounded in Inuit culture that improved their confidence and self-esteem.

It [Inuktitut] taught me in so many different ways, knowing that I can understand, my own Elders, of what they say ... and life-wise, knowing how hard it's going to be when you get older. They taught me how to live a strong life ... to never give up, no matter how hard it gets (Pameolik 2012).

22.2.2 Inuit educators as leaders and role models

This research revealed that increasing the numbers of Inuit staff in schools, as administrators, teachers, language specialists and student support assistants, has a positive impact on student morale, performance and engagement. First of all, it is important for students to see Inuit in leadership positions acting as role models, helping to instill pride in Inuit identity, and promoting bilingualism and Inuit culture in the schools. Further, Inuit administrators, teachers, and staff are more likely to stay in the school for longer periods of time, as they come from the community and are connected to the students and their families (Chapter 9). In addition, students are more comfortable with Inuit staff, teachers, and administrators, because they know the school staff outside the school, they are part of the community, and understand the culture, language, and social dynamics. One young person commented that:

[I] feel strongly that there should be more Inuktitut teachers in the school. Even ones teaching other subjects, not Inuktitut, let's say shop class, let's say sewing, let's say social studies, anything, just more Inuit teachers in the school system, to make the students feel comfortable. Not only that, but, you know, to empower Inuit, to show that we can take those jobs, that we can teach our youth, in the ways we want (Kilabuk 2012).

22.2.3 Encouragement and support for students to improve engagement, attendance, and confidence

In 2013, the Office of the Auditor General of Canada found the Nunavut Department of Education was not analyzing and using key information. The report stated, “We found that information on key elements of the [Education] Act, namely assessment and attendance, is not being used to identify the impact of the Act to date and to enhance its ongoing implementation” (p. 20). A lack of implementation often means that much-needed changes in education do not take place.

Based on Statistics Canada averaging methods and records from the Nunavut Department of Education, Nunavut-wide high school graduation rates increased from 22.8% in 2001 to 39.3% in 2009. While the increase is certainly encouraging, the National Strategy on Inuit Education 2011, when considering all four regions in Inuit Nunangat, notes that “roughly 75% of [Inuit] children are not completing high school” (p. 7). The decline in attendance at the high school level is a concern, particularly at the grade 9 and 10 levels, with an average 37% decrease in enrolment between grades 9 and 12 over the ten-year period of analysis in the ArcticNet statistical analyses (McGregor 2014). (See Chapter 9 for further details).

Given these statistics, the goal of improving student engagement and attendance remains a high priority for Nunavut high schools. In her report on Maani Ulujuk High School in Rankin Inlet, a school with relatively consistent and stable leadership, Heather McGregor writes, “Over approximately the last five years the three schools in Rankin Inlet have been working closely together to establish a community ‘school system’ whereby they integrate various programs and initiatives. For example, the three schools conduct orientation and professional development for staff together, they are using the same behavior management approach, they have pursued an in-depth school improvement process, and many other events are held with all schools together. This results in shared leadership and responsibility amongst staff” (2013, p. 18). This shared approach to leadership is

focussed on improving issues of attendance and student engagement in the entire community and reflects a collaborative way of sharing challenges. Given substantial improvements in the student population in Grades 10–12 “from 99 in 2001 to 192 students in 2011” (McGregor 2014, p. 22), as well as consistent attendance rates, there is some evidence that this approach is meeting with success.

At Kugluktuk High School (KHS) the introduction of a trades pilot program resulted in a “high grade 10 enrollment in 2005–06...and the high grade 12 graduation two years later” in 2008 (McGregor 2014, p. 19). This suggests that even in a community with attendance challenges, it is possible to foster academic success when delivering a specialized cohort model that is linked directly to employability within industries surrounding the community.

This research also indicates that programs based on IQ as well as the presence of Inuit leaders needs to be an essential component of efforts to make change. In addition, encouragement and support from parents, grandparents, teachers, administrators, and DEA members can positively influence high school students. Shawn Sivugat from Clyde River stated, “...it really does help build confidence when you have tremendous support around you when trying to finish school” (Sivugat 2010). The support and encouragement of parents and grandparents is significant when it comes to student engagement and building confidence. Grandparents can often be the strongest connection that young people have to their Inuit culture and identity. Time spent in conversation in Inuktitut or Inuinnaqtun, while hunting, or sewing, or visiting with grandparents connects youth with their traditions, values, and culture and offers important psychological support.

[M]y grandmother...taught us how to be strong, no matter how tough life gets, she taught us to keep our chin up high and to be happy and to keep going and not to give up on life. ...my childhood wasn't really all that happy, and I had a pretty tough life, but she taught me how to keep it strong, and to keep going. So I'm still here right now because of my grandmother (Misherlak 2012).

Parental support ranges from waking up children for school in the mornings to encouraging them to work hard, and reminding them of the importance of education for their future.

In Kugluktuk, Sean Sivugat, an employed graduate of the trades program at Kugluktuk High School, commented that he was, “Glad that I had pretty strong parents who supported me in what I did” (Sivugat 2010, Walton et al. 2011).

Parents also have a role to play in working together with school administrators, teachers, staff, and DEA members in supporting and encouraging students. The Inuit principals in Clyde River and Pangnirtung took an IQ approach to supporting and encouraging students. This involves taking a personal interest in students who are struggling or missing classes, addressing disruptive behaviour and conflict in a way that is direct but respectful, and working with parents to address concerns. It is important that principals, teachers, and parents work collaboratively to address problems and look for creative solutions. Jukeepa Hainnu goes on to state,

[T]hose who are the most supportive tell me or ask how well their students are doing. I reply, As long as the home, school, DEA and student work collaboratively and closely...students do not feel less of themselves. With distance [or] no collaboration students tend to struggle. When people work closely it seems they're locked in place and move onward (Hainnu 2010).

Inuit youth are highly influenced by their friends and peers, and in some cases this is a contributing factor to either engaging in school or disengaging and dropping out. Youth who have the support of family and teachers, and have a strong sense of confidence and identity, are able to encourage their friends to work hard at school and graduate. High rates of teen pregnancy are a factor influencing young Inuit teenage girls to drop out of school. Often, these young women want to return to school after their babies are born, but may find it difficult to balance the demands of family and school, or are reluctant to return to class with younger and less motivated students.

[W]e get a little shy when we get older, trying to go back to school. Maybe if they had a different class for older people that would be different and would be easier to finish...I tried going back to school again, but they are a lot younger than me, it's kind of embarrassing (Akulukjuk 2012).

22.2.4 Education standards in academic and IQ programs: preparing youth for the world

Standardization of the curriculum and improving overall academic standards, as well as the implementation of IQ, all factor into the success of high school students in Nunavut.

Academic standards are another concern in Nunavut high schools. Students and youth interviewed are finding it is a challenge to maintain motivation or access a range of academic courses required for university programs

[M]y average is about 90%, but we still can't get into nursing because we don't have chemistry, physics, biology. A lot of my friends are taking college foundations because they can't get into NTEP, Nunavut Teachers, or nursing or any of these hard, not hard but, anything we want to get into we can't get into, because we don't have the prerequisites (Kilabuk 2012).

Some of the youth interviewed in this research believe they needed more homework or structure to develop the skills to help them manage their work and time in post-secondary programs after graduating.

[S]o high school was really good. But when I went to NS [Nunavut Sivuniksavut] I felt like I was way behind in my English, and I felt like, it was like this [snapping fingers in rapid succession] with homework and our work at NS. And in high school it was kind of slow for me, even though I might not have known when I was in high school. I found out later (Ishulutak 2012).

Some youth also state that there was not enough guidance support in high school to help them decide on their future direction or options for higher education and employment to enable them to reach their goals. A lack of career or guidance counseling in some schools means that high school

students often end up lacking career or education goals to motivate them to work hard and engage in school. They are not fully aware of the possibilities available for further education or careers.

22.3 Research gaps, priorities and future action

The preceding discussion highlighted the research findings related to high school education in Nunavut. It generated knowledge to inform educational issues in the context of education at the high school level in Nunavut, addressing aspects of modernization in the new territory. It is important to identify research gaps and priorities for the future.

Longitudinal research in education at the high school level in Nunavut is immensely valuable as it tracks achievement levels and monitors progress over a period of time, but more importantly it can identify key elements that contribute to higher levels of student success. Both qualitative and quantitative research are required, with specific statistically-based measures being used consistently across the years to record data, as well as carefully analysed interviews with a range of participants and stakeholders including students, parents, school administrators, and DEA members. The opinions of Inuit are very valuable in shaping the future of education in a territory with an 85.4% majority-Inuit population (Statistics Canada 2011). The four case studies briefly described in this chapter offer both statistical as well as qualitative findings, providing data on high schools in Nunavut. Gathering and analysing longitudinal data will produce additional findings to confirm the directions suggested in this ArcticNet research. As stated in this chapter, there is a need for consistent standardized of the records of high school attendance and graduation that need to be maintained and reported by high schools and the Department of Education on an annual basis (Office of the Auditor General of Canada 2013). There is also a need for more Inuit-led and community-based research, as the issues facing Nunavut schools are best understood by those most deeply connected and affected, the Inuit majority in an Arctic environment.

There is a great deal more that needs to be studied when it comes to the implementation of IQ in Nunavut high schools. The *Education Act* from 2008 is still young, and administrators, teachers, staff, and DEA members are working out what it means to use IQ as the foundation of education in Nunavut. This requires ongoing efforts by schools and DEAs, working collaboratively with the Department of Education to clarify expectations and ways of evaluating and assessing IQ (McGregor 2014). Even with these kinds of tools, it takes ongoing effort and commitment by Inuit and Qallunaat (non-Inuit) educational leaders, to ensure that IQ becomes the foundation of education in Nunavut.

To support this process, more in-depth research is needed about knowledge transmission from Elders to youth at the high school level. High school students and youth indicate the desire to have more time with Elders to learn about Inuit culture and language. They recognize that there is a gap between Elders and youth that needs to be addressed, so that they can connect to their Inuit identity and prevent further loss of culture and language. Several young people interviewed for this research reported that they no longer understand Elders because language loss is so prevalent.

There is also a further need to study what student success means in Nunavut high schools and how it can be measured. The education system is evaluating academic success based on standards established by agencies such as the Western and Northern Canadian Protocol (WNCP), the Council of Ministers of Education, Canada (CMEC), or the Programme for International Student Assessment (PISA) and this is necessary, but it is also vital that Inuit knowledge and languages become a foundation for high school education. Nunavut high schools face great challenges in providing bilingual, bicultural programs, and managing realities that are quite different from the rest of the country. The educational system in Nunavut is engaged in a process of transition as culturally appropriate education develops while efforts are simultaneously taking place to improve academic standards in keeping with Canadian standards. This challenge is exacerbated by the



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high turnover of non-Inuit teachers and the urgent need to hire more Inuit into teaching and leadership positions.

Further research is needed to document the chosen careers or education paths of Inuit young people. Continued efforts by the Department of Education, educators, and DEAs can provide high school students with options to enable them to pursue an academic education, or to develop skills to access trades. A new multiple options program in Nunavut will address some of these needs. Creativity and collaboration are needed to provide diverse options for the young people who are pursuing high school education in Nunavut.

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Chapter 23 Postsecondary Education: Understanding Inuit Students' Experiences and their Educational and Professional Success

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Key implications for decision makers

The low progress of Nunavut Inuit at the postsecondary level over the past decades is attributed to many structural factors:

- The absence of a university in Nunavut.
- High school programs often don't prepare students adequately for postsecondary education.
- The long-term relevance of vocational programs is limited.
- Few university-designed programs for Inuit have proven to be sustainable.
- Online programs are not well adapted to Nunavut.
- The aspirations of many Nunavut students differs from that of southern students.

Support is central and takes many forms:

- Counseling and orientation are important.
- Receiving support from the school, employer or family and friends help increase success.
- The cohort approach is successful because it allows students to support each other on a personal and academic level.

Programs and courses must be relevant:

- Programs, courses and curricula should have a northern focus and integrate IQ.
- Incorporation of Inuktitut is important.
- Preference for cohort model programs.
- Courses delivered in face-to-face classes are more appreciated by Inuit students.

Need for more postsecondary education options:

- Vast majority of Inuit with postsecondary education wish to go back to school.

Studying in the North vs. studying in the South:

- North: Lack of programs, but it is easier to receive support from relatives.
- South: More options, but lack of support at school and at home (from relatives who remain behind).

The impact of the lack of housing:

- The lack of housing has a negative impact on access to postsecondary education.

The funding needs to be improved:

- Lack of funding is the second factor explaining the non-completion of a postsecondary program.
- The differing funding criteria amongst the three Nunavut regions creates an inequity in terms of funding.
- Funding should fit the needs of the students.

Inuktitut speakers are at a disadvantage:

- Students who speak Inuktitut at home are less likely to succeed at school, thus showing that the school system is not well adapted to the Inuktitut speaker.

Education is contributing to Nunavut communities:

- Inuit with postsecondary education are very likely to go back to their community.

Abstract

This report presents the data gathered during the ArcticNet project “Improving Access to University Education in the Canadian Arctic”. This identified some of the key issues that affect Inuit students’ success in post-secondary education. The team found that Inuit students pursuing post-secondary education choose to enroll in a program that fits their needs, not necessarily in a program designed specifically for them. Furthermore, support is one of the most important factors in their success and many students would like to receive more support for themselves and their families. Most of the study’s participants say they put great value in having programs with relevant content and onsite delivery, with more respondents choosing a Nunavut-based course. Funding has proven to be a constant concern among participants, especially the lack of funds they have access to, the inequity between Nunavut regions and the difficulty of applying to funding. We also found that most respondents are satisfied by their postsecondary educational experience, but more importantly, postsecondary education has greatly improved their income and job outcomes. Postsecondary education also clearly contributes to capacity building since more than half of the respondents work in their community, and a majority of the respondents who are not in their community want to work there. However, there is gender inequality in terms of job status and systemic discrimination against Inuktitut speakers in the educational system. Students also prefer a cohort approach, as it is the case in the UPEI MEd program, since it creates a community that supports and motivates each other. Finally, this research also highlights the need for an Inuit Nunangat university.

23.1 Introduction

“Improving Access to University Education in the Canadian Arctic” is an ArcticNet-funded project led by Thierry Rodon of Université Laval. It was specifically designed to provide evidence-based research on Inuit participation in University education throughout Inuit Nunangat, and promote a national discussion amongst providers of postsecondary programs, northern institutions and Inuit organizations in order to develop a more coordinated effort in program delivery and curriculum development.

Main research objectives have been to:

- 1) Prepare an inventory and evaluation of past and present university initiatives in Inuit Nunangat or for Inuit in terms of curriculum, delivery methods and success;
- 2) Evaluate the needs and experiences of Inuit with postsecondary programs or courses in order to better understand academic and professional paths and university successes from the point of view of the Inuit; and
- 3) Develop different scenarios to improve access to postsecondary education for Inuit and northerners in Inuit Nunangat.

Data has been gathered using four different methods: surveys, interviews, focus groups, and workshops. This chapter presents first the results from two surveys. One survey focused on Inuit students’ needs, and was conducted with 62 respondents (Rodon et al. 2015). The other survey focused on educational and professional success funded by the Nunavut General Monitoring Plan, and was conducted amongst 362 Inuit students from Nunavut with postsecondary experience (Rodon and Lévesque 2014a, b). The second part of this chapter presents results from the interviews, focus groups and workshops. This qualitative data complements the quantitative data of the surveys. In addition, two reports summarizing the discussions held during two workshops in Ottawa and Kuujjuaq have been published (Rodon et al. 2011, Rodon and Lévesque 2012).



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23.2 Understanding Inuit students’ experiences in postsecondary education

In the first survey, 62 Inuit students were interviewed, 79% were female and the majority (79%) were between 17 and 25 years of age when they attended their postsecondary programs. Sixty-two percent of respondents are Inuit students from Nunavut.

The majority (86%) of respondents who participated in this survey report that their experience with postsecondary education has been generally positive. However, they highlight a number of factors that contribute to preparing for postsecondary education, have impacts on their success, help increase their access to postsecondary education and increase their academic, personal and professional success. These factors (personal development, support, programs and courses, North/South, housing and funding) are discussed here.

23.2.1 Choices of personal development are important

The results from the analysis of the first survey highlight that participants mention that their main motivation to undertake postsecondary education is to achieve personal educational goals. The most common of the educational goals they identify is “complete a university program”, followed by “training toward employment”, “act as a leader or mentor for others”, and lastly “register for more university



FIGURE 1. Post-secondary Inuit student personal and educational goals.

courses.” It is noteworthy that one third of respondents pursue postsecondary courses or programs because they are made available by their employers (Figure 1).

These findings suggest that the decision to attend post-secondary institutions comes from a combination of personal motivation and support from others (family members, employers, etc.), coupled with an interest in classroom style learning. This means students prefer to enroll in programs that fit their needs, not necessarily in programs that are designed and offered specifically to them by northern and southern institutions or by those who fit the requirements of the industry (i.e., mining extraction). Nunavut students want to become role models for the younger generations and they also enjoy learning, but their main motivation is personal.

23.2.2 Support is crucial and takes many forms

Support (which could include support from families, instructors and classmates, friends and employers) is one of the most important factors in the success of postsecondary students (Chapter 9). This importance comes from the

fact that for most Nunavut students, pursuing postsecondary education is much more than just going to school: it is an all-encompassing experience that profoundly alters their way of life by forcing them to move away from home to northern regional centres (i.e., Yellowknife or Iqaluit) or cities in the South (i.e., Edmonton, Ottawa and Montreal). In doing so, they are deprived of their support network, leave relatives behind (parents, spouse, and often children), are isolated in environments they do not know well, have to manage their own budget (often for the first time), are unable to speak their mother tongue, live according to their own cultural values, or eat country food (seal, caribou, Arctic char, etc.). In this context, strong support is essential.

Participants mention that they would like to receive more counseling support, including the programs, funding occasions, housing facilities, and so on. Students feel that they do not know much about the programs they are undertaking. Their content, objectives, requirements, and the involvement needed, are all subjects they feel they could be better informed about. They say they do not know enough about the kind of support that was available to them when they started the program.

Students also mention that support from classmates, relatives and friends is extremely important. Personal support can come from being part of a learning community, by undertaking a program with a cohort of other Inuit, online with tutors, at home with relatives who encourage them to pursue their programs, and in any context that provides a range of supports. As long as students do not feel isolated, feel supported and can share their experience with other people, their chances of success are greatly increased. In fact, students are more likely to complete their programs if they study with their peers than by themselves. The most successful programs operate on the cohort model, which allows students to support one another on a personal and academic level for the duration of the program (i.e., Nunavut Sivuniksavut, UPEI Nunavut Master of Education and the Akitsiraq Law School are good examples of such programs).

Many Inuit students are parents of young children or take care of older relatives. For those who need to leave their home communities, this proves to be extremely challenging. Even students who study in their home communities say it is challenging to balance their family life with the program requirements. Parents who want to undertake postsecondary education should have access to structures and programs designed to support them as parents-students as well as their relatives that remain behind and often take care of the children. Several programs and institutions recognize this challenge: the Nunavut Arctic College offers several

housing units to families. Others, like the Nunavut Teacher Education Program or the University of Prince Edward Island (UPEI) Master of Education, are designed so that classes are given only for short periods, allowing students to go back to their home communities. This, however, lengthens the duration of programs, which in itself makes their completion more challenging.

23.2.3 Programs and courses must be relevant for Inuit

Whether they choose to pursue postsecondary education in the North, in the South or online, Inuit postsecondary students favor curricula that are relevant for them. They put great value in having ‘Inuitized’ programs that include relevant content, *Inuit Qaujimagajatuqangit* (IQ), have open schedules as well as flexible evaluations. These kind of programs like the Akitsiraq Law School, Nunavut Sivuniksavut, the Nunavut MEd or the Certificate in Nunavut Public Service Studies at Carleton University seem to have better graduation rates.

Clearly, onsite delivery is the preferred method of course delivery, with more respondents choosing a Nunavut-based course, followed by one delivered onsite in the South (Figure 2).

Interestingly enough, students prefer courses delivered onsite in the South to online courses they could take from

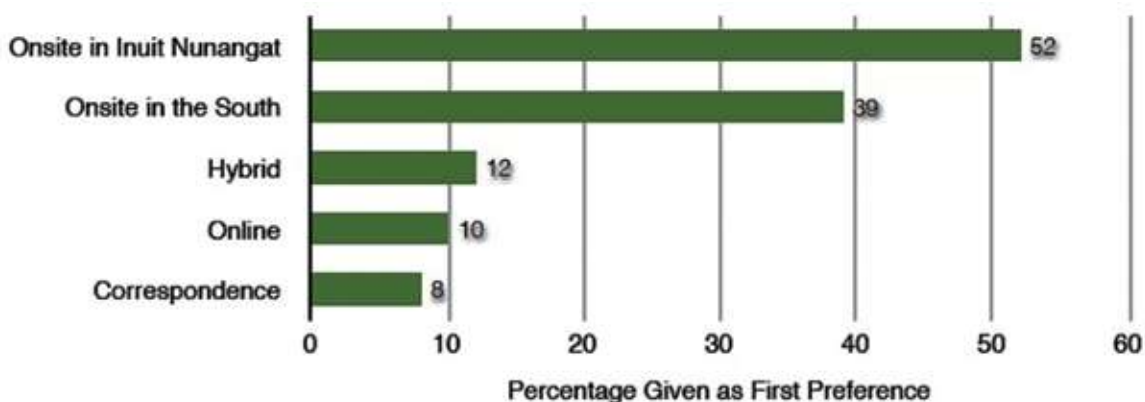


FIGURE 2. Ranking of course delivery preferences.

their home in Nunavut. This can be explained by the importance Inuit students give to relationships and academic and personal support (see above). The most successful programs are those that operate on the cohort model. Online programs do not often offer this kind of support, and the programs are seldom adapted to Inuit and northern realities. Another is that Internet connections are not as fast and reliable in northern communities – especially in smaller ones – as they are in the South.

Ninety-seven percent of participants report that the incorporation of an Inuit language is at least “somewhat important” to them. Participants also consider that being taught in Inuktitut is an important component of any program. However, the importance varies by program. While 81% of Nunavut Sivuniksavut students reported that Inuktitut is “extremely important,” students from the Nunavut Certificate program have the highest percentage of respondents who report that the use of Inuktitut in post-secondary programs is “not important”. This can be traced to the fact that Nunavut Certificate students are more fluent in Inuktitut and therefore do not need language courses.

23.2.4 Northern-and southern-based education offers different rewards and challenges, but both can be relevant

The research reveals several positive aspects of northern-based education. It allows Inuit students: to live in a familiar environment closer to relatives and friends, to have easier access to a support network, to live in a familiar cultural environment, to have access to country food, speak Inuktitut, and be in classes with fewer students.

The disadvantages of northern-based education are the limited program options, the lack of academic challenges associated with some of these programs, the lack of facilities, the difficulties of finding adequate housing, and the high cost of living (especially for students with low revenues). Finally, respondents note that if students do stay in the North, they might never leave home to live new experiences.

Southern-based education allows Inuit students to gain autonomy, to experience new things, to have access to more

amenities, activities, resources, programs, and facilities and to meet new people. Participants note that a positive aspect of southern-based education is the larger number of available programs and courses.

The disadvantages of southern-based education are being away from home, family and friends, feeling disconnected from the land and from their culture, and homesickness. Big classes, loneliness, lack of network and support, irrelevance of certain aspects of curricula, funding difficulties, and money management are also preoccupations. The lack of academic support is also identified as an issue. Nunavut Inuit students need support programs to succeed and that would include workshops, tutors, instructors with knowledge of the North, as well as support for the relatives who stayed in the North. Finally, adapting to different education standards and overcoming the latent racism of southern institutions can prove extremely challenging (Table 1).

TABLE 1. Northern and southern-based education: advantages and disadvantages.

	Northern-based education	Southern-based education
Advantages	<ul style="list-style-type: none"> • Close to home and family/friends; • Access to land and country food; • Familiar environment; • Close to community/support network; • Easier to identify with people and society. 	<ul style="list-style-type: none"> • Gaining autonomy; • Live new experience; • More amenities and activities; • More resources/better facilities; • New people and relationships.
Disadvantages	<ul style="list-style-type: none"> • Limited resources/programs/options; • Lack of facilities; • Might not leave home and live new experience; • High cost of living; • Community/family obligations and distractions. 	<ul style="list-style-type: none"> • Far from home; • Away from family and friends; • Disconnected from the land; • Disconnected from Inuit language and culture; • Homesickness.

The elements identified by respondents are mostly symmetrical since northern-based education advantages are symmetrically opposed to southern-based education disadvantages.

23.2.5 Housing

The research shows that availability of housing can be a determining factor in deciding whether or not to undertake postsecondary education.

In Nunavut, units are available for students with children but their number is limited. Parents who do not have access to them have to find other solutions, like living with relatives in often already crowded houses or to share rooms with other students.

Students who are not married and have no children fare even worse since they do not have access to priority housing. If they find a unit, it will not be subsidized so they will have to pay for its full cost, something impossible with rents that can reach well above \$2000 monthly in Iqaluit. The only way to pay for the rent is to find work, which can be detrimental for academic success. It is true that single and childless students studying in Iqaluit are offered the opportunity to stay at the Nunavut Arctic College residence, an old United-States Air Force Barracks. However, this opportunity is only available for those studying in Iqaluit.

Students who already have access to public housing in their home communities in Nunavut may also be reluctant to leave their community to undertake postsecondary education for fear of losing their house.

Inuit students pursuing postsecondary education in the South also face challenges regarding housing. They have access to a very limited number of Inuit non-profit housing. Therefore, they are either forced to stay in residences or rent an apartment or a room somewhere in town. Costs can be extremely important for students who live off funding. Furthermore, many students find it difficult to live alone, often for the first time, in an environment with which they are barely familiar.

23.2.6 Funding

Adequate funding that meets the needs of students of all parts of Nunavut is important. Students want to have enough income to pay for their rent, their food, their tuition and other living expenses. Yet, funding has proven to be a constant concern among participants, especially the limited funding they have access to, the inequity between Nunavut regions, and the difficulty of applying to funding.

Student loans are insufficient for most students and they have had problems to make ends meet. Some mention they have enough to get by but cannot go back home during the holidays to see their relatives and friends. Most feel they need to find work, which jeopardizes their academic success. Some also find it problematic that the funds are cut when they drop below 60% of the course load either because they feel they cannot succeed in a course, or because they need to work.

Respondents raise the fact that it was a problem that Financial Assistance for Nunavut Students (FANS) provides the same funding for everyone despite the fact that cost of living differs in the North and in the South. Nunavut Inuit students also say there is a regional inequity regarding funding because regional Inuit organizations (e.g., Qikiqtani Inuit Association, Kitikmeot Inuit Association) provide funding but use different criteria to determine who is eligible. And not all organizations fund students: in some regions, students can receive funding at the same time from FANS and from their regional organization, not in others. It was also mentioned that students who need more financial support (i.e., those studying in in the South or who do not have access to subsidized housing) should receive more than those who study in their home communities, have access to subsidized housing or stay with relatives.

23.3 Monitoring educational and professional success amongst Inuit of Nunavut who have registered in a postsecondary program

The results from the second survey presented in this section are based on data collected between 2012 and 2013 for the project “*Monitoring educational and professional success amongst Inuit of Nunavut who have registered in a postsecondary program*”.

This survey sought to measure:

- The graduation rate of Nunavummiut students in postsecondary programs.
- The links between graduation and employment.
- The employment rate of Nunavut Inuit who have postsecondary experience.
- Whether jobs are related to postsecondary programs taken.
- The links between academic satisfaction and job satisfaction.
- The links between gender, and educational and job success.
- The links between the language spoken at home, and educational and job success.
- The relation with home community, gender, wage and language.
- The effectiveness of financial assistance programs on postsecondary education and the differences in regional funding.

The data was collected among 362 Nunavut Inuit with postsecondary experience. Two-thirds of respondents are women, one-third men. Forty-eight percent of them were born in the Qikiqtaaluk, 39% in the Kivalliq, 9% in the Kitikmeot, and 4% are from outside of Nunavut. Forty-five percent of respondents use an Inuit language at home, 43% use English, and 12% use both. Finally, 65% of respondents live in their home community.

Here are the key findings:

- The Inuit with postsecondary education are very likely to go back to their home community, 65% of the respondents are living in their home community, showing that contrary to patterns seen with Canadian students, graduated Inuit are contributing to their communities. Amongst the one living outside their community, a vast majority (67%) wish they could work in their home community.
- Amongst students who didn’t complete their program, the main reasons are in order: 1) lack of motivation, 2) financial reasons, 3) family responsibility and 4) homesickness.
- A vast majority of the Inuit with postsecondary education are willing to go back to school if they could; therefore access to postsecondary education is a key issue. In term of programs, business and public administration was by far the favoured choice, followed by education, and social sciences.
- Respondents who speak English at home or who are fluent in English have an easier time getting a postsecondary education.

Compared to the Inuit of Nunavut, the Inuit with postsecondary education are:

- More likely to be employed and to have a better job status.
- More likely to have a higher income.
- Less likely to speak an Inuit language.

Data thus indicates that education in Nunavut, like elsewhere, improves individual outcomes. The data also show that respondents who speak English at home or who claim they are fluent in English have an easier time in getting a postsecondary education.



The research team that conducted the survey amongst Inuit of Nunavut with a postsecondary experience. From left to right: Francis Lévesque, Mataali Okalik, Thierry Rodon, Pamela Gross and Blair Stevenson.

Finally, the statistical analysis allowed us to uncover the following statistically significant relations:

- There is a strong correlation between academic satisfaction and job satisfaction. Respondents who are satisfied academically are also satisfied by their jobs.
- Women are more likely to be successful at the academic level, are more likely to want to further their education and are more likely to be full-time employed, however men tend to have a better job (position and income).
- Family matters: Inuit students are more likely to attain a higher level of education if their parents have a higher level of education; they are more likely to attain a higher level of education if their brother/sister have a higher level of education and they are more likely to have an higher income if their parents have a higher education.
- Respondents who speak Inuktitut at home are more likely to have lower academic achievement, to feel not qualified for their job, and to be unemployed. However, looking closely at the data indicates that a minority of Inuktitut speakers are very successful.
- Most respondents consider that funding is not adequate, but the data indicates also strong regional disparities. People in Kivalliq are more likely to receive funding

from their Inuit organization and less likely from FANS. The relation is reversed in Kitikmeot where you are more likely to receive funds from FANS and less from Inuit organisations. Respondents studying outside Nunavut have very low access to FANS.

This survey has thus clearly shown the individual and collective value of postsecondary education for Nunavut. Most respondents are satisfied by their postsecondary educational experience, but more importantly, postsecondary education has greatly improved their income and job outcomes. Finally, postsecondary education clearly contributes to capacity building since half of the respondents work in their community, and a majority of the respondents who are not in their community want to work here. There is therefore a strong link between postsecondary education and community building.

However, some issues need to be addressed by policy-makers: the most notable being the gender inequality in term of job status, the fact that Inuktitut speakers are less likely to succeed at the postsecondary level and the need to provide more access to postsecondary education, since a vast majority of respondents wish to go back to school. Funding should also be looked at, since it is the second factor explaining the non-completion of a postsecondary program. The differing funding criteria amongst regions also create an inequity in terms of funding.

23.4 Inuit students postsecondary experience and needs: graduate experience

In the ArcticNet-funded project “Improving access to university education in the Canadian Arctic”, researchers and educators at UPEI have worked closely with Inuit UPEI Master of Education (MEd) students and graduates to learn about their experiences and needs in accessing graduate-level education. The results from interviews and focus group discussions with MEd students and graduates reveal some of the following issues and concerns regarding their experience in accessing graduate education in Nunavut:

- Inuit students and graduates are motivated by a desire to learn and improve their skills, along with a desire to be strong role models and to contribute to their communities.

[G]iving back to my community and learning from other educators. Meaning I took the program...not to be top of everybody, but being part of my community...(Uluadluak, 2010).

- Some Inuit educators pursue graduate studies as a personal challenge, but also to show that Inuit can achieve the highest academic goals and become strong educational leaders in their communities.

[W]e're just as capable...I would benefit from going back to school. And...also to show other Inuit that, why not? Don't stop where you are right now, challenge yourself...I want my children to finish school, to go as high as they can, or as high as they want, and not having to rely on anybody else but themselves (Pitsiulak-Stephens 2012).

- When more Inuit achieve academic success in graduate studies, role models are present in Inuit communities as younger Inuit find their own academic and career direction, demonstrating that youth have options and can be proud of their Inuit identity.
- The UPEI MEd is a hybrid program, combining on-site courses in Nunavut and at UPEI, along with distance education through an online support tool, Knowledge Forum. This model allows MEd students to pursue graduate level education, while remaining in their communities with their families, and continuing with their careers. Students appreciate the flexibility of this model, however, it does require significant determination and support for distance education to work. Students tend to prefer on-site classes, which allows the cohort to work together and provides more access to their instructors. Students find that they may not have the space to do their work at home, and alternative spaces might not be easily accessible.

[D]istance courses work, but it takes determination and commitment to fulfill your dreams. It works when you have supports in place (Flaherty 2011).

- The UPEI MEd model involves a cohort approach, with students working together as a community of Inuit scholars, sharing their experiences and offering each other support. Students and graduates indicate that the cohort

is very important to motivate them when they are struggling on their own with their work.

[I] know the loneliness of the university setting, to be the only Inuk in the classes. The cohort approach, I love it because we can do it together and have a sense of belonging (Kauki 2012).

Issues that emerge as challenges for MEd graduates and students include:

- Balance of home life, careers, and academic work.
- Need for financial and resource support for themselves and their families during their studies.
- Distance learning challenges.
- Bilingual language skills challenges.
- Desire for a wider range of programs, accessible from the community level.
- Provide critical and professional skills, at the same time as incorporating Inuit culture, values, and epistemologies.

MEd students and graduates are hopeful that university access is improving for themselves and the next generations. Partnerships between southern universities and the Nunavut Department of Education, Nunavut Arctic College, and the Nunavut Research Institute are strengthening, but the real goal would eventually see a university in Nunavut reflecting Inuit culture, offering bilingual programs at undergraduate and graduate levels, and providing a diverse range of programs and courses, as well as research opportunities for qualified Inuit professors and researchers. This is a goal that the UPEI MEd students and graduates hope they can work toward.

23.5 Research gaps, priorities and future action

This project based on extensive surveys, interviews, and focus groups was able to identify some of the key issues that affect Inuit students success in post-secondary education: Most students pursuing post-secondary education choose to enroll in a program that fits their needs, not necessarily



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in a program designed specifically for them. Furthermore, many students would like to receive more support for themselves and their families. Most students say they prefer having programs with relevant content and onsite delivery, with a preference for Nunavut-based course.

Funding has proven to be a constant concern among participants, especially the lack of funds they have access to, the inequity between Nunavut regions and the difficulty of applying to funding. We also found that most respondents are satisfied by their postsecondary educational experience, but more importantly, postsecondary education has greatly improved their income and job outcomes. Postsecondary education also clearly contributes to capacity building since more than half of the respondents work in their community, and a majority of the respondents who are not in their community want to work there. However, there is gender inequality in terms of job status and systemic discrimination against Inuktitut speakers in the educational system. More details are provided in Rodon and Lévesque (2014b). Students also prefer a cohort approach, as it is the case in the UPEI Med program and the Akitisiraq Law program, since it creates a learning community that supports and motivates each other.

Finally, this research also highlights the need for an Inuit Nunangat university, while some discussions to that effect have started, they remain in their early stages but it is important to keep this discussion alive (Government of Nunavut 2011, Rodon and Lévesque 2012, Rodon et al. 2014a,b, Kennedy Dalseg and Black 2015).

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