



FROM SCIENCE TO POLICY IN THE WESTERN AND CENTRAL CANADIAN ARCTIC

AN INTEGRATED REGIONAL IMPACT STUDY (IRIS)
OF CLIMATE CHANGE AND MODERNIZATION

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Canada 



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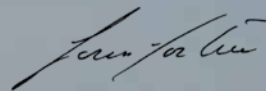
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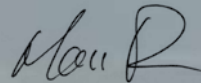
Foreword

Our climate is changing rapidly and nowhere else on Earth is this change as intense as in the cold expanses of the Arctic. Rapid sea-ice decline transforms the ecosystems of Arctic seas, opening new sea-lanes to navigation and access to untapped oil reserves and mineral resources. Thawing permafrost destabilizes roads, airstrips, houses and the ecosystems of the tundra. Access to traditional fishing and hunting grounds and to safe drinking water is increasingly difficult for Northerners who are ever more dependent on southern goods, including tobacco, sugar, and industrial food that bring increasing health issues. This disruption of traditional ways of life and accelerated change are also impacting the mental health and social wellbeing of Inuit. Industrialization and modernization of the North provide obvious economic opportunities, but also pressure the environment, the health system, the education system and the culture of northern societies. These multiple environmental, socio-economic and geopolitical perturbations are interacting to bring about a major transformation of the North. ArcticNet is a Canadian Network of Centres of Excellence jointly funded by the Natural Sciences and Engineering Research Council of Canada, the Social Sciences and Humanities Research Council of Canada, the Canadian Institutes of Health Research and Industry Canada to help the country prepare for the impacts of this transformation. The central objective of ArcticNet is to generate the knowledge and assessments needed to formulate adaptation strategies and policies that

will help northern societies and industries to prepare for the full impacts of environmental, economic and societal changes in the Canadian Arctic and Subarctic regions. Our vision is to build a future in which, thanks to two-way knowledge exchange, scientists and Northerners jointly monitor, model and build capacity to attenuate the negative impacts and maximize the positive outcomes of these changes. The ArcticNet IRIS (Integrated Regional Impact Study) structure provides an exciting opportunity to further develop linkages between natural science specialists, networks of expertise in northern health, and specialists in societal issues such as cultural change, adaptation and the recognition and respect of Inuit perspectives. We thank all of our network investigators, students, other researchers, colleagues and partners for helping ArcticNet achieve such success, and the Western and Central Arctic IRIS steering committee and editorial team for bringing this important document through to completion.



*Prof. Louis Fortier,
Scientific Director of ArcticNet*



*Dr. Martin Fortier,
Executive Director of ArcticNet*



Preface

ArcticNet is a Network of Centres of Excellence of Canada that brings together scientists and managers 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 in the coastal Canadian Arctic. ArcticNet adopted an Integrated Regional Impact Study (IRIS) framework to make current knowledge of climate change and other stressors comprehensible and accessible for everyone, particularly for resource managers and decision-makers at all political levels.

The four designated ArcticNet IRISes are 1) the western and central Arctic (encompassing the Inuvialuit Settlement Region (ISR), including the North Slope of Yukon and Herschel Island, and the Kitikmeot region of Nunavut); 2) the Eastern Arctic; 3) Hudson Bay; and 4) the Eastern subarctic (see figure right). The intention of the IRIS framework is to develop a volume of Regional Impact Assessments (RIAs) which include western science and traditional knowledge generated by ArcticNet and other organizations. The RIAs are designed to assist policy and decision-makers in formulating strategies to cope, adapt, and even benefit from the impacts of climate change.

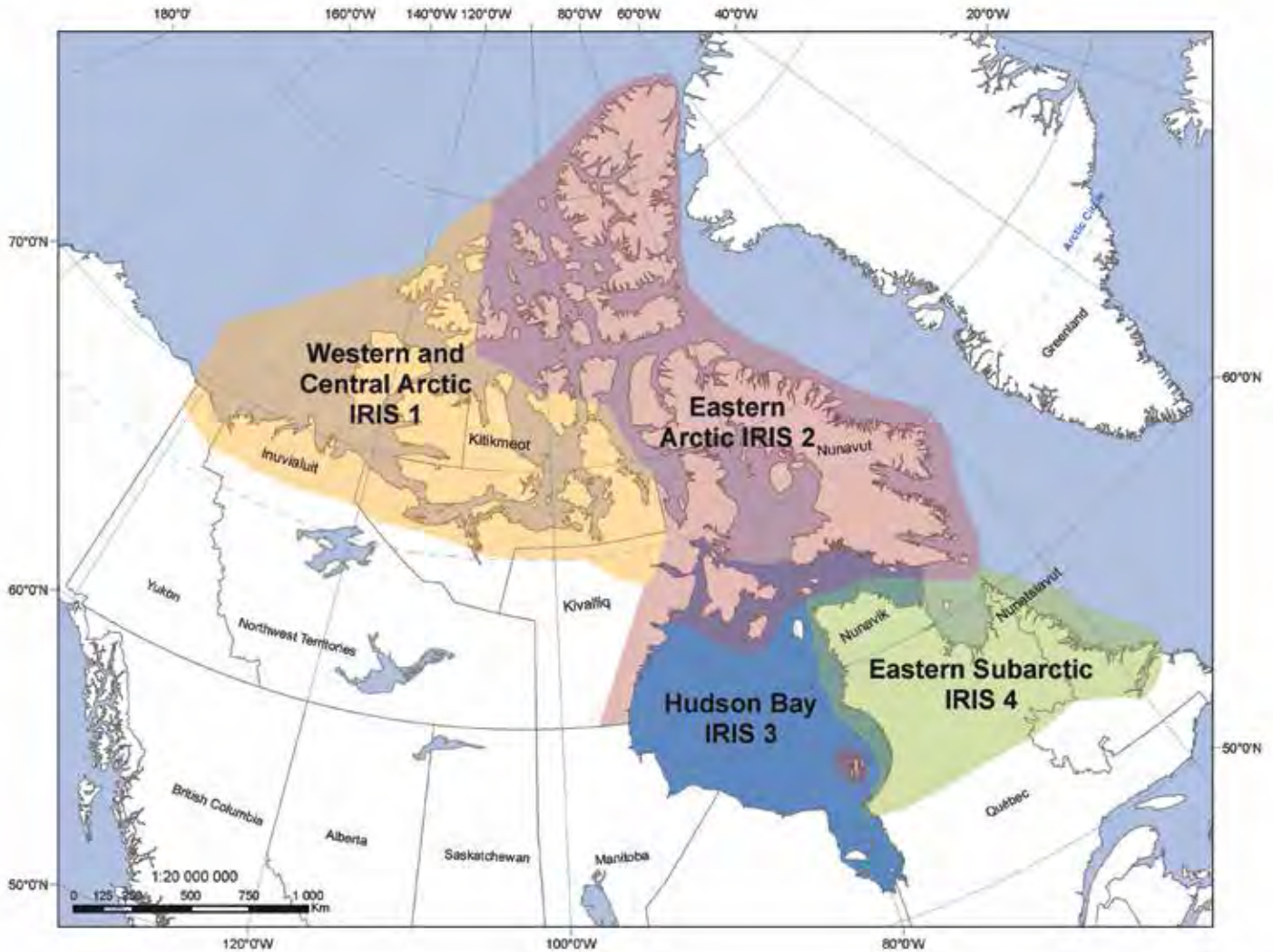
The procedure for developing the western and central Canadian Arctic IRIS (“IRIS 1”) regional impact assessment, lead by editors Gary Stern (IRIS 1 leader) and Ashley Gaden (IRIS 1 coordinator) at the University of Manitoba, was a collaborative process. Meetings and workshops with stakeholders identified environmental, health and societal vulnerabilities and climate change adaptation priorities. Meetings and workshops included:

- Kitikmeot regional consultations, Cambridge Bay (September 19-20, 2012);
- International Polar Year 2012 Conference, Montreal (April 22-27, 2012);



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- Meeting at NTI headquarters, Iqaluit (March 29, 2012);
- Meeting with Department of Fisheries and Oceans Canada, Winnipeg (February 20, 2012);
- Inuvialuit Game Council meetings, Whitehorse (September 11, 2010 and September 19, 2011);
- IRIS regional workshop, Inuvik (April 12-15, 2011);
- Fisheries Joint Management Committee meeting, Winnipeg (January 18, 2011);
- Regional Research Working Group meeting, Inuvik (February 5, 2010);
- IRIS 1 workshop, ArcticNet Annual Scientific Meeting, Victoria (December 11, 2009);
- ArcticNet Annual Scientific Meetings (2010-2014); and
- IRIS Steering Committee and Kitikmeot Sub-committee meetings on an as-needed basis (2011-2014)



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

Consultation with the IRIS 1 Steering Committee, composed of representatives from the ISR, Nunavut, ITK and ICC, and the IRIS 1 Kitikmeot sub-committee continued to guide the development of the RIA to ensure its information and recommendations were relevant to decision makers and stakeholders within the ISR and the Kitikmeot region.

Thank you to all past and present IRIS 1 steering committee and Kitikmeot sub-committee members, supporters and observers, as well as network investigators, students,

researchers, and partners for contributing to this document which will serve as a beacon of knowledge of climate change and modernization in the western and central Canadian Arctic.

Introduction

For generations Inuit have successfully lived on the land and adapted to change as necessary to uphold their way of life and well-being. However, over the last several decades the acceleration and complexity of change imposed by climate and modernization (e.g. negotiation of self-governance, increased mobility and connections to the South, more wage-based employment, transition from country foods to store-bought foods, increased pressure to exploit northern resources such as oil, gas and minerals) in the North have deterred abilities to cope or adapt to new environmental, socio-economic and health conditions.

Much research and knowledge has been gathered about changing conditions in the Arctic, but sometimes such sources of information are irrelevant (e.g. too large of scale), inaccessible (e.g. written for scientists) or simply just unavailable (e.g. journal subscriptions needed for online articles). The ArcticNet Regional Impact Assessment (RIA) for the western and central Canadian Arctic is a compilation of all available knowledge (e.g. scientific/traditional, studies within/outside of ArcticNet) for the Inuvialuit

Settlement Region (ISR) and the Kitikmeot region of Nunavut and addresses regional interests and needs. The aim of the RIA is to facilitate better accessibility of knowledge and to provide relevant, practical and comprehensible information for sound decision-making at a regional scale.

Inside this document

The Regional Impact Assessment (RIA) consists of two parts: the larger volume of text is a knowledge report divided into ten topic-defined chapters: (1) overview of the western and central Canadian Arctic; (2) climate variability and projections; (3) terrestrial and freshwater systems; (4) marine ecosystems and contaminants; (5) human health; (6) travel and navigation; (7) infrastructure; (8) food and cultural security; (9) resource development; and (10) climate change policy responses for Canada's Inuit population. Within most of these chapters scientists and other experts have made linkages between environmental change and regional priorities. Furthermore, downscaled climate projections from the Canadian Global Climate Model using the Canadian Regional Climate Model have provided insight into future environmental conditions for the 2050 horizon (see Chapter 2), from which estimations of associated impacts and benefits have been made with respect to regional vulnerabilities and priorities.

The other part of the RIA, presented first, is the *Synthesis and Recommendations* article which summarizes the information provided in the larger knowledge report into key findings and associated recommendations. This part of the RIA is provided as a reference guide to help managers, policy-makers and other decision-makers develop adaptation plans, strategies, policies and programs for sustainable, safe and healthy communities.



CRAIG EMMERTON/ARCTICNET



Synthesis and Recommendations

The Western and Central Canadian Arctic IRIS Steering Committee, formed of representatives from the ISR, Nunavut and other Inuit organizations, and the Kitikmeot Sub-committee were involved in the writing of the *Synthesis and Recommendations* to ensure that the recommendations put forth were culturally and politically appropriate and would serve to improve quality of life, protect the environment, facilitate sustainable development, and address knowledge gaps in the western and central Canadian Arctic.

This article is divided into seven themes which cut across many of the larger knowledge chapters of the western and

central Canadian Arctic IRIS Regional Impact Assessment and speak to the interests and priorities of the ISR and the Kitikmeot region of Nunavut: (1) human health, (2) food security, (3) human safety, (4) preservation of culture, (5) resource exploitation and socio-economic development, (6) infrastructure, and (7) wildlife and environment.

Human Health

Key Findings

The Inuit Health Survey (IHS) reported that 70% of adults in the ISR and the Kitikmeot region smoke, and that second-hand smoke is prevalent in 85% of homes. Cigarette smoke is a risk factor for lung cancer, chronic respiratory disease, heart disease and stroke, and is a source of cadmium.

Further findings from the IHS indicated that 30% of adults in the ISR and the Kitikmeot region are deficient in Vitamin D and that iron deficiency is also a concern, especially in women (29% of female IHS participants were deficient).

With summer temperatures expected to increase in the region, the risk of dehydration, sunburn/sun stroke and insect bites to people on the land will also likely increase.

Recommendations

Promote the consumption of traditional foods which boosts vitamin D and iron levels, as well as improves food security.

Promote community-based counselling services and online resources to quit smoking.

Subsidize healthy store foods by transferring offset costs to cigarettes, encouraging healthy eating and discouraging the purchase of cigarettes and other nicotine-containing substances.

Increase access to health care (e.g. establish more clinics in remote communities).

Educate and promote hydration and the use of sunscreen and insect repellent.

Incorporate TK/IQ into policies, programs and services addressing health needs and goals.

ASHLEY GADEN





STANLEY YEE

Food Security

Key Findings

Nearly 70% of households in the ISR and the Kitikmeot region have an active hunter – this is very positive with respect to improving food security in the region. Community freezers are an important tool for food sharing and also help to improve food insecurity. Land mammals (e.g. caribou) and fish are the most popular sources of traditional foods in the region, and traditional food consumption is higher among older (>40 yrs) adults than younger adults.

Nevertheless, 60% of Inuit Health Survey participants in the ISR and the Kitikmeot region have expressed experiencing food insecurity. Underlying factors influencing food insecurity are unemployment, poverty, low education, high costs of food, household crowding, households needing major repairs, not having a snow machine or boat, and high costs of supplies and gas to go hunting or fishing.

Recommendations

Strengthen food sharing networks within communities (e.g. food storage and distribution systems). Associated plans, strategies and policies to restore food security need to be directed by Inuit and should also be evaluated in light of climate change.

Increase access to harvester-support programs, especially for more isolated communities.

Increase outreach and education of healthy traditional foods, how to prepare them and means of accessing them (e.g. explain and promote harvester-support programs).

Promote research on (1) the relationship between housing, food security and climate change and (2) the effects of climate change on water quality, particularly sources which are accessed on the land for drinking water.



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Human Safety

Key Findings

The thickness of marine ice has been decreasing over time in the western and central Canadian Arctic, making travel on the sea dangerous during the ice-covered period. Furthermore, the largest decreases in concentration of sea ice have been observed between 2001-2010, particularly during September, for the Western Parry Channel (53%), M'Clintock Channel (50%), Eastern High Arctic and Eastern Parry Channel (38%), Beaufort Sea (26%) and Franklin Strait region (27%).

More extreme, frequent or sudden thunderstorms have compromised the safety of travellers on land and sea (as well as coastal infrastructure and wildlife habitat).

Variable, unpredictable weather and ice conditions have meant Inuit are less able to correctly forecast weather conditions – a necessity for a safe hunt. Safety supplies and other necessities are needed to go out on the land (e.g. extra fuel, GPS, satellite phone), but not all hunters have means of accessing these.

Recommendations

Increase survey coverage (e.g. bathymetric mapping) of ice-free waters to support safe marine passage, strengthen search and rescue capabilities, reduce accidents at sea and prevent unnecessary disruption to marine animals.

Develop regulatory measures to prohibit vessels from navigating unsurveyed waters.

Improve weather forecasting and associated communications within communities. Find ways of making forecasts more relevant to northern communities (e.g. report relevant parameters, use local terminology).

Provide/increase accessibility of safety equipment to harvesters and provide them with associated hands-on training through harvester-support programs.

Incorporate awareness of climate change impacts in search and rescue training, as well as to harvesters (e.g. through harvester-support programs); update search and rescue procedures in light of current and future landscape/climate change.

Preservation of Culture

Key Findings

One in four households in the ISR and the Kitikmeot region use an Inuit language.

Most adults (60%) do not complete secondary school. A lack of education has been associated with health problems, unemployment and food insecurity.

Inuit have experienced limited opportunities to pass on traditional knowledge and land-based skills to youth in light of the pace of changing (and sometimes dangerous) land and weather conditions, as well as changes to the abundance, distribution and health of harvestable species.

Recommendations

Integrate traditional knowledge, land skills and Inuit languages in school curriculums and on-the-land programs (including camps) throughout the whole year (e.g. multiple trips out on the land to experience the harvest of seasonal wildlife migrations, changes in weather, etc). Furthermore, emphasizing skills development will help Inuit be better prepared to adapt to changing conditions.

Thoroughly investigate the relationships between education in northern communities with other socio-economic factors (e.g. health, employment). Promote education as preparation towards the workforce with respect to similar schedules and acquired skills and knowledge.



Resource Exploitation and Socio-economic Development

Key Findings

Despite a number of environmental hazards associated with oil and gas and mineral exploration (e.g. hazardous multi-year sea-ice conditions, geohazards, thawing permafrost), such resource development, which is driven more by global demand and energy, and associated activities (e.g. shipping and transportation) are likely to continue into the future in the western and central Canadian Arctic. Research programs are in place to mitigate uncertainty with respect to hazards, and federal agencies require environmental protection measures in place for energy developments. These measures will help to protect renewable resources and the traditional Inuit way of life.

A lack of education and skills limit Northerners' participation in wage-paying jobs offered by resource industries.

Tourism is growing in the region but is limited to available services and facilities within the communities.

Recommendations

Inuit must be participants in the decision-making process with respect to resource development projects and conducts of tourism. Companies should clarify all stages of a project life cycle that Inuit can provide input.

Organize and promote training programs needed to fill the skills gap and enable increased Inuit participation in the industrial economic sector.

Form partnerships between communities and the cruise tourism industry to collaborate on codes of conduct, accommodations and other services for tourists, and find ways to minimize risks and maximize benefits to the communities.



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Promote research to examine the impacts of resource development, shipping and tourism as sources of vulnerability on northern communities.

Infrastructure

Key Findings

Permafrost soil temperatures in the western Arctic have increased about 2°C since the 1970s. Projected climate conditions are likely to increase permafrost thaw, particularly in the southern margins of the region, which can compromise terrain stability and thus the integrity of infrastructure, including drainage structures such as culverts and bridges.

Coastal erosion rates throughout the Beaufort Sea seem to have remained relatively stable from 1972-2000. However, there has been significantly high shoreline retreat at the Coppermine Delta at Kugluktuk, NU from 1950-2008.

According to a report by the Geological Survey of Canada (James et al. 2014), sea level could rise by up to an additional 0.4 m at Tuktoyaktuk, NT, by 2060, and 0.9 m by 2100. However, sea levels at Kugluktuk, NU, may fall until 2050, when levels could rise greater than 0.3 m by 2100. Accounting for ice loss from the West Antarctic Ice Sheet by 2100, sea levels are expected to increase by 1.4 m at Tuktoyaktuk and 0.7 m at Kugluktuk.

Recommendations

Account for the impacts of climate change in community planning – don't let past conditions guide decisions. Consult related publications by the Canadian Standards Association, the Transportation Association of Canada, and territorial governments that raise awareness about best practices for developing infrastructure on permafrost.

Large scale systematic mapping of both surface landforms/sediments and subsurface features (with combined drilling and ground penetrating radar) can determine areas susceptible to permafrost disturbance and thus support sustainable community planning and transportation networks.

Establish proactive measures: make regular inspections and maintenance of community infrastructure to minimize risks and repair costs of otherwise reactive approaches.

Develop or re-address region-wide and community adaptation action plans to adhere to local and regional needs.



TOWN OF INUVIK



Wildlife and Environment

Key Findings

Habitats upon which all types of animals depend are changing.

- Permafrost thaw and lake expansion are expected to continue as temperatures in the Arctic increase. Lake growth has the potential to transport large sediment loads to freshwater and coastal habitats, degrading quality of habitat (e.g. lower oxygen levels in fall and winter resulting from increased organic matter decomposition) which is particularly problematic for Dolly Varden. On the other hand, the draining or evaporation of some tundra ponds will remove habitat for waterfowl and shorebirds.
- Warmer waters may reduce the temperature barrier for the range expansion of some non-native fish species such as Pacific salmon, sand lance and capelin, which may outcompete Arctic specialists like Arctic cod, a key prey item for beluga, ringed seals and seabirds.
- Alder, willow and birch shrubs are increasing in numbers, coverage and height. This trend is expected to continue over the next 50 years in the region. These changes have attracted more shrub-nesting birds and moose but may potentially displace upland tundra bird species.
- Coastal erosion/storm surges are wiping out coastal vegetation and shorebird habitat.

- Additional winter thaw events will impact herbivores (e.g. caribou, lemmings) by limiting winter foraging opportunities, particularly the Peary caribou herd which has already suffered population declines due to winter starvation.
- Increasing sea surface temperatures, a reduction in sea-ice concentrations and increased vertical mixing (which delivers nutrients from the seafloor to the water column) will stimulate primary productivity in the Beaufort Sea and will attract fish, marine mammals and seabirds. Decreased benthic productivity could negatively impact bottom-dwelling fish and their predators (e.g. bearded seals).
- Polar bears are following their prey (ringed seals) further out on multiyear ice. Weaker ice and a reduction of multiyear ice will likely increase the risk of caribou, such as from Dolphin and Union herd, drowning as they cross frozen channels.

Infrastructure, such as roads, and human activities (e.g. shipping) have the potential to impact the abundance, survival and health of wildlife, particularly birds and marine mammals (e.g. whales, polar bears).

Despite international agreements to reduce pollutant emissions, mercury concentrations are increasing in lake sediments and some freshwater biota, and concentrations are unusually high in Beaufort Sea polar bears. Climate-driven



processes such as changing sea-ice dynamics, thawing permafrost and increasing productivity are being studied with respect to influencing the exposure and uptake of mercury and persistent organic pollutants to wildlife species.

Recommendations

Promote community-based monitoring projects, especially in partnership with all involved stakeholders. Such projects need coordinated spatial and temporal patterns, updates and reviews on a regular basis, and changes to reflect current conditions and interests.

Engage all stakeholders, including Inuit, in decision-making related to conservation efforts to promote more sustainable approaches of resource stewardship. Traditional knowledge is an important source of long-term knowledge and should be used alongside western science in which to base decisions.

Set aside marine harvesting grounds which are off-limits to commercial shipping.

Support studies and monitoring projects to establish baseline data for gaps such as

- Disease and parasites in fish, birds and mammals

- Impacts of thawing permafrost on birds' nesting success
- The role of snow in forming habitat (e.g. lemmings)
- Growth and survival of caribou calves in association with migration, time of birth, and the quantity and quality of food
- The range expansion of boreal herbivores (e.g. snowshoe hare, beaver) and carnivores (e.g. grizzly bears, wolves)
- The distribution and abundance of insects, zooplankton, fish, birds and marine mammals
- Contaminant concentrations in air, soils/sediment, water, ice, snow and animals of freshwater and marine environments, especially for lower trophic levels (e.g. phytoplankton, zooplankton), fish, birds and marine mammals, particularly in light of increased resource development in the region
- Impacts on the Husky Lakes ecosystem in light of its proximity to infrastructure and human activities, as well as other lakes upon which northern communities depend
- The general cyclic dynamics of many animal populations (e.g. caribou, lemmings)



Chapter 1. Navigating the North: A Snapshot of the Western and Central Canadian Arctic

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ABSTRACT

The Inuvialuit Settlement Region of the Northwest Territories and the Kitikmeot region of Nunavut are home to nearly thirteen thousand people in eleven communities, plus two seasonally populated communities, in the beautiful western and central Canadian Arctic. Inuvialuit and Nunavummiut uphold traditional land activities, culture, and environmental protection. However, both the Inuvialuit Settlement Region and the Kitikmeot region also face challenges with respect to Inuit language retention, housing (e.g. repairs, crowding), education, and non-renewable resource exploration pressures. Add to this the overarching complex climate change impacts affecting virtually all facets of life. Based on Inuit observations across the western and central Canadian Arctic, the most common climate change phenomena are unpredictable/variable weather and longer ice-free seasons, both of which have serious implications for the safety, security and well-being of Inuit and Arctic wildlife. The Inuvialuit Settlement Region and Nunavut/Kitikmeot managerial organizations are responsible for protecting Inuit livelihoods, ecosystems, and land through the implementation of the Inuvialuit Final Agreement and the Nunavut Land Claim Agreement, respectively. Many of these organizations aspire to understand how climate change will continue to impact livelihoods and resources. Past and present assessments and studies throughout the Inuvialuit Settlement Region and the Kitikmeot region continue to accumulate knowledge for the purposes of assisting northern communities, the public and private sectors, and other stakeholders prepare for and adapt to climate change.

1.1 Societies, cultures and economies

1.1.1 Inuvialuit Settlement Region

The Inuvialuit Settlement Region (ISR) of the Northwest Territories was constitutionally recognized with the signing of the Inuvialuit Final Agreement in 1984. The ISR boundaries include the Yukon North Slope, the Mackenzie River Delta, the Beaufort Sea and six communities in the Northwest Territories including Aklavik, Inuvik, Tuktoyaktuk and Paulatuk on the mainland, Sachs Harbour (Ikaahuk) on Banks Island, and Ulukhaktok (formerly Holman) on Victoria Island (Figure 1).

Inuvialuit Final Agreement

Approved by the Parliament of Canada in 1984 as the *Western Arctic Claims Settlement Act*, the Inuvialuit Final Agreement (IFA) bound the Inuvialuit and Government of Canada – together with the governments of the Yukon and Northwest Territories – to protect the land and preserve the Inuvialuit cultural identity and values in a formal land claim agreement. The Inuit of the ISR, or Inuvialuit, were given legal ownership of 91,000 km² of land including 13,000 km² with subsurface rights to oil, gas and minerals. The agreement serves the broad purposes of providing means for the Inuvialuit to participate fully in the northern and national economy and society, and protecting and preserving the Arctic wildlife, environment, and biological productivity.

The basic goals of the Inuvialuit Final Agreement (IFA) as expressed by the Inuvialuit and recognized by Canada are (1) to preserve Inuvialuit cultural identity and values within a changing northern society, (2) to enable Inuvialuit to be equal and meaningful participants in the northern and national economy and society, and (3) to protect and preserve the Arctic wildlife, environment and biological productivity.

The Inuvialuit, under the direction of the Inuvialuit Regional Corporation (IRC), are negotiating self-government with the federal and territorial governments. These Inuvialuit self-government negotiations began in April 2006. All three



PEGGY JAY

Traditional dress contest at the Northern Games in 2000.

parties signed a Process and Schedule Agreement, which outlines the negotiators' workplan and timeline, in May 2007. This is the first step in a journey to concluding a Self-Government Agreement for the Inuvialuit.

Demographics and language

As of 2011 the total population of the Inuvialuit Settlement Region is 6,230 (Statistics Canada). The largest community is Inuvik, NT (3,403 individuals), and is the government, business and transportation centre in the ISR. The remaining communities of the ISR have fewer than one thousand residents each. Between 2006 and 2011 the population of each community changed by less than 10% (Figure 2).

Figure 3 illustrates the number of individuals by age groups in the ISR. The proportion of individuals under the age of fifteen years (21%) corresponds well to the proportion in the Northwest Territories (22%) and to the rest of Canada (17%) (Statistics Canada). Adolescents and young adults (ages 15-34) comprise 40% of the ISR population, which is similar territorially (46%) and nationally (42%).

English is spoken throughout the ISR. The prevalent Inuit language is Inuvialuktun which consists of dialects Ummarmiut (native to Aklavik and Inuvik) and Siglitun

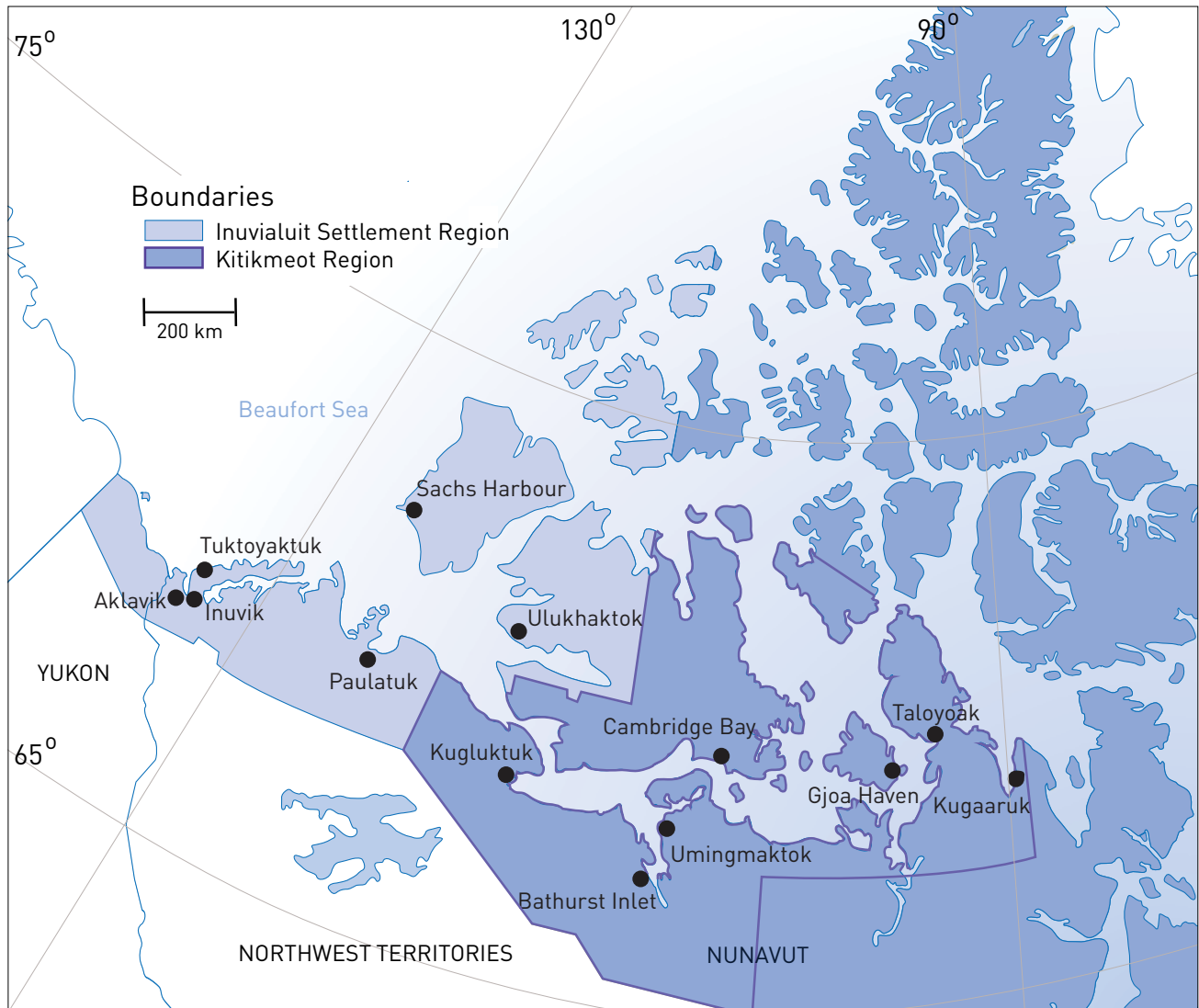


FIGURE 1. Map of communities in the Inuvialuit Settlement Region and the Kitikmeot region of Nunavut.

(native to Tuktoyaktuk, Paulatuk and Sachs Harbour). Inuinnaqtun is spoken in Ulukhaktok while Gwich'in is also spoken in Aklavik and Inuvik (Figure 4).

Economic sectors and employment

Oil and gas exploration provided vast employment and business opportunities in the Beaufort Sea and Mackenzie Valley during the 1970s and 1980s. After a moratorium on a Mackenzie Valley pipeline to settle land claims and

establish wildlife conservation areas, as recommended by the Mackenzie Valley Pipeline Inquiry (1974-1977), petroleum exploration once again gained momentum in the region by the mid-2000s (see Chapter 9).

With respect to the wage economy, most residents in the ISR, particularly in Inuvik, work in government offices or in trades companies (e.g. tourism, construction, transportation). Inuvialuit beneficiaries also receive distribution payments made possible through the Inuvialuit Regional

Corporation’s subsidiary corporations (see section 1.3.1). While fishing, hunting, gathering (summer) and trapping (winter) continue to be important subsistence, cultural, and recreational activities, Inuvialuit have exemplified

economic diversification of such activities to include the harvesting and sales of Mackenzie Delta reindeer meat (Chapter 8, Box 1), small-scale Arctic char fisheries, and a growing arts and crafts industry (e.g. printmaking and muskox hair (qiviut) spinning in Ulukhaktok). As of 2006 the employment and unemployment rates in the ISR were 60% and 16%, respectively, and were fairly similar to the Northwest Territories’ rates (68% and 10%, respectively) and the national rates (62% and 6%, respectively) (IRC 2013).

1.1.2 Kitikmeot region of Nunavut

The Kitikmeot region is the westernmost region of Nunavut, lying within the central Canadian Arctic. In comparison to the other two regions of Nunavut, the Kivalliq (formerly Keewatin) and Qikiqtaaluk (formerly Baffin) regions, the Kitikmeot region is the least populated and the second largest in size covering nearly 447,000 km². Communities in the Kitikmeot region include Kugluktuk (formerly Coppermine), Cambridge Bay on Victoria Island, Gjoa Haven on King William Island, Taloyoak (formerly Spence Bay) on Boothia Peninsula, and Kugaaruk (formerly Pelly Bay) (Figure 1). Bathurst Inlet and Umingmaktok (formerly Bay Chimo) located in Bathurst Inlet are mainly seasonal communities. Until 1999, when Nunavut became an official territory, the Kitikmeot region extended further west to include Holman (now Ulukhaktok) which is now part of the Northwest Territories.

Nunavut Land Claim Agreement

When the Nunavut Land Claim Agreement (NLCA) was signed by the Prime Minister of Canada on May 25, 1993, Nunavut became the largest Aboriginal land claim settlement in Canadian history (350,000 km²) and was officially made a territory in 1999. The objectives 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,

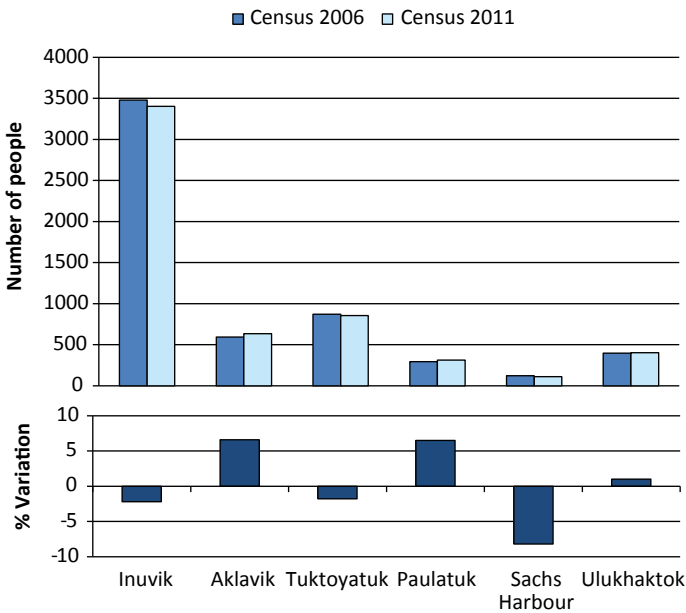


FIGURE 2. Number of people in each of the communities in the Inuvialuit Settlement Region in 2006 and 2011, followed by the variation between 2006 and 2011 censuses. Data from Statistics Canada.

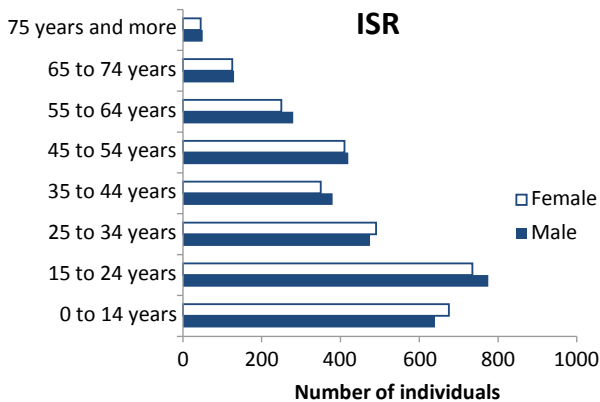


FIGURE 3. Demographic context classified by age group in the Inuvialuit Settlement Region. Data from Statistics Canada.

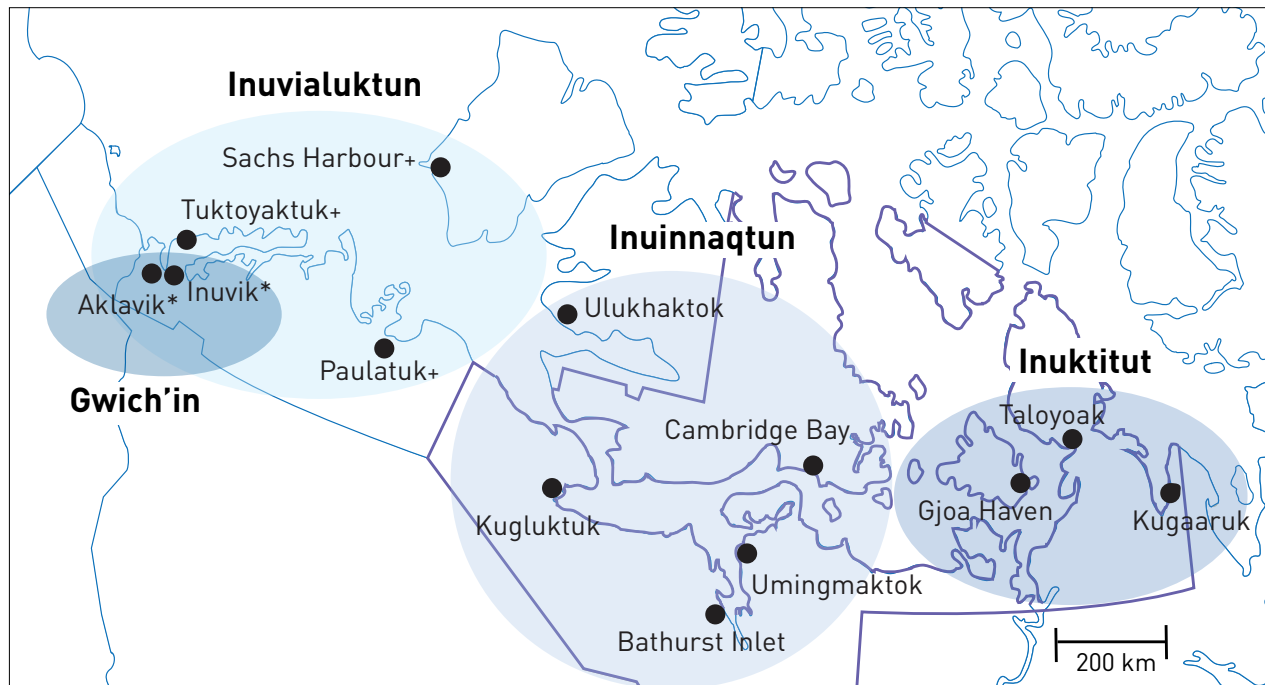


FIGURE 4. Official Inuit languages of the Inuvialuit Settlement Region and the Kitikmeot region of Nunavut. This map was created from information compiled from the IRC language webpage (<http://www.irc.inuvialuit.com/culture/language.html>), the Prince of Wales Northern Heritage Centre website (http://www.pwnhc.ca/exhibits/aboriginal_languages.asp), and Nunavut's Official Languages website and resources therein (<http://langcom.nu.ca/nunavuts-official-languages>), all accessed June 16, 2014. Note: *Inuvialuktun dialect used is Uummarmiutun; +Inuvialuktun dialect used is Siglitun

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.

Demographics and language

The 2011 Census indicated 6,620 people are living in the Kitikmeot region (Statistics Canada). Cambridge Bay, the regional health, transportation, and administration centre, and Kugluktuk hold the largest populations with 1,608 and 1,450 individuals, respectively. Communities in the eastern Kitikmeot contain between 700 and 1300 residents each. The population of all Kitikmeot communities experienced positive growth between 2006 and 2011 (Figure 5).

Figure 6 illustrates the number of individuals by age groups in the Kitikmeot region. With respect to individuals under the age of fifteen years, the proportion in the Kitikmeot region (31%) is on par with the rest of Nunavut (33%) but higher compared to the rest of Canada (17%). Adolescents and young adults (ages 15-34) comprise 40% of the Kitikmeot population; this proportion is in line with values for Nunavut and Canada (37% and 42%, respectively).

Aside from English, which is common throughout the Kitikmeot region, Inuinnaqtun is spoken in Cambridge Bay, Kugluktuk, Bathurst Inlet and Umingmaktok, while Inuktitut (written in syllabics) is spoken by the remainder of the Kitikmeot communities (Gjoa Haven, Taloyoak, Kugaaruk) (Figure 4). Natsilingmiutut, a dialect of Inuvialuktun, is also spoken by the Netsilik Inuit in the eastern Kitikmeot communities (Dorais 2010).

Economic sectors and employment

A mixed economy consisting of a wage economy, government transfer payments, and subsistence harvesting exists in the Kitikmeot region. Government and private sector jobs

(e.g. tourism, mineral exploration) comprise the wage economy. As of 2006 the employment and unemployment rates in the Kitikmeot region were 50% and 20%, respectively, and were fairly similar to Nunavut’s rates (55% and 15%, respectively) but were a bit skewed compared to the national rates (62% and 6%, respectively) (Statistics Canada). Traditional activities such as hunting, trapping, fishing and gathering as well as arts and crafts are important for providing households food, income (e.g. outfitting, sales), and a sense of living harmoniously with the environment (NTI 2001). Additionally, some businesses have diversified their services, such as Kitikmeot Foods Ltd. in Cambridge Bay which hires harvesters and processors of Arctic char and muskox for distribution to southern Canada, and Taluq Designs in Taloyoak which specializes in wool textiles and collectables (e.g. packing dolls).

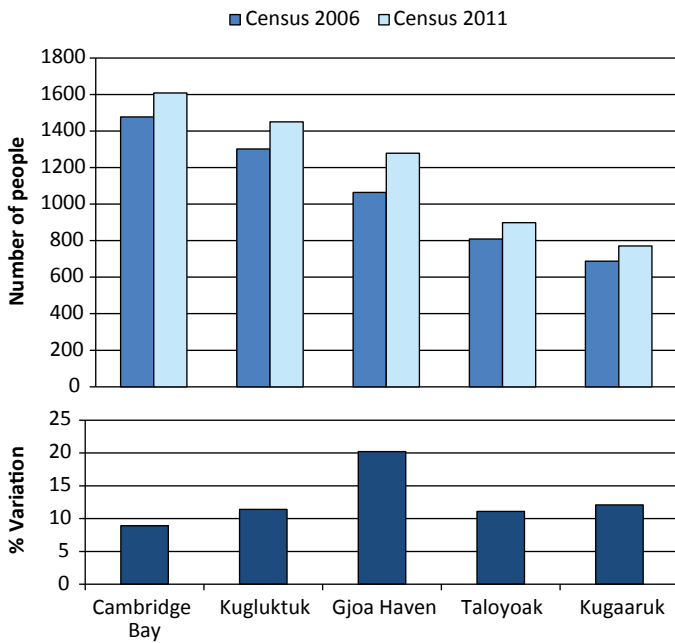


FIGURE 5. Number of people in each of the communities in Kitikmeot region in 2006 and 2011, followed by the variation between 2006 and 2011 censuses. Data from Statistics Canada.

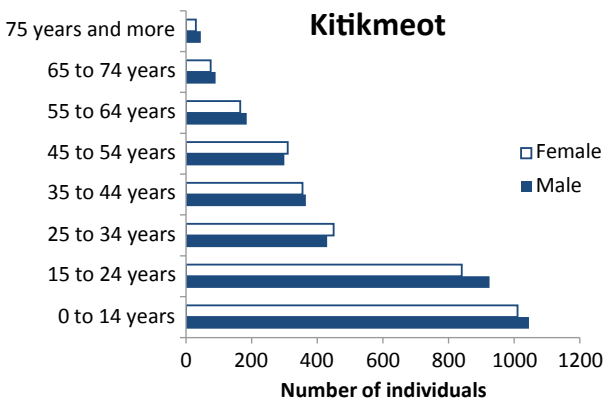


FIGURE 6. Demographic context classified by age group in the Kitikmeot region. Data from Statistics Canada.

1.2 A portrait of climate change

Inuit from all communities in the western and central Canadian Arctic have observed environmental changes. A summary of some of the documented observations made by Inuit in the ISR and the Kitikmeot region of Nunavut is provided in Table 1 but is by no means a full account of all the communities’ experiences with recent changes. Some of the changes are observed by most communities (e.g. longer ice-free season) but most observed changes (at least those referenced in the literature) are clearly local in nature and not consistent across the region. The observations presented in Table 1 illustrate, to some extent, the grand variability of climate change.

1.2.1 Observations of climate change

Most communities across the western and central Canadian Arctic have experienced variable climate changes including warmer temperatures in recent decades. Intense summer heat is a factor for ablation of summer sea and land fast ice, with a myriad of impacts on human and wildlife communities. Specific issues related to human health include

sunburns, heat stroke, and dehydration. For wildlife and the natural environment the warmer climate increases the frequency of forest fires and permafrost thawing, resulting in landscape slumping and shoreline erosion. Thawing permafrost has also impacted permafrost freezers and meat spoilage. While out on the land, hotter temperatures not only can make travelling, hunting and camping difficult for people, but they also can make travel and foraging difficult for caribou and other wildlife. Community members of Cambridge Bay are concerned that warmer temperatures may lead to bacterial growth in Water Lake, their main water source (Calihoo and Romaine 2010).

With respect to precipitation, communities have tended to observe a decrease in snowfall or later snowfall, impacting snowmobile travel and the habitat of ringed seals and polar bears. Less rainfall (Inuvik) impacts vegetation growth and berry production; more rainfall or more forceful rain replenishes freshwater sources but also contributes to increased erosion. Residents from Paulatuk, Tuktoyaktuk, Inuvik, Kugluktuk and Kugaaruk have witnessed more freezing rain. This phenomenon covers ground vegetation in an ice layer, making forage impenetrable for caribou and can result in their starvation and death (NTI 2001; Thorpe et al. 2001).

One of the most profound experiences expressed by representatives from all of the communities in the ISR and the Kitikmeot region is an inability to predict weather. For Inuit across the North, forecasting skills are critical for determining safe conditions for successful subsistence activities. Many Inuit have also experienced changes in the strength and direction of winds and frequency and intensity of storms. Impacts of stronger winds include more dust in the air and associated respiratory illnesses, reduced drinking water quality on the land, hazards in communities (e.g. downed power lines), erosion, damaged infrastructure, and fewer opportunities for travelling on the land. Changing wind directions render snowdrifts as unreliable navigational markers on the land and can also create hazards when they develop across airstrips or other main travel routes. With respect to thunderstorms, most communities

have experienced more extreme and/or frequent storms. Not only do such conditions deter travel and participation in subsistence activities on the land, but they also contribute to erosion and can damage infrastructure.

All communities have observed longer ice-free seasons, and all Kitikmeot communities have noted a shorter duration of freshwater ice and snow. These changes have serious safety implications for travel both for people and caribou. Longer periods of open water can also lead to more coastal erosion, and shorter ice-covered seasons can negatively impact marine mammal habitat.

The most commonly observed changes to the landscape in the western and central Canadian Arctic include more erosion, less permafrost, lower freshwater levels, and lower sea level. These changes can negatively impact fish habitat and migration, the foundation or integrity of infrastructure, the quality and quantity of drinking water on the land, and boating and navigation activities. Along with hazy skies, communities in the Kitikmeot region have observed shifts in the positions of the sun, moon and/or stars. Forest fires just south of the Kitikmeot region are likely responsible for the quality of the air further north. These hazy (and unpleasantly odorous) conditions have presented concerns both for human/animal health and for travel and subsistence activities (Thorpe et al. 2001). The shifts in the sun, moon and/or stars can also affect travellers with respect to their orientation on the land.

The presence, abundance, condition and distribution of numerous wildlife species have changed. Mosquitoes have appeared more numerous and persisted longer seasonally, increasing harassment to caribou. Hunters in the western Kitikmeot region have noticed that caribou sometimes spend more time escaping insects than foraging, leading to weight loss and deteriorated body condition by fall (Thorpe et al. 2001). However, the increased forage and shade as a result of faster growing vegetation is also attracting caribou (Thorpe et al. 2001). There have been numerous sightings of new or more abundant species in the western and central Canadian Arctic. For example, pelicans, sea lions,

TABLE 1. Documented observations made by Inuit in the western and central Canadian Arctic.

OBSERVATIONS	INUVALUIT SETTLEMENT REGION						KITIKMEOT REGION						REFERENCES
	Aklavik	Inuvik	Tuktoyaktuk	Paulatuk	Sachs Harbour	Ulukhaktok	Kugluktuk	Cambridge Bay	Bathurst Inlet & Umingmaktok	Gjoa Haven	Taloyoak	Kugaaruk	
Temperature													
Warmer summers or more extreme warm temperatures in summer	X	X	X		X	X	X	X	X	X			1-5, 7, 8, 14-17
More intense heat from the sun	X	X	X		X	X	X	X				X	
Cooler summers				X		X							
Longer summers, shorter winters	X	X	X		X			X		X	X		
Fewer winter extreme cold temperatures and/or generally milder winters	X	X	X	X	X	X						X	
Increase in temperature fluctuations					X	X						X	
Precipitation													
More rainfall			X	X	X	X							1, 2, 4, 6, 15-17
More forceful rain	X				X	X							
More freezing rain		X	X	X			X					X	
Less snowfall or later snowfall	X	X	X	X		X	X	X		X	X		
Weather, wind & storms													
Variable and unpredictable weather	X	X	X	X	X	X	X	X	X	X	X	X	1-8, 10-13, 15-17
Stronger winds	S		S	X	X	X							
Weaker winds	W	X	W										
Winds blow in different directions	X			X	X	X	X			X	X	X	
More extreme, frequent or sudden thunderstorms	X	X	X		X	X		X		X	X	X	
Snow and ice													
Thinner ice or less multi-year ice and ice-bergs	X	X	X	X	X	X	X	X	X	X	X	X	1-8, 13, 15-17
Longer ice-free season (earlier sea-ice break-up and later freeze-up)	X	X	X	X	X	X	X	X	X	X	X	X	
Shorter duration of freshwater ice (ice melts earlier and forms later)	X						X	X	X	X	X	X	
Snow melts earlier or quicker; permanent snow packs or icepacks are melting		X		X	X	X	X	X	X	X	X	X	
Snow melts to create an ice layer over vegetation				X			X	X	X				
Differing characteristics of snow		X		X	X			X		X	X	X	

TABLE 1. (continued)

OBSERVATIONS	INUVIALUIT SETTLEMENT REGION						KITIKMEOT REGION						REFERENCES
	Aklavik	Inuvik	Tuktoyaktuk	Paulatuk	Sachs Harbour	Ulukhaktok	Kugluktuk	Cambridge Bay	Bathurst Inlet & Umingmaktok	Gjoa Haven	Taloyoak	Kugaaruk	
Landscape													
More erosion along riverbanks	X	X	X	X	X	X	X					X	1-10, 13, 15-17
Melting permafrost	X	X	X		X	X	X					X	
Lower freshwater levels		X	X		X	X	X	X	X	X	X	X	
Higher sea level				X	X	X							
Lower sea level	X						X	X	X	X		X	
New or bigger islands or sandbars	X	X					X						
Less clear or more hazy skies					X		X	X	X	X	X	X	
Shift in sun, moon and/or stars' positions						X		X			X	X	
Wildlife													
New wildlife of mammals, fish, birds, plants & insects and increased insect abundance/duration/distribution	X	X	X	X	X	X	X	X	X	X		X	1-10, 12, 13, 15-17
Disappearance of some species and habitats, altered migration routes or distributions					X	X	X	X	X	X	X	X	
Degrading health among wildlife	X	X	X	X	X	X				X	X	X	
Vegetation is growing faster and is more lush					X		X	X	X			X	

X = observation; S = summer observation; W = winter observation

References: (1) Nickels et al. 2005; (2) NTI 2001; (3) GeoNorth Ltd. 2000; (4) Keith 2005; (5) Thorpe et al. 2001; (6) Prno et al. 2011; (7) Friendship et al. 2011; (8) Pearce et al. 2010a; (9) Pearce et al. 2010b; (10) Dumond 2007; (11) Jolly et al. 2002; (12) Calihoo and Romaine 2010; (13) Keith and Arqviq 2006; (14) Nickels et al. 2002; (15) Knopp et al. 2011; (16) Knopp et al. 2012; (17) Ashford and Castleden 2001



capelin, moose, red fox and pike (Kugluktuk), sparrows, robins, osprey, moose, grizzly bears and more snow geese (Cambridge Bay), increased muskox (Ulukhaktok), coho salmon, robins and warblers (Sachs Harbour), grizzly bears (Kitikmeot region) and new types of lichens and flowering plants on Victoria Island have all recently become part of the biodiversity of the region (GeoNorth Ltd. 2000; NTI 2001; Thorpe et al. 2001; Calihoo and Romaine 2010; Prno et al. 2011). However, the presence of lapland longspurs, snow bunting and red phalarope have diminished around Kugaaruk and Kugluktuk (NTI 2001), there are fewer small birds, lemmings, foxes, owls, caribou and polar bear observed around Ulukhaktok (GeoNorth Ltd. 2000), and there have also been fewer observations of polar bears and polar bear habitat around Kugluktuk (Keith 2005).

1.2.2 Summary of implications

As a result of climate change, northern traditional ways of life are changing quickly in the western and central Canadian Arctic. Possibly the most significant climate change impacts to the Inuit way of life are the limitations experienced towards subsistence activities and associated indirect impacts. When unpredictable and/or hazardous conditions arise, hunters must adapt and either learn new safety and navigational skills for successful hunting or forfeit such trips; both outcomes present a hardship. Oftentimes the pace of change is too fast for a single generation to adapt to new conditions. When hunters are able to travel on the land, the extra fuel and supplies purchased for safety measures is costly. When conditions or resources are limited for travel, people are deterred from participating in subsistence hunts, negatively affecting their emotional and physical health (Nickels et al. 2005; Pearce et al. 2010b). More people also resort to store-bought foods which are not only expensive but also less nutritious (Pearce et al. 2010a; Friendship et al. 2011) and contribute to the nutrition transition underway with serious health impacts on communities (Council of Canadian Academies 2014). Additionally, when youth are unable to participate in cancelled hunting and fishing trips, they lose valuable opportunities to gain

survival skills and traditional knowledge (NTI 2001, 2005). This outcome leads not only to increased safety risks for new hunters, but also a loss of traditional knowledge to future generations.

1.3 Management regimes in the ISR and the Kitikmeot region

This section provides an overview of some of the key governing organizations and agencies in the Inuvialuit Settlement Region and the Kitikmeot region with respect to Inuit rights and well-being, environmental stewardship, economic interests, resource development, research, and climate change programming. Furthermore, the research priorities of some of these parties are presented to convey a sense of what they consider to be important information needed for their operations.

1.3.1 Inuvialuit Settlement Region and the Northwest Territories

Inuvialuit Corporate Group

The origin of the Inuvialuit Corporate Group, composed of the Inuvialuit Regional Corporation (IRC) and its subsidiary corporations including the Inuvialuit Land Corporation, Inuvialuit Investment Corporation, Inuvialuit Petroleum Corporation and Inuvialuit Development Corporation (Figure 7), began with the signing of the Inuvialuit Final Agreement on June 5, 1984, between the Government of Canada and the Inuvialuit. The purpose of the Inuvialuit Corporations is to receive and manage IFA benefits, and, in the case of the Inuvialuit Land Administration, manage Inuvialuit lands.

Inuvialuit Regional Corporation

IRC was established with the overall responsibility of managing the affairs of the Inuvialuit Settlement Region as outlined in the IFA. Its mandate is to continually improve the

economic, social and cultural well-being of the Inuvialuit through implementation of the IFA and by all other available means.

Through a democratic process, Inuvialuit beneficiaries directly control IRC and its subsidiaries. The Chairs of each Community Corporation (Figure 7), together with the Chair of IRC, form the IRC Board of Directors.

IRC Research Policy and Agenda

In part to improve the conditions of ISR beneficiaries, IRC developed a research policy and agenda. The IRC Research Policy highlights its leadership role in encouraging responsible and ethical research that includes Inuvialuit and their lands. The policy provides specific guidelines and processes for Inuvialuit organizations and for researchers interested in working in the ISR, and for how Inuvialuit can partner productively and respectfully on research projects.

The research priorities contained in IRC's Research Agenda include the following themes: (1) social, cultural and economic baseline data; (2) sustainable community-based economies; (3) impacts of government policies on sustainable development and culture; (4) specific health determinates to achieve sustainable communities; (5) the development of Inuvialuit Institutions as governing and economic entities; (6) the influence of policy and directives of the Governments of Canada and Northwest Territories; and (7) meaningful participation in regulatory agencies, industry and other stakeholder processes.

Inuvialuit Game Council and co-management bodies

Inuvialuit Game Council

The Inuvialuit Game Council (IGC) was incorporated as a Society under the NWT Societies Ordinance on April 20, 1983. Under the IFA, the IGC represents the collective Inuvialuit interest in all matters pertaining to the management of wildlife and wildlife habitat in the ISR. This

responsibility gives the IGC authority for matters related to harvesting rights, renewable resource management, and conservation.

The duties of the IGC include appointing Inuvialuit members for all Inuvialuit co-management bodies under the IFA (Figure 8) and assisting these bodies whenever requested, advising government agencies, through the co-management bodies or otherwise, on renewable resource policy, legislation, regulation, and on any proposed Canadian position for international purposes that affects wildlife in the ISR. The IGC also allocates Inuvialuit quotas among the six ISR communities and appoints members for any co-management body dealing with Inuvialuit fish and wildlife harvesting and the environment.

Wildlife Management Advisory Council (NWT)

The Council focuses on the conservation of terrestrial wildlife species (which includes polar bears) and birds. Its geographic area of jurisdiction is that part of the ISR within the Northwest Territories. The Council's mandate is to advise appropriate ministers on all matters relating to wildlife policy, and the management, regulation, research, enforcement and administration of wildlife, habitat and harvesting for the western Arctic Region, within the NWT. It is also the responsibility of the Council to determine and recommend harvestable quotas. Working in partnership with Hunters and Trappers Committees, Community Corporations and Elders Committees, the Wildlife Management Advisory Council (NWT) drafts Community Conservation Plans to identify key renewable resource areas and describe management and conservation measures for such (SCE WG 2008). Figure 9 illustrates the various management designations of the Community Conservation Plans in the ISR.

The Council also reviews and advises the appropriate governments on existing or proposed wildlife legislation and any proposed Canadian position for international purposes that affect wildlife in the Western Arctic Region. Research within the ISR by governments is reviewed by the Council annually.

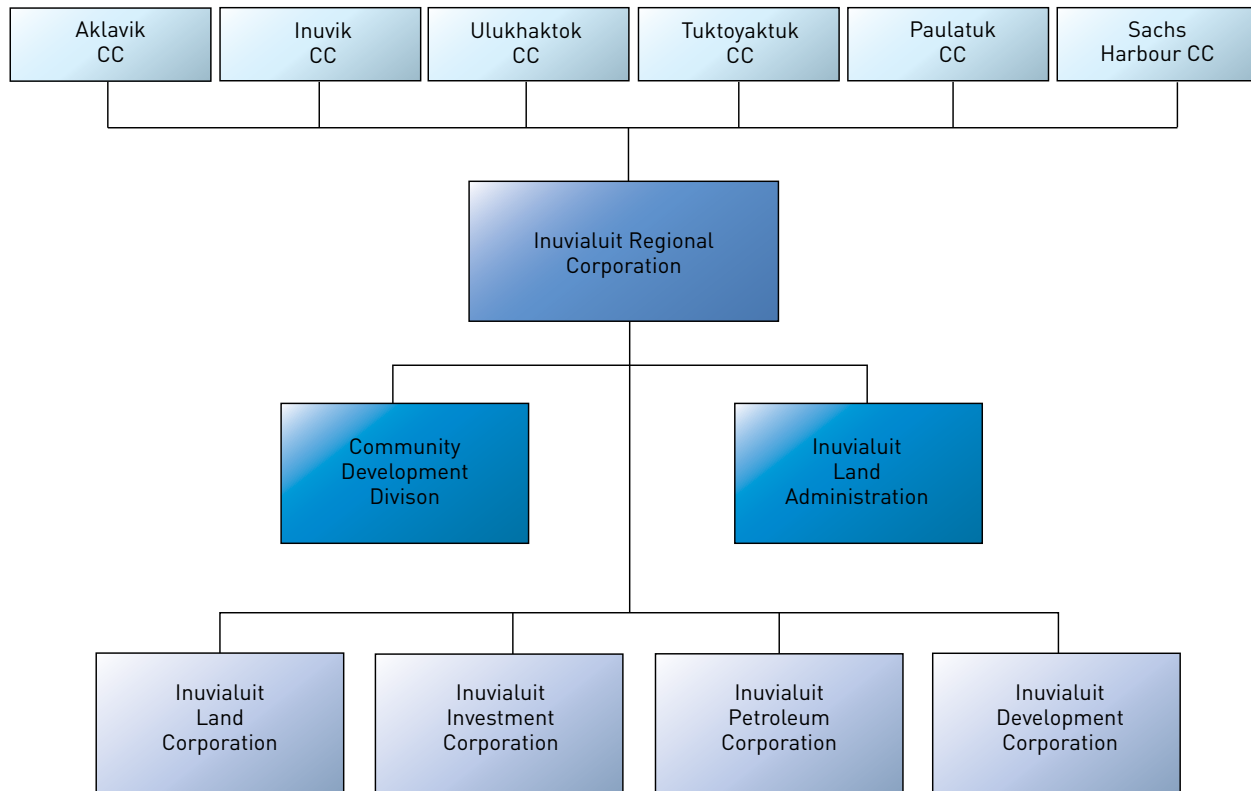


FIGURE 7. The corporate structure of the Inuvialuit Corporate Group. Each Inuvialuit community has a Community Corporation (CC) with elected directors. The directors of the six Community Corporations elect the Chair/Chief Executive Officer of IRC. Adapted from the Inuvialuit Regional Corporation’s website (www.irc.inuvialuit.com), accessed June 5, 2013.

Fisheries Joint Management Committee

Canada’s Minister of the Department of Fisheries and Oceans (DFO) established the Fisheries Joint Management Committee (FJMC) in 1986, as required by the IFA. FJMC’s mission is to ensure that the renewable marine, anadromous and freshwater resources of the ISR are managed and conserved for the wise use and benefit of present and future generations. FJMC has the following responsibilities: (1) to assist Canada and the Inuvialuit in administering the rights and obligations related to fisheries under the IFA; (2) to assist the Minister in carrying out his/her responsibilities for the management of fisheries and marine mammals in the ISR; and (3) to advise the Minister on all matters relating to Inuvialuit and ISR fisheries.

Environmental Impact Review Board

The Board carries out detailed environmental impact assessments and public reviews of development projects. The Environmental Impact Review Board (EIRB) decides whether a project should proceed and, if so, under what specific terms and conditions. In making its decision, the EIRB considers the need for wildlife compensation, mitigation, and remedial measures. The EIRB has developed Operating Procedures to provide guidance to developers, regulatory authorities and the public, regarding the rules of procedure which the Board will follow when a development proposal is referred to it for public review.

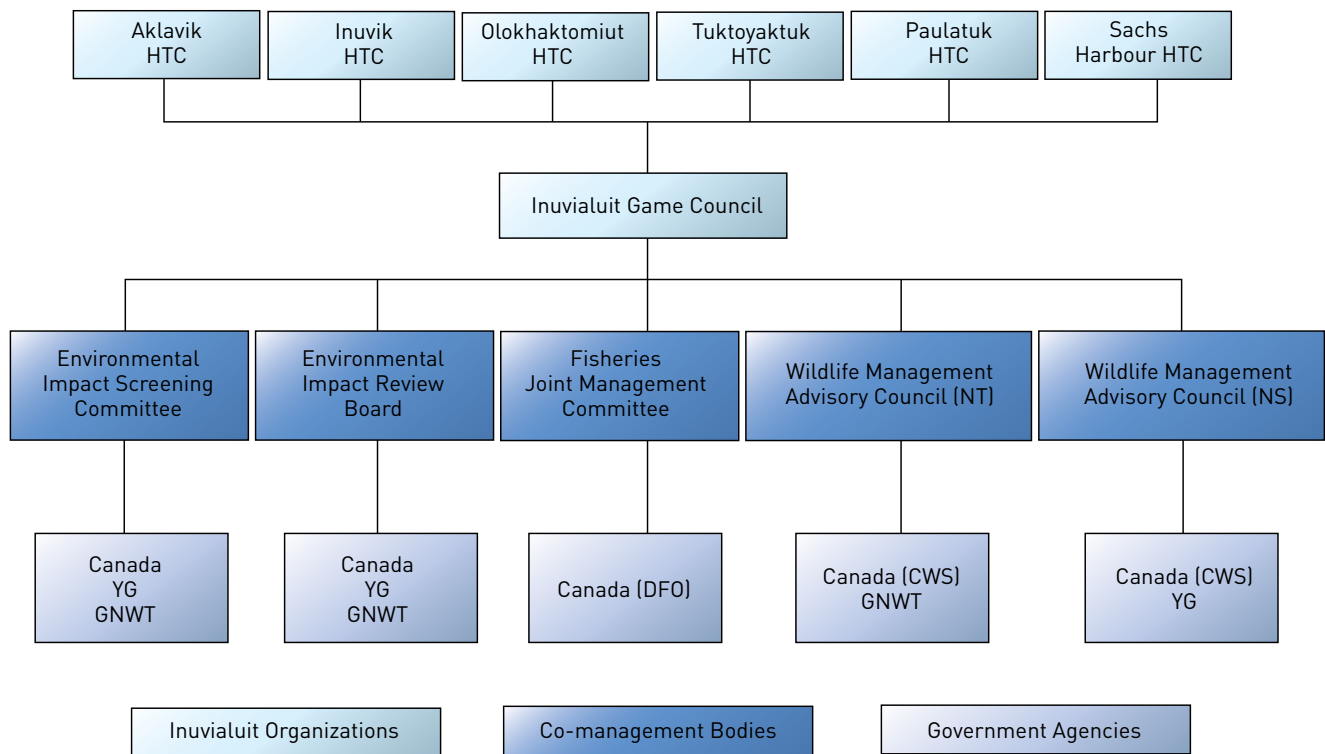


FIGURE 8. Flowchart illustrating the co-management agreement between the Inuvialuit Game Council (IGC) and government agencies. Hunters and Trappers Organizations (HTOs) appoint members to form the IGC. The IGC and government agencies appoint or designate representatives to the five co-management bodies. Adapted from the Joint Secretariat website (www.jointsecretariat.ca), accessed June 4, 2012. YG –Yukon Government; GNWT–Government of Northwest Territories; DFO–Department of Fisheries and Oceans; CWS–Canadian Wildlife Service

Environmental Impact Screening Committee

The Environmental Impact Screening Committee (EISC) conducts environmental screening of development activities proposed for both the onshore and offshore areas of the ISR. Developments considered include those related to oil and gas, mineral exploration and extraction, industrial site clean-up and restoration, granting of water rights, commercial tourism ventures, and land use associated with government sponsored or funded research. The EISC has developed Operating Guidelines and Procedures to provide information and guidance to developers, government authorities, the Inuvialuit community, and other organizations regarding the structure, procedures and information requirements of the EISC. For projects on the Yukon North

Slope, the environmental screening and review process established by the IFA and the *Yukon Environmental and Socio-Economic Assessment Act* both apply.

Aurora Research Institute and the Western Arctic Research Centre

The Aurora Research Institute (ARI) is a territory-wide organisation that licenses, conducts, and coordinates research in the Northwest Territories in accordance with the *NWT Scientists Act*. This includes serving as a publically-accessible repository of research information and data, and promoting communication between researchers and the citizens of the land on which they work. Additionally, as part of Aurora College, ARI strives to support post-secondary

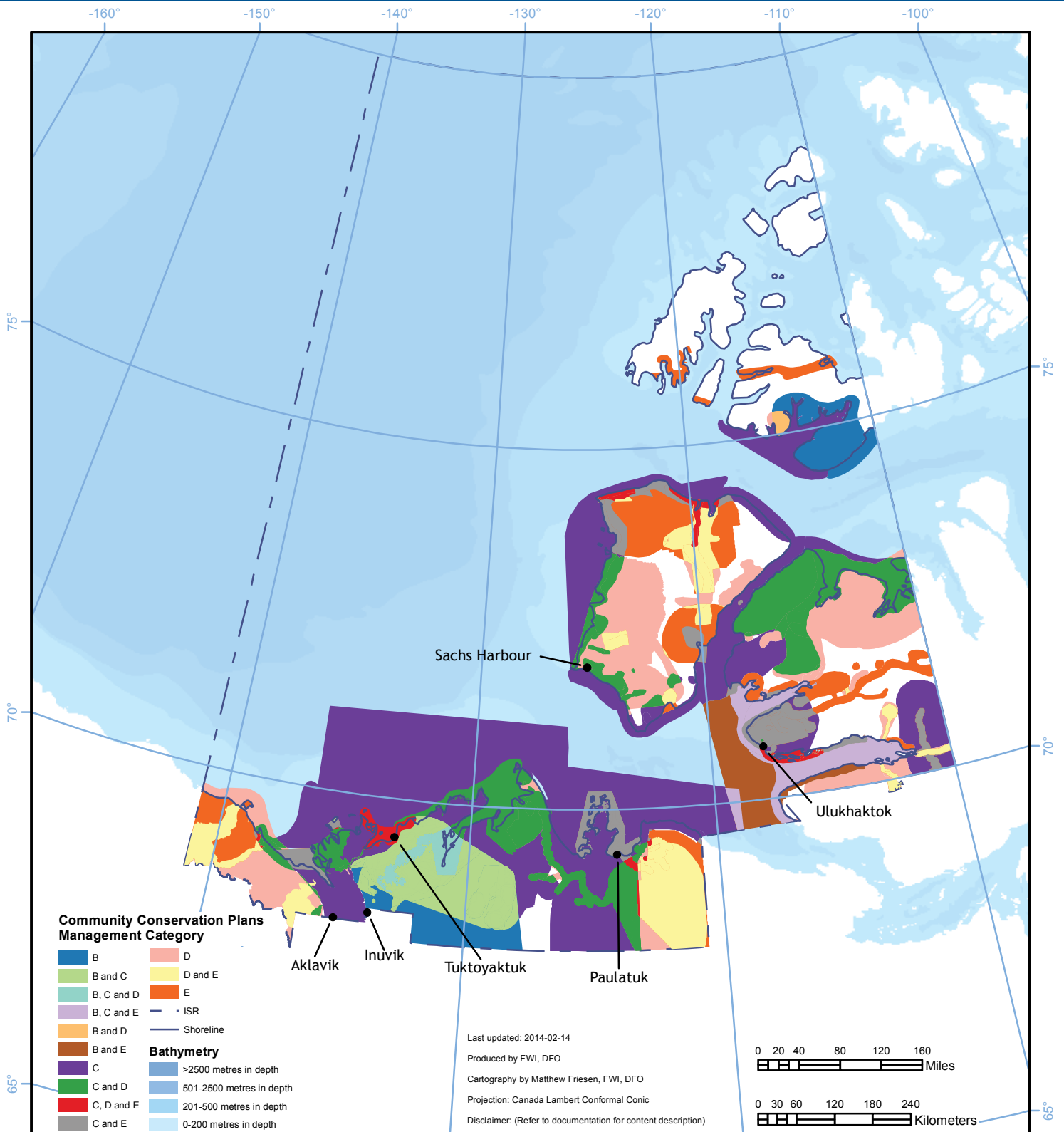


FIGURE 9. ISR Community Conservation Plan management designations. Management categories include: (1) Category B – lands where cultural or renewable resources are of some significance; (2) Category C – lands of particular significance during specific times of the year; (3) Category D – lands of particular significance throughout the year; and (4) Category E - lands of extreme significance and sensitivity. For further details please refer to the Community Conservation Plans online (<http://www.jointsecretariat.ca/documents.html>).

education and career training in research, monitoring and science administration. The ARI headquarters is located in Inuvik, with regional research centres located in Yellowknife, Fort Smith, and Inuvik, NT.

The Western Arctic Research Centre (WARC) in Inuvik is ideally situated to support research in the Beaufort Delta and western Arctic coastal regions. WARC, which opened in September of 2011, is a brand new state-of-the-art research facility that was constructed using Arctic Research Infrastructure Funds provided by the Government of Canada. The new facility houses labs, gear storage and staging areas, meeting rooms, office space, and a research library containing over 15,000 volumes, many of which are specific to the western Arctic and Beaufort Delta regions. All of these are available to members of the research and local communities.

ARI and WARC remain committed to supporting and facilitating research throughout the Northwest Territories. Climate change, cumulative impacts monitoring and traditional knowledge studies are currently of particular importance and relevance, as the data produced during these studies reflect the interests and concerns of local populations facing a changing environment. Documentation of shifting regional climate and environmental conditions not only contributes to policy and development decisions, but it also has a direct bearing on the day-to-day lives and activities of those living in western Arctic communities.

1.3.2 Kitikmeot region and Nunavut

Nunavut Tunngavik Incorporated

Nunavut Tunngavik Inc. (NTI) was established to manage and facilitate Inuit rights and responsibilities set out in the Nunavut Land Claim Agreement (NCLA) and to ensure territorial and federal governments fulfill their obligations under the agreement. Working towards Inuit economic, social and cultural well-being through the implementation of the NLCA, NTI, along with Nunavut's three



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Regional Inuit Associations (Figure 10), manages all Inuit owned land and advocates the interests of Nunavut Inuit (Nunavummiut). NTI is administered by an elected nine-member Board of Directors.

Articles 5, 11, 12, 21, and 32 of the NLCA also describe the manner in which certain forms of research must be undertaken in the Nunavut Settlement Area (NSA). NTI's primary aim in all research undertakings is to break down the historical researcher-focused model and replace it with respectful partnerships that incorporate Inuit control, Inuit priorities, and Inuit capacity building into all aspects of research. NTI's research priorities are wide ranging and include climate change, social and cultural development, sustainable development, mental health and human health, and wildlife research.

Kitikmeot Inuit Association and three Institutions of Public Government

Kitikmeot Inuit Association

The Kitikmeot Inuit Association (KIA) is a non-profit society designated as an Inuit Birthright Organization under the NCLA. Established in 1976, KIA assumed its birthright status in 1993 when the NLCA was given Royal Assent. The Kitikmeot Inuit Association is one of the three Regional Inuit Associations, along with the Qikiqtani Inuit Association (Baffin region) and the Kivalliq Inuit Association (Kivalliq region) (Figure 10).

KIA represents all Inuit beneficiaries in the Kitikmeot region, which consists of the communities Cambridge Bay, Kugluktuk, Gjoa Haven, Kugaaruk, Taloyoak, and Umingmaktok/Bathurst Inlet.

KIA's mandate is to represent the interests of Kitikmeot Inuit by protecting and promoting their social, cultural, political, environmental and economic well-being. For the benefit of Kitikmeot Inuit, KIA directly focuses on important social, cultural, political and economic issues. KIA also manages 106,360 square kilometres of Inuit Owned Lands. Because Inuit culture and language is inherently connected to the land, KIA places considerable importance and resources on land management.

Nunavut Planning Commission

The Nunavut Planning Commission (the Commission) is a public land use planning agency mandated under Article 11 of the NLCA. The Commission is established to formulate a single land use plan for the NSA and to implement and monitor regional land use plans within the NSA. A Draft Nunavut Land Use Plan (NLUP) is available online (<http://npc.nunavut.ca/en/draft-plan>) and is expected to be finalized by 2015. Once the NLUP is in place, it will be a living document that the Commission will continue to develop through regional and sub-regional study.

Under the NLCA Article 11 "land" includes both surface and sub-surface land, fresh water, and renewable and non-renewable resources including wildlife. The Article also applies to both land and marine areas within the NSA and the Outer Land Fast Ice Zone.

The Commission formulates land use plans which guide and direct resource use and development consistent with its planning policies, objectives, goals and priorities regarding the conservation, development, management and use of land in the NSA. In consideration to objectives and guidelines for short-term and long-term development, land use plans take into account factors such as (1) demographics considerations, (2) the natural resource base and existing patterns of natural resource use, (3) economic opportunities and needs, (4) transportation and communication services and corridors, (5) energy requirements, sources and availability, (6) environmental considerations, including Parks and Conservation Areas, and wildlife habitat, (7) cultural factors and priorities, including the protection and preservation of archaeological sites and outpost camps, and (8) special local and regional considerations.

Future research needs for land use planning will also be related to (1) the identification and management of cumulative effects, (2) climate change and how land use planning can mitigate the effects of climate change, (3) specific regional and sub-regional land use planning issues, and (4) the management of land use in Water Management Areas identified by the Nunavut Water Board.

The NLCA requires the collection of information to formulate land use plans. The Commission, federal and territorial governments and NTI sit on the Nunavut General Monitoring Plan (NGMP) Secretariat responsible for developing and implementing a general monitoring plan for the current and cumulative long-term state and health of the ecosystems and socio-economy of Nunavut. The current NGMP monitoring priorities of the Commission are related to the effects of climate change and resource development. The Commission works closely with the NGMP to ensure that it is kept up-to-date on the Commission's research priorities.

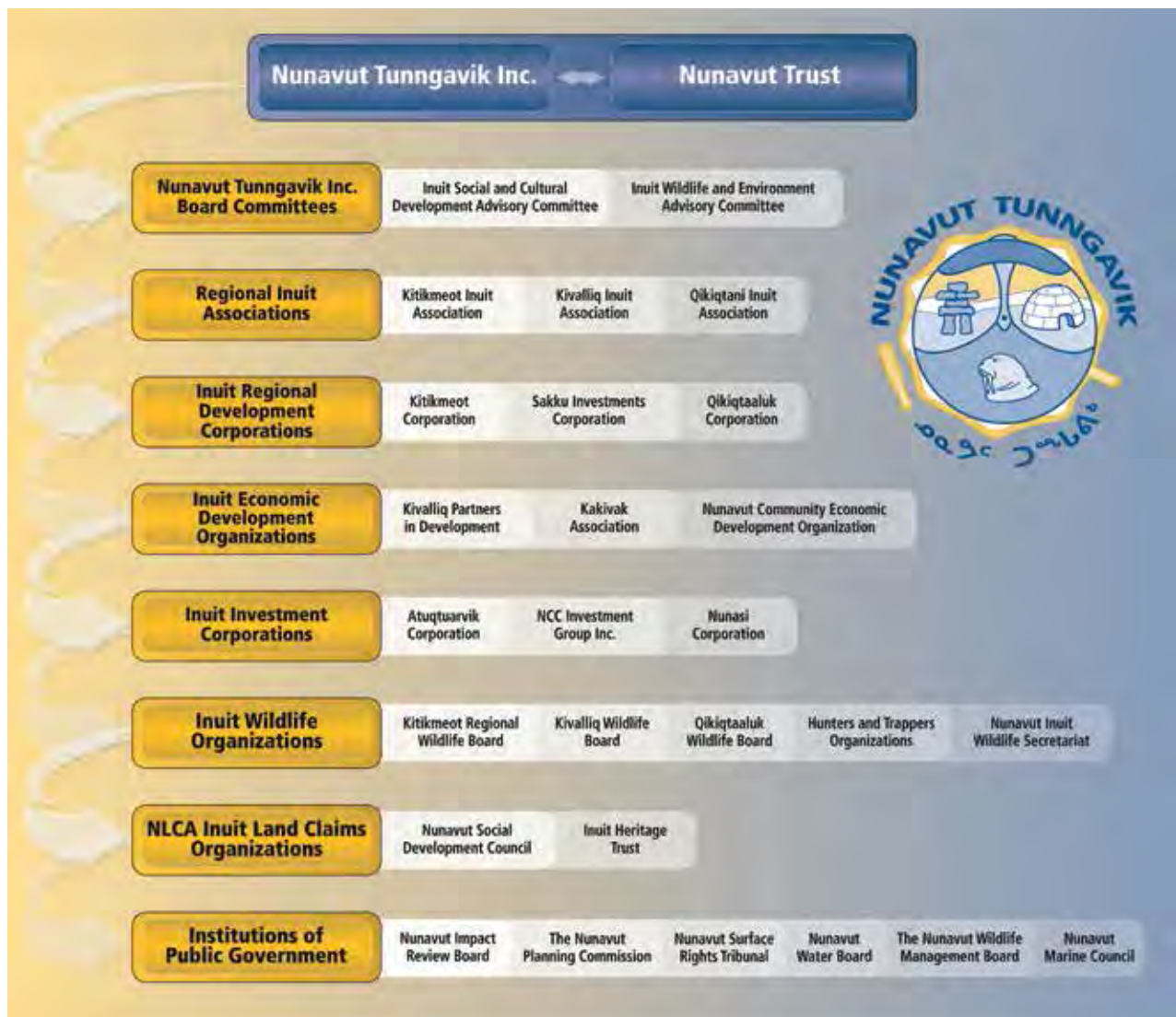


FIGURE 10. Inuit and land claims organizations overseen by Nunavut Tunngavik Incorporated (NTI). From the NTI website (www.tunngavik.com), accessed March 17, 2015.



Nunavut Impact Review Board

The mission of the Nunavut Impact Review Board (NIRB) is to protect and promote the well-being of the environment and Nunavummiut through the impact assessment process. The NIRB screens project proposals to determine whether or not a review is required. Conducting reviews of the ecosystemic and socio-economic impacts of proposed projects in the NSA, the Board determines whether project proposals should proceed, and if so, under what terms and conditions. The NIRB is also responsible for the monitoring of approved projects.

As such, it is important for the NIRB to understand the ecosystemic and socio-economic impacts of a project in a changing climate. The NIRB requires that proposals for projects that have the potential to adversely impact the environment include impacts of climate change within their environmental impact assessment.

Nunavut Water Board

The Nunavut Water Board (NWB) is an Institution of Public Government (IPG) that was created pursuant to Article 13 of the NLCA.

The NWB holds the responsibilities and powers over the use, management, and regulation of inland waters in Nunavut. As such, the NWB's primary function is to evaluate applications for the use of waters and/or deposits of waste and subsequently issue licenses for those that comply with established regulatory criteria and requirements. The NWB does not hold enforcement powers over the licences it issues. Compliance and enforcement of water licences fall under the jurisdiction of Aboriginal Affairs and Northern Development Canada (AANDC). The NWB is required to consider any detrimental effects of the potential use of waters or a deposit of waste on other water users and to hold, where appropriate, public hearings. This requirement corresponds with a key objective of the NWB's mandate to provide for the conservation and utilization of waters in Nunavut – except in national parks – in a manner that will provide optimum benefits for the residents of Nunavut in particular and all Canadians in general.

At this time, the NWB has yet to develop a formal position on climate change. The primary responsibility of the NWB is to implement its mandate as specified in the NLCA, the *Nunavut Waters and Nunavut Surface Rights Tribunal Act*, and the Regulations, which dictate that the central purpose of the NWB is to accept, evaluate, and

make recommendations on water license applications in Nunavut. Given the expansive and sensitive environment that comprises Nunavut, the NWB does anticipate that climate change issues and considerations will be increasingly brought to the NWB's attention in the future.

The NWB looks forward to an exciting and always challenging future! Moving forward the NWB will continue to work closely with its partners and especially its sister Institutes of Public Government (Figure 10) to ensure that the integrity of Nunavut's ecosystems are maintained and that the regulatory environment in Nunavut is optimal for all those involved.

Department of Environment, Government of Nunavut

The Government of Nunavut (GN) Department of Environment (DOE) facilitates the coordination of climate change adaptation activities in Nunavut including coordinating intra-governmental climate change funding programs, developing adaptation policies, developing research programs on key wildlife species and ecosystems, and building community adaptation programs, tools, and resources for Nunavummiut. In 2012, DOE developed the Nunavut Climate Change Centre or NC³ (www.climatechangenunavut.ca) in response to the need for more centralized, plain language, and current information on climate change in Nunavut. As there are numerous groups developing tools and community resources for climate change adaptation and research in Nunavut, incorporating all of these resources into one centralized location better facilitates the sharing and dissemination of climate change knowledge in Nunavut (and reduces duplication). The NC³ provides a venue for researchers and community members to report on relevant climate change projects or issues and to share their findings with the general public. This site also helps to connect communities with researchers directly and provides a tool for communities to participate in these activities by gaining increased access to pertinent information (i.e. upcoming research, results, etc.). DOE strongly encourages all researchers carrying out climate change research in

Nunavut to provide updates to, and publish their activities through, the NC³ website.

Currently, Nunavut is wholly reliant on fossil fuels for energy and with little in the way of viable alternatives; this will be the situation for the foreseeable future. While the GN is taking steps, where it can, to reduce the consumption of fossil fuels, its main efforts with respect to climate change have been concentrated towards adaptation; that is, to building adaptive capacity within the territory. The GN's adaptation strategy *Upagiaqtavut – Setting the Course: Impacts and Adaptation in Nunavut* (released in 2011) clearly identify the territory's priority areas for adaptation and focuses on closing knowledge gaps on climate change through collaborative research and monitoring. *Upagiaqtavut* is built on four key themes: (1) building partnerships to increase capacity; (2) monitoring impacts through collaborative research initiatives; (3) promoting climate change awareness and knowledge transfer; and (4) integrating climate change considerations into policy and planning. *Upagiaqtavut* is the foundation document for the development of the Nunavut Climate Change Adaptation Action Plan, which should be completed by 2014.

Inuit Qaujimagatuqangit (IQ), also known as 'traditional knowledge', is critical to understanding climate change impacts in Nunavut, especially when it is combined with the scientific work done in partnership with the communities. With very little historic scientific data currently available for most of Nunavut, we are better able to understand the changes that have taken place in the Eastern Arctic through documenting knowledge held by Nunavut Elders. IQ provides us with a window into the past and provides a context against which to assess current scientific research.

Further research is still needed in Nunavut to determine the full implications of climate change on the Arctic ecosystems, Nunavummiut, and the Inuit way of life. Through strong partnerships with research organizations and centers of excellence, the GN hopes to gain a clearer understanding of the changes that are currently ongoing. Coupled with our knowledge of the past climate in Nunavut (in particular through

IQ), the GN will continue working to increase its adaptive capacity to aid Nunavummiut in preparing for the future.

Nunavut Research Institute

The Nunavut Research Institute (NRI) is the Science Division of the Nunavut Arctic College in Iqaluit, NU. The institute leads the development and promotion of traditional knowledge, science and technology for the well-being of people in Nunavut. Administering the *Nunavut Scientists Act*, NRI licenses about 120 scientific research projects annually in the natural, health and social sciences across the territory, advising, coordinating and supporting broad scale scientific activity across Nunavut. Additional objectives of the institute are to (1) support meaningful involvement of Nunavut residents in scientific research, (2) promote the development and application of new technology to improve the quality of life of Nunavummiut, (3) help broker research projects and partnerships that meet the needs of Nunavut

residents, and (4) organize, facilitate, and promote research training and outreach programs designed to enhance awareness and build local research capacity in Nunavut.

NRI provides a range of logistic and field support services through facilities that include a new state-of-the-art research centre in Iqaluit, NU, and a network of research field units in Igloolik, Rankin Inlet, Arviat and Cambridge Bay, NU. The new Iqaluit amenities offer dedicated teaching and research laboratories facilities, equipment rentals and storage, office and meeting spaces, a research library and other resources.

Nunavut research priorities and interests emphasized by NRI relate largely to social and health concerns. Research is needed to address important issues in Nunavut communities such as unemployment, addictions, suicide, nutrition and health (NRI 1997). Furthermore, there is a desire for Nunavut communities to develop and participate in such



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projects. Additional research is needed for the areas of politics and governance, economics, history, geography, linguistics and language, education and training, physical sciences and engineering, and technology development (NRI 1997). With respect to the environment, NRI emphasizes the importance of baseline monitoring of ecosystem components, particularly for impacts related to climate change and resource development.

Canadian High Arctic Research Station

Scheduled to open in Cambridge Bay, NU in June 2017, the Canadian High Arctic Research Station (CHARS) will be a world-class, year-round facility focusing upon research into environmental and resource development issues. The location of CHARS was announced August 24, 2010 after a feasibility study that also considered Pond Inlet and Resolute Bay, NU. As of 2012, the Government of Canada has allocated \$142.4 million to build and equip the facility, including \$18 million for its design phase, and will also provide \$46.2 million towards the CHARS Science and Technology Program. The station is a component of the Government of Canada's integrated Northern Strategy and is expected to secure the network of northern Canadian research infrastructure, strengthen Northern economic growth, and build capacity through training, education and outreach. On December 3, 2010 the Government also announced that the station would advance "sovereignty and healthy communities for the benefit of Northerners and all Canadians" (Government of Canada 2010). CHARS will also demonstrate stewardship of natural resources and foster collaborative partnerships among Aboriginal, government, private and academic communities.

1.3.3 Yukon

Wildlife Management Advisory Council (North Slope)

The Wildlife Management Advisory Council (North Slope) (WMAC (NS)), one of the ISR co-management bodies, was created in 1988 under the *Western Arctic (Inuvialuit)*

Settlement Act. With its signing, certain requirements and responsibilities were delegated to the WMAC (NS) including the conservation and protection of wildlife, habitat and traditional Inuvialuit use within the Yukon North Slope, an area comprising all of the northernmost land in the Yukon and the adjacent Beaufort Sea. Since its inception, the Council has been a catalyst for cooperative management on the Yukon North Slope.

The Council is active on a number of fronts, including (but not limited to) (1) providing advice on wildlife policy and the management, regulation, and administration of wildlife, habitat and harvesting for the Yukon North Slope, (2) giving guidance to the Porcupine Caribou Management Board, the Yukon Land Use Planning Commission, the Environmental Impact Screening Committee and the Environmental Impact Review Board, and other organizations, (3) recommending quotas for Inuvialuit game harvesting on the Yukon North Slope, and (4) working on concrete measures to protect critical habitat for wildlife or harvesting purposes.

The WMAC (NS) created the Yukon North Slope Wildlife Conservation and Management Plan to fulfill requirements in the IFA. The plan outlines goals, objectives and concrete actions needed to conserve and protect the North Slope. The plan offers guidance and information to government, co-management organizations, environmental assessment bodies, Inuvialuit and other Aboriginal organizations, and the general public. The plan is available at www.wmacns.ca.

Government of Yukon

Yukon government's Climate Change Secretariat has the lead role in ensuring Yukon government actions support a healthy and resilient Yukon in a changing climate. It works within the Yukon government and with its partners to identify needs, opportunities and priorities, promote and support action, and monitor and report on progress.

The Climate Change Secretariat works closely with climate change organizations in the territory like the Energy

Solutions Centre and the Northern Climate ExChange of the Yukon Research Centre, Yukon College. The Northern Climate ExChange provides a credible independent source of information, develops shared understanding, promotes action and coordinates research on climate change in the Yukon and across northern Canada.

The Energy Solutions Centre promotes an increase in energy efficiency in Yukon homes and businesses and an increased understanding, use and development of Yukon's renewable energy resources.

Together, the climate change related organizations in the Yukon are taking action on changing climate.

1.3.4 Federal agencies governing environmental protection and community adaptation to climate change

Department of Fisheries and Oceans

The Department of Fisheries and Oceans (DFO) Canada was established to administer safe and accessible waterways, healthy and productive aquatic ecosystems, and sustainable fisheries and aquaculture to Canadians on behalf of the Government of Canada. DFO is responsible for developing and implementing policies and programs in support of Canada's scientific, ecological, social and economic interests in oceans and fresh waters.

In 1997 the Government of Canada adopted the *Oceans Act* to provide a framework for a national ocean management strategy. This legislation extended Canada's jurisdiction out to 200 nautical miles, enabling DFO to protect Canada's marine environment, regulate scientific research and control offshore installations. The Beaufort Sea Large Ocean Management Area (LOMA) (Figure 11) was identified in 2005 as one of the priority areas for Integrated Ocean Management (IOM). DFO's IOM in the Beaufort Sea LOMA facilitates a collaborative

approach towards fostering sustainable development (see section 1.4.4).

Climate change is affecting the conditions of the oceans. DFO pursues research to better understand and predict these changes to develop effective adaptation strategies. In particular, DFO prioritizes the assessment and interpretation of downscaled global climate model projections, flood risks, and the resilience of aquatic populations.

Parks Canada

National parks in the ISR (Figure 11) are managed to meet the obligations of the IFA, which has as a goal the protection and preservation of Arctic wildlife, environment and biological productivity through the application of conservation principles and practices. Managers of Canada's national parks are also obligated by the *Canada National Parks Act*, Bill C-27, to '...maintain or restore the ecological integrity' of all national parks. Given predicted increased rates of warming at Arctic latitudes (see Chapter 2), it can be expected that ecological change will accelerate over the coming decades to create conditions that seriously compromise the management objectives of national parks across the Canadian Arctic.

National parks can make excellent natural 'laboratories' for monitoring and understanding ongoing regional ecological change, for projecting these changes onto an uncertain future, and for interpreting and communicating these changes in the context of the needs of management partners and northern communities. In beginning a climate adaptation strategy for Arctic national parks, Parks Canada Agency has implemented a five year project entitled 'Understanding Climate Driven Ecological Change in the North'. The project will work with park cooperative management boards to identify key vulnerabilities and opportunities occurring in the short (5-15 yr), medium (15-50 yr), and long (>50 yr) term, and to develop focussed knowledge on key issues so as to provide more proactive management actions. The project will develop state-of-the-art, process-based ecological inventories for all northern national parks, help establish

baselines and protocols for reporting ecosystem change through park monitoring programs, develop forward-looking ecosystem models that project a range of future scenarios, and predict potential changes to key ecological services (e.g. iconic park species, country food, visitor safety, visitor opportunities, climate change feedbacks).

Aboriginal Affairs and Northern Development Canada

Aboriginal Affairs and Northern Development Canada (AANDC) has been implementing climate change programming in the Canadian Arctic since 2000. From 2000 until 2007, the main focus of the program was to raise awareness of climate change, energy (renewable and efficiency) and climate change impacts in Aboriginal and northern communities across the country.

Since 2007, AANDC has been implementing two climate change programs (<http://www.aadnc-aandc.gc.ca/eng/1312222759090>). The first is the ecoEnergy for Aboriginal and Northern Communities which focuses on supporting Aboriginal and northern communities' development of renewable energy projects and implementation of energy efficiency initiatives. The program was renewed in June 2011 and will end in 2016.

The second program is the Climate Change Adaptation Program which focuses on providing support to Aboriginal communities as well as northern communities/governments/institutions to conduct community vulnerability assessments, develop community adaptation plans and develop tools for communities to assist them in adapting to climate change. This program collaborates with Health Canada's Climate Change and Health Adaptation in Northern/Inuit Communities program and the Natural Resources Canada's Regional Adaptation Collaboratives. In its first 4 years of implementation, the program supported over 93 projects in 85 communities, most of which was in the North. The program was renewed in September 2011 and will be operating until 2016.

At the end of the selection process for 2012-2014 projects, 19 projects received funding. In addition, AANDC has been developing four year plans with the territorial governments. Each territory will receive funds to support their efforts in developing tools for integration of adaptation into decision-making and to assist their municipalities/hamlets in adapting to climate change.

1.4 Assessments and climate change research

The following section highlights some of the environmental assessments and research that are on-going or have been previously undertaken in the ISR and the Kitikmeot region. Of note, many projects and assessments conducted in the western and central Canadian Arctic have fed into the Arctic Council's working group assessments and monitoring initiatives (e.g. Arctic Monitoring and Assessment Program (AMAP), Sustaining Arctic Observing Networks (SAON), Conservation of Arctic Flora and Fauna (CAFF)) at the circumpolar and international scales; however, these extend beyond the scope covered here and will not be discussed further.

1.4.1 Assessments

Beaufort Regional Environmental Assessment

In August 2010, the Government of Canada announced the Beaufort Regional Environmental Assessment (BREA), a \$21.8 million investment in support of increased research to inform regulatory decisions for potential offshore exploration and development activities in the Beaufort Sea.

BREA is a multi-stakeholder initiative that provides an opportunity for Inuvialuit communities, industry, federal and territorial governments, academia and regulators to prepare for oil and gas activity in the Beaufort Sea by building a regional socio-economic and scientific knowledge base

that will fill regional information and data gaps related to offshore oil and gas activities and support efficient and effective regulatory decision-making.

BREA consists of a research program and working group activities to address priority issues in the region. Twenty-three research projects have been funded to-date, based on priorities identified in earlier analyses and subsequently refined collaboratively through multi-stakeholder committees. All projects were selected based on their relevance to the priority research areas, as well as their contribution to regulatory efficiency and community preparedness, the two primary goals of BREA.

Separate working groups are addressing issues related to climate change, cumulative effects, information management, oil spill preparedness and response, social, cultural and economic indicators, and waste management.

The BREA Climate Change working group was formed to support efficient and effective environmental assessment and regulatory decision-making as related to aspects of climate change of relevance to offshore oil and gas activities in the Beaufort Sea. To this end, the Working Group awarded Stantec Consulting Ltd. a contract to conduct a study to assess the impacts of climate change on oil and gas activities in the Beaufort. The study included an assessment report as well as an expert workshop to validate findings. The workshop was held in November 2012 in Inuvik, and a final report titled *Assessment Report on the Potential Effects of Climate Change on Oil and Gas Activities in the Beaufort Sea* was released in 2013 (www.BeaufortREA.ca).

Community climate change adaptation (action) plans

Several documents targeted at helping northern communities plan for climate change adaptation were published in 2010 and 2011. Developed in collaboration with the communities, the reports for Aklavik (Friendship et al. 2011), Paulatuk (Pearce et al. 2010a) and Ulukhaktok (Pearce et al. 2010b) were published by ArcticNorth Consulting (and

RavenQuest for Aklavik), while the Canadian Institute of Planners initiated the plans for Cambridge Bay (Calihoo and Romaine 2010) and Kugluktuk (Johnson and Arnold 2010). Most plans provided objectives, actions, and resources for climate change issues and impacts with respect to health, culture, infrastructure, transportation, subsistence activities and business management.

The majority of top priority action items in the plans for the ISR communities related to increasing learning opportunities for job training, traditional skills and language, nutrition, parenting, safety, technical writing and climate change. By developing skills and knowledge needed for subsistence activities, employment, social networks and acquiring associated resources, the premise is that while communities strengthen social, cultural and economic ties, they will also build adaptive capacity to manage issues associated with climate change.

While the plans for Cambridge Bay and Kugluktuk also highly recommended climate change education for the communities, the Kitikmeot reports focused more on improvements/protection for planning and infrastructure development in light of thawing permafrost and changing water levels. Such proactive adaptation actions will enhance human safety, health, the environment, and will minimize long-term costs to the communities by otherwise taking a reactive approach to impacts incurred by climate change.

Mackenzie Basin Impact Study

The Mackenzie Basin Impact Study (1991-1996) was a comprehensive, collaborative research investigation into the potential impacts of climate change on the Mackenzie Basin, including the communities dependent upon the basin. It was also one of the first integrated regional assessments of climate change in Canada. Through studies, case studies and modelling efforts, participants of the study assessed a large suite of environmental indicators including water levels and flows, suspended sediments, snow, permafrost, landslides, vegetation, forest dynamics and infestations, fire susceptibility, animals and their habitat,

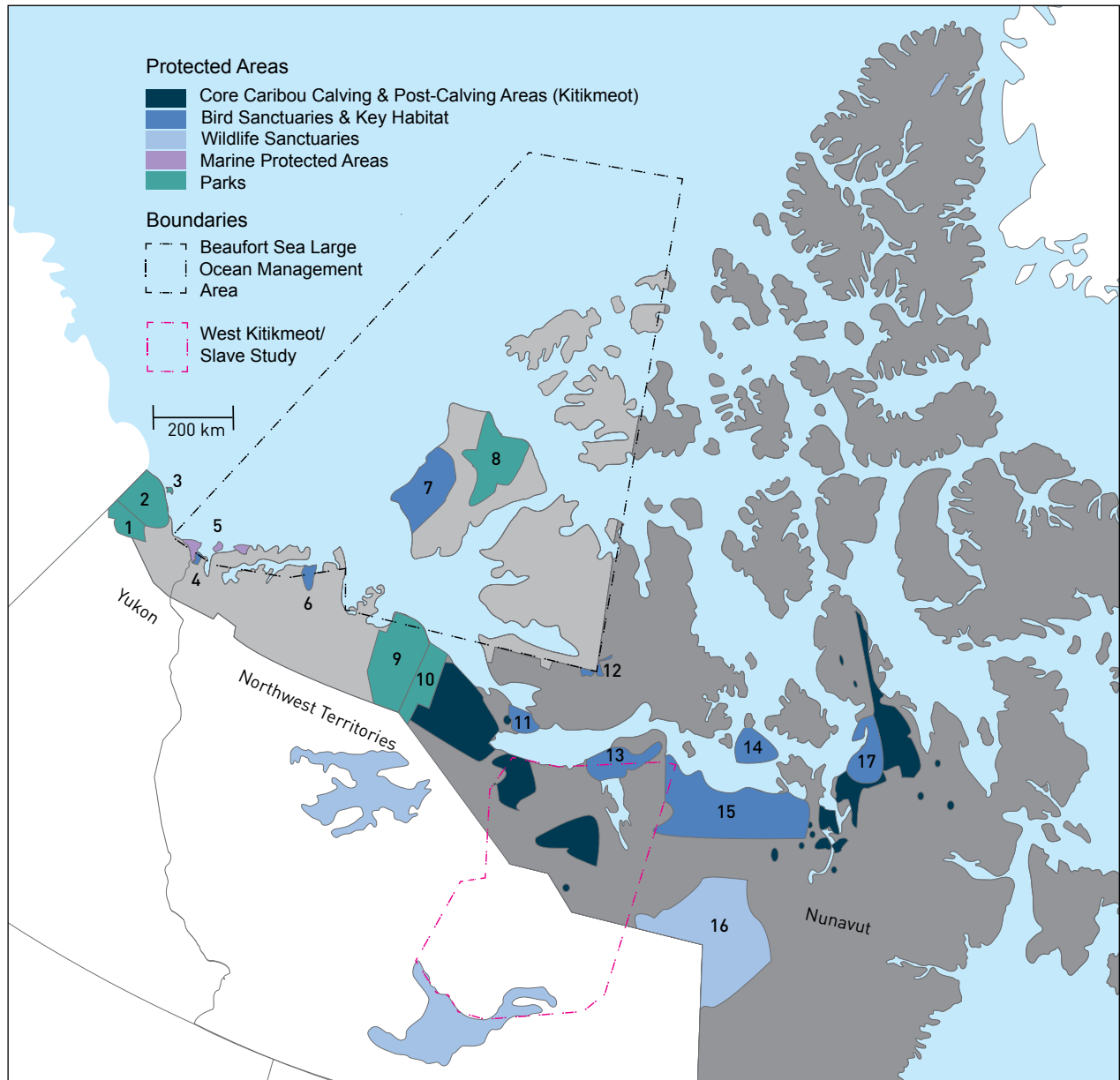


FIGURE 11. Protected areas within the Inuvialuit Settlement Region and the Kitikmeot region of Nunavut along with the boundaries of the Beaufort Sea Large Ocean Management Area and the West Kitikmeot/Slave Study. The latter encompasses the West Kitikmeot and Slave Geological Province. 1 – Vuntut National Park, 2 – Ivvavik National Park, 3 – Herschel Island-Qikiqtaruk Territorial Park, 4 – Kendall Island Migratory Bird Sanctuary, 5 – Tarium Nirvutait Marine Protected Area, 6 – Anderson River Delta Migratory Bird Sanctuary, 7 – Banks Island Migratory Bird Sanctuary, 8 – Aulavik National Park, 9 – Tuktu Nogait National Park, 10 – Blue Nose Lake Area (proposed national park in Nunavut), 11 – Lambert Channel, 12 – Kagloryuak River, 13 – Bathurst/Elu Inlets, 14 – Nordenskiöld Islands, 15 – Queen Maud Gulf Migratory Bird Sanctuary, 16 – Thelon Wildlife Sanctuary, and 17 – Rasmussen Lowlands. Items 10-17 and the core caribou calving and post-calving areas in the Kitikmeot region are referenced from the Draft Nunavut Land Use Plan, Schedule A (<http://www.nunavut.ca/en/downloads>) accessed June 25, 2014 and are subject to change. For information on caribou herds in the region, see Chapter 3, Figure 9.

floods, and socio-economic implications for forestry, agriculture, hydrocarbon production, tourism and settlements (Cohen 1997). Some of the key recommendations from the assessment included the incorporation of climate change research and planning into management regimes and the support for community involvement in research and adaptation activities.

West Kitikmeot/Slave Study

One of the largest collaborative, multidisciplinary studies to occur within central Nunavut and the Northwest Territories was the West Kitikmeot/Slave Study which took place in the West Kitikmeot and Slave Geological Province (Figure 11). In response to concerns about the impacts of future resource development on livelihoods and wildlife in the largely untapped, mineral-rich region, Aboriginal and co-management organizations, government agencies and industry partnered to create a society (“West Kitikmeot/Slave Study (WKSS) Society”) in 1996 for the purpose of collecting baseline data for future environmental and cumulative effects assessments. Documenting traditional knowledge and western science, projects studying wildlife and habitat, the physical environment (e.g. water, sediments), and the socio-economy were led as part of WKSS until 2001. WKSS continued to fund some of the monitoring projects until 2007 and concluded in 2009 (WKSS 2009).

1.4.2 Canadian Arctic research networks

Canadian Arctic Shelf Exchange Study

Funded by the Natural Sciences and Engineering Research Council (NSERC) in 2001, the Canadian Arctic Shelf Exchange Study (CASES) Research Network was established to study the biogeochemical and ecological impacts of sea-ice variability and oceanographic changes on the Mackenzie Shelf. Research was undertaken on the Canadian Coast Guard Ship (CCGS) *Amundsen* during the very first overwintering field season in the Canadian Arctic during 2003-2004. The various components studied within

the multidisciplinary project included coastal circulation, interactions between the sea ice and atmosphere, nutrients, primary production, the different marine food webs, and carbon cycling and flows. The CASES results were provided to the decision-making bodies of the ISR, such as the Inuvialuit Game Council and co-management bodies, to further their knowledge for management purposes.

ArcticNet

Since 2003, ArcticNet has led a variety of projects within the ISR and the Kitikmeot region of Nunavut. Many of ArcticNet’s projects in the field of natural sciences utilize the expeditions aboard the CCGS *Amundsen* to examine sea ice, oceanography, the sea bed, contaminants, carbon exchange, marine productivity, food webs and geomicrobiology (the study of microbes and geochemical processes and their interactions). There are also projects that investigate permafrost, coastal landscapes, hydrology, terrestrial ecosystems, marine mammals and remote sensing. Social, political and economic research has looked into issues such as food security, sovereignty, education, communication, and community adaptation to climate change impacts. Two of three health sciences projects are continuations of two of the Canadian International Polar Year (IPY) studies, investigating health indicators in an Inuit cohort and dietary changes in northern communities, and the third project examines the *H. pylori* bacteria, responsible for stomach infections, in ISR communities (Chapter 5, Box 1).

Nasivvik Centre for Inuit Health and Changing Environments

Funded by the Canadian Institutes of Health Research-Institute of Aboriginal Peoples’ Health, the Nasivvik Centre is a multidisciplinary research and training centre based at Laval and Trent Universities. The Nasivvik Centre promotes training and research opportunities for northern residents, organizations and communities with the aim of building capacity in Inuit health research throughout all four regions of the Inuit Nunangat (Inuit homeland). With respect to Inuit environmental and health issues, the centre’s specific



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objectives include identifying research priorities, collaborating between Inuit community members and University-based researchers, funding academic scholarships and research projects, and overall supporting the generation and distribution of new knowledge. Examples of research supported by the Nasivvik Centre which have taken (or continue to take) place within or including the ISR and the Kitikmeot region include projects looking into developing an Inuit food guide and database, investigating educational mediums, assessing second-hand smoke exposure, environmental and contaminants monitoring, and examining the relationship between people and plants.

Northern Contaminants Program

The Northern Contaminants Program, part of AANDC, was established to research, monitor and communicate information about contaminants (e.g. persistent organic pollutants, mercury) in northern traditional and country foods (e.g. fish, marine mammals, seabirds and eggs, caribou). Monitoring and research activities funded by the program (including community-based activities) help to assess the human health risk from dietary exposure of contaminants. In turn, this information is provided to health authorities to formulate advice about the consumption of country foods to northerners. The program also funds human health research, environmental monitoring (e.g. contaminant levels in air and water), communication and outreach activities, and the coordination of national, regional and Aboriginal organizations. By informing international parties and agreements to

reduce/eliminate the production and release of contaminating substances, the Northern Contaminants Program also aims to lower (or eliminate) contaminant concentrations in country foods.

Inuit Research Advisors

Supported by ArcticNet, the Nasivvik Centre for Inuit Health and Changing Environments, the Northern Contaminants Program, and the four Inuit land claim organizations (Inuvialuit Regional Corporation, Nunavut Tunngavik Inc., Kativik Regional Government, and Nunatsiavut Government), Inuit Research Advisors coordinate research engagements for the aforementioned research centres/programs in each of the Inuit land claim regions (ISR, Nunavut, Nunavik, Nunatsiavut). The research advisors play a pivotal role in assisting both researchers and Inuit communities with project proposal development and the dissemination and communication of research results. They also develop new research projects driven by Inuit interests, engage youth in training and educational opportunities, and build research capacity in each of the land claim regions. Not only are the Inuit Research Advisors an important link between Inuit interests and scientific research, but they also promote traditional knowledge as a complement to western science, encouraging a more holistic framework for research in the North.

1.4.3 International Polar Year: Circumpolar Flaw Lead Project and Inuit Health Survey

Almost half of all 2007-2008 Canadian IPY projects had identifiable survey or sample locations in the western and central Canadian Arctic (www.canadiangeographic.ca/ipy-api/map-carte). Many of the studies utilized existing national (e.g. ArcticNet) or international (e.g. International Tundra EXperiment) networks. The majority of Canadian IPY projects studied the physical, chemical, biological and ecological components of the Arctic, but many also investigated social, cultural and health indicators in communities.

The largest IPY-Canada project was the Circumpolar Flaw Lead (CFL) project conducted in the Beaufort Sea. This unique, multidisciplinary climate change study involved field work on the CCGS *Amundsen* ice-breaker in the Banks Island flaw lead for a full winter season (October 2007 to July 2008). The main objective of the CFL project was to examine climate processes in the context of the flaw lead in comparison to adjacent fast ice. Specifically the project studied oceanic, cryospheric and atmospheric processes on the lead and how these moderated biological/ecological functions, contaminant transport, and nutrient, carbon and greenhouse gas exchange. A complementary component of the study was an integration of traditional knowledge of the ISR with the science teams.

Another intensive IPY project in the Canadian North was the Inuit Health Survey (see Chapter 5). During the late summer and fall of 2007 and 2008, an Adult Inuit Health Survey (ages 18+) was conducted in all communities in the ISR, Nunavut and Nunatsiavut, and a children's health survey (ages 3-5) took place in Nunavut only. Once again the CCGS *Amundsen* was used as the main platform for travelling to the communities and carrying out the research on the adult participants. In total 2,595 adults and 388 children participated in the surveys (<http://www.mcgill.ca/cine/resources/ihs>). While the adult survey focused on topics such as chronic disease risk, food security and mental health, the children's survey looked at nutrition, growth, vision, mercury exposure, and medical histories.

1.4.4 Integrated Ocean Management Plan

Multiple government departments, co-management bodies, Inuit organizations, research networks and businesses come together towards reaching common goals under the Beaufort Sea Partnership, a consortium supporting healthy ecosystems and sustainable communities and economies in the Beaufort Sea LOMA (Figure 11) since 2005. One of the tools strengthening the governance and communication within the Beaufort Sea Partnership is the Integrated Ocean Management Plan (IOMP) established by DFO. The

IOMP facilitates multi-stakeholder planning to provide a long-term strategic roadmap for integrated, adaptive, and ecologically sound management of marine activities related to marine conservation, recreation, subsistence fisheries, oil and gas activities, and shipping among others (www.beaufortseapartnership.ca). Working Groups within the governance structure of the Beaufort Sea Partnership identify specific goals and associated knowledge gaps with respect to stakeholder interests. The research and baseline studies developed within the Beaufort Sea Partnership assist in fulfilling the advancement of the IOMP.

1.4.5 Community-based monitoring

Monitoring is defined by Spellerberg (2005) as “the systematic measurement of variables and processes over time... [and] assumes that there is a specific reason for that collection of data such as ensuring that standards are being met” or to contribute towards management and decision-making. Community-based monitoring (CBM) fits on a spectrum spanning from externally driven monitoring with local data collectors through to community-based monitoring carried out entirely by local resource users (Danielsen et al. 2008).

The Inuvialuit Settlement Region - Community-Based Monitoring Program (ISR-CBMP), which began in January 2013, is a regional coordinated approach to community-based monitoring in the ISR. The data and knowledge collected and shared through CBM are the direct results of community participation in monitoring efforts driven by local and regional information needs, in turn contributing to the management of local resources. The overall goal of the ISR-CBMP is to support the Inuvialuit Final Agreement institutions mandated “to protect and preserve the Arctic wildlife, environment and biological productivity” to achieve the principles of the IFA and enhance decision-making. The program is a partnership that includes the six ISR Hunters and Trappers Committees, the ISR wildlife co-management boards and the Inuvialuit Game Council. Community interests and priorities are integral to the design and implementation of the program, along with

the management needs and priorities of Inuvialuit organizations, wildlife co-management boards and federal and territorial resource management authorities. The ISR-CBMP incorporates local expert traditional knowledge as well as local ways of monitoring in the regional program (<http://www.jointsecretariat.ca/ISR-CBMP>).

In the Kitikmeot Region, the Nunavut Wildlife Management Board ran a Community-Based Monitoring Network (CBMN) Pilot Study from February 2012 – January 2013 with the community of Cambridge Bay. The CBMN had local expert hunters and harvesters record wildlife observations and harvests in the field on handheld devices while they were out harvesting on the land. “The intent of the CBMN is to help compile information that is needed to address concerns affecting wildlife management, conservation, and Inuit harvesting rights and to obtain Inuit Qaujimaqatungit (IQ) information in a format that can communicate with scientific modeling.” (NWMB 2013)

Other on-going CBM projects within Aklavik and Inuvik include the Arctic Borderlands Ecological Knowledge Co-op, a separate initiative from the ISR-CBMP. This program began in 1996 and works with community researchers to conduct interviews with local experts each year about their observations of changes to fish, berries, caribou, unusual animal sightings, and weather conditions. This program is carried out within the range of the Porcupine Caribou herd spanning Alaska, Yukon and the western portion of the ISR and is run out of Environment Canada in Whitehorse, YT (<http://taiga.net/coop>).

The Cumulative Impact Monitoring Program operating out of GNWT’s Department of Environment and Natural Resources since April 2014 has funded many CBM projects since its inception in 1999, including the ISR-CBMP and Arctic Borderlands programs. Led by Aboriginal and government representatives and partnered with other Northerners and organizations, the program supports a wide range of environmental and socio-economic monitoring activities in the NWT (including the portion of the ISR in the NWT) to build upon baseline data and capture

cumulative impacts in the region, ultimately improving an understanding of the region to make sound decisions around resource management.

The FJMC is a strong advocate of CBM, as reflected in the funding and support provided to many of their projects that involve the cooperation of local Hunters and Trappers Committees (HTCs). The FJMC supports CBM research projects for beluga, seals, Dolly Varden and Arctic char in all six ISR communities. Other researchers also include communities in their research projects, resulting in both parties sharing their respective knowledge. For example, several IPY projects (e.g. Arctic Freshwater Systems; Climate Variability and Change Effects on Chars in the Arctic; Climate Change Impacts on Canadian Arctic Tundra) utilize CBM in association with their research methods. The ArcticNet-funded *H. pylori* infection study in the ISR (see Chapter 5, Box 1), the historical WKSS in the Kitikmeot region (this chapter, section 1.4.1), and several beluga monitoring programs funded by FJMC, NCP, DFO, Oceans North Canada, the ISR-CBMP, and the World Wildlife Federation are examples of community-driven CBM projects.

1.5 Conclusion

Together with their regional, territorial and federal partners, Inuvialuit and Nunavummiut in the Kitikmeot region are dedicated to safeguarding and sustaining their culture, rights, land and resources. It is clear that, through Inuit observations and numerous scientific investigations, the western and central Canadian Arctic is subject to a vast array of climate change impacts which can threaten the Inuit way of life. To help protect northern livelihoods and support networks against this threat, it will be important to continually garner and assess scientific and traditional knowledge to help formulate adaptation strategies to cope with climate change.

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Chapter 2. Climate Variability and Projections

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KEY MESSAGES

Air temperature

- Between 1981 and 2010, the climate stations in the IRIS region show an average increase of 0.7–1.2°C per decade in the mean annual temperature.
- The climate station data indicate the current rate of warming is a relatively recent phenomenon occurring after ~1980 in winter, spring and summer, and after ~1990 for the fall (October-December).
- Output from the Ouranos CRCM4 model shows that the largest projected changes in air temperature will occur during the fall and winter seasons (~5-6°C increase in air temperature) for the timeframe 2041-2070.

Permafrost and ground temperature

- There was recent rapid warming of permafrost over the North American Arctic during the 1980s and 1990s with warming rates since 1970 averaging from a few tenths of a degree up to 1°C per decade. The rate and timing of the warming shows important regional variability.
- Different projections for the region indicate that near surface permafrost temperatures could increase between 2 and 5°C for the timeframe of 2041-2070.

Precipitation and snow

- Precipitation shows little evidence of significant changes over the recent 1981-2010 period but both snowfall and rainfall exhibit significant increasing trends over the longer 1950-2010 period of available climate data.
- The largest total precipitation increases were observed for winter (11.5% per decade), followed by fall (7.3%), spring (3.7%), and summer (2.9%).

- Total annual snowfall increased at 9.8% per decade.
- Total annual rainfall increased at 6.0% per decade.
- Over the 1950-2010 period all the climate stations had significant trends toward a later start to the snow cover season and a shorter period of continuous snow cover.
- Projected changes in precipitation for the 2041-2070 timeframe from the Ouranos CRCM4 show increases in total annual precipitation of 20-30% (14-30% increases in total annual solid precipitation) resulting in increased maximum snow depths (~1 to 10 cm) despite a projected shortening of the snow cover season by 10-30 days.

Sea ice

- During the timeframe 1981-2010, the largest decreases in total sea-ice concentration occurred during late summer and early fall (August, September and October) with a decline of approximately 5-7% per decade.
- During the timeframe 1981-2010, the amount of multi-year sea ice present in the Beaufort Sea declined nearly 9% per decade during late summer and fall (September through to December), while the other regions showed little or no trends in multiyear sea ice. The most dramatic decline of total sea-ice concentration occurred from 2001-2010 and was during September, the typical sea ice minimum. The largest decreases for the 2001-2010 during September are given based on the Canadian Ice Service defined sub-regions:
 - Western Parry Channel showed a decline of 53% for the September monthly average total sea-ice concentration during 2001-2010.

- M'Clintock Channel showed a decline of 50% for the September monthly average total sea-ice concentration during 2001-2010. The Eastern High Arctic and Eastern Parry Channel both showed a decline of 38% for the September monthly average total sea ice concentration during 2001-2010.
- Beaufort Sea showed a decline of 26% for the September monthly average total sea-ice concentration during 2001-2010.
- The Franklin Strait region showed a decline of 27% for the September monthly average total sea-ice concentration during 2001-2010.

River and lake ice

- The period when ice is considered safe for travel by observers exhibits considerable variability between sites reflecting local climate conditions and ice dynamics. The shortest ice safe period (~4 months) is observed at Inuvik and the longest (7-8 months) at Cambridge Bay and Mould Bay.
- The freshwater ice thickness observations in the region all show statistically significant decreases in maximum ice thickness since 1960 ranging from -3.5 to -7.4 cm per decade. There is also evidence that break-up severity has declined in recent decades near the Mackenzie Delta in response to changing hydrology and thinner ice.
- Model based scenarios suggest that freshwater ice cover will decrease by approximately 10-30 days by 2050 with a decrease of 20-50 cm in ice thickness over the western part of the IRIS region.

Winds and storms

- There were very few regions with significant trends in wind magnitude over the 1981-2010 period. During March, July, and October the magnitude of the winds in the Eastern High Arctic increased by 1.1, 1.3 and 1.5 m s⁻¹ per decade, respectively.
- During the warmer months there was a shift in direction for most regions. During August there was a decreasing zonal (east-west) component of the wind for the Beaufort Sea, Western High Arctic, Eastern High Arctic, Western Parry Channel, and Eastern Parry Channel.
- The Beaufort Sea region had an increase in winter storm strength in recent years, most likely due to an increase in open water extent in fall.

2.1 Introduction

The Arctic is currently going through rapid changes; sea-ice extent has decreased significantly in the past decade, with the eight lowest September sea-ice extents from 1979 to 2014 all occurring within the past eight years (2007–2014). Studies have shown that the increase in surface air temperature is responsible for warming Arctic waters and associated with a decline in sea ice extent (Zhang 2005). The September 2012 record minimum sea-ice extent was 16% lower than the previous record set in 2007 (NSIDC 2012). Many scientists believe that the recent Arctic warm period and the accelerated changes in sea ice are unprecedented (Barber et al. 2008; Overland et al. 2008; Kinnard et al. 2011) over the period of human habitation.

The Arctic climate is closely tied to snow, ice, and frozen ground. Collectively, these reservoirs of frozen water are referred to as the cryosphere. Sea ice and snow can act as a barrier blocking heat and moisture exchange across the ocean and atmosphere interface. The albedo of sea ice is an important component in the earth-ocean-atmosphere system; sea ice reflects up to 50% of incoming solar radiation while snow-covered sea ice can reflect up to 90% of incoming solar radiation. (Comparatively, open water reflects only 6% of incoming light, while a forest reflects approximately 15%). The high reflectivity of sea ice sustains both cold Arctic temperatures during sunlit seasons as well as the equator-to-pole temperature gradient that governs hemispheric-scale heat circulation.

The purpose of this chapter is to highlight the key characteristics of the climate of the western and central Canadian Arctic (herein referred to as the “IRIS region”) that are important for natural systems, ecosystem services and human activities, to characterize the rate of change in these climate indicators over the past 30 years, and to present scenarios of the projected changes that may occur over the next 50 years.

2.1.1 The climate of the IRIS region

The region of interest extends from 65°N to 80°N, and from 145°W to 80°W (Chapter 1, Figure 1). This is a vast region, extending from Tuktoyaktuk, NT in the west to Kugaaruk, NU in the east and Mould Bay in the north. The region is characterized by some of the harshest climate conditions on the North American continent.

According to the Köppen-Geiger climate classification (Kottek et al. 2006) the IRIS region contains two climate regions divided by the approximate northern position of the tree line. The southern parts of the IRIS region in the Yukon and the Northwest Territories are relatively warmer and more moist and are classified as Subarctic or Boreal (e.g. Kugluktuk, Inuvik and Tuktoyaktuk). The rest of the IRIS region is classified as a Polar Tundra climate, where the monthly mean temperature of the warmest month is between zero and 10°C (e.g. Kugaaruk, Cambridge Bay and Sachs Harbour).

The Canadian eco-climatic classification (EcoRegions Working Group 1989) separates the IRIS region into three zones based on climate and ecological factors: high Arctic (e.g. Prince Patrick Island), mid-Arctic (e.g. Victoria Island) and low Arctic regions (e.g. Bathurst Inlet). The three zones represent a gradient in air temperature, precipitation and vegetation, from polar desert and sparse low vegetation in the north to relatively warmer and more moist summers and a nearly continuous cover of dwarf tundra vegetation in the south.

The main factors influencing the climate of the IRIS region are the low solar energy inputs for much of the year, the sea-ice and ocean regimes, the large scale atmospheric circulation (e.g. the Polar Vortex and distance from areas with cyclonic activity), and the physical geography, vegetation and topography. These factors combine to generate distinct landscapes across the region. Most of the IRIS region is located north of the tree line and the line of continuous permafrost, has generally low relief with gently sloping terrain, and has a maximum elevation below 1000 m.



FIGURE 1. A map of the Arctic Ocean showing the ice motion and transport. The average landfast ice is shown in light blue, with the 2007 minimum sea-ice extent in green and the 2012 sea-ice minimum extent in darker blue. Adapted from Barber et al. (2015).

The IRIS region experiences seasonal snow and ice cover for almost nine months of the year with multiyear sea ice and semi-permanent snow cover patches present during the summer months. The Arctic islands in the region are considered “Arctic desert” (Maxwell 1980) because of the cold-dry conditions and low frequency of cyclone penetration; the local air temperatures are affected by the Arctic inversion resulting from the intense surface cooling over the winter period. The snowpack is characteristically shallow

and dense over the tundra because of the low frequency of precipitation, low vegetation, and high winds.

The global climate system is strongly influenced by the Arctic Ocean (Barry et al. 1993). A contributing factor to this is the overlying sea ice cover, which acts as a highly reflective barrier between the ocean and the atmosphere, limiting the heat and energy exchanges between the two (Barry et al. 1993; Barber et al 2008). The areal extent of

sea ice in the IRIS region varies annually with the maximum usually occurring in March and the minimum occurring in September (Barber et al. 2012). Regional variability and the seasonal cycle of ice conditions are influenced by complex interactions between in situ thermodynamic growth and decay and by ice transport (Lukovich and Barber 2006; Lukovich et al. 2009; Barber et al. 2012), which is in turn driven by atmospheric and oceanic forcing (Barry et al. 1993; Barber et al. 2008; Candlish et al. 2014), Figure 1.

Weather and climate regimes of the IRIS region depend on a number of features that are related to atmospheric and oceanic variability. These variability modes represent standing or slowly evolving oscillations influencing Arctic regions on seasonal to decadal time scales. In response to wind forcing, the upper-layer of the Canadian basin of the Arctic Ocean circulates in a clockwise (anticyclonic) direction. Variations in the freshwater content and strength and position of this circulation, called the Beaufort Gyre (Figure 1), alter Arctic climate on seasonal to decadal timescales by influencing the extent of sea-ice cover, surface albedo, temperature and salinity in the Arctic Ocean (Proshutinsky et al. 2009).



DOUG BARBER/ARCTICNET

2.2 Climate variables and data sources

It is a challenge to precisely characterize the climate of the IRIS region because of the uneven coverage of observations. Climate stations are far apart and many are opened and closed for different times and in different locations. Moreover, climate data are subject to random and systematic errors related to observers, instrumentation, and changes in measurement sites and observing procedures. Satellite data can help fill in the gaps in surface networks for some variables, e.g. surface temperature, sea ice and snow cover (Helfrich et al. 2007; Takala et al. 2011), but the period of coverage tends to be relatively short and there are few surface observations for validating satellite products over large areas of the IRIS region. Although a number of reanalysis products (reanalysis data is a combination from different historical datasets, typically weather balloons combined with station or buoy observations and satellite data) are also available over the IRIS region for various periods and resolutions, these products can include problems related to changing sources of information. The following chapter presents a summary of observed climate trends in temperature (over land and ocean surfaces), permafrost and ground temperature, precipitation, snow cover, and wind and storms. The challenges of using these data emphasize the need for local Traditional Knowledge, and using multiple sources when evaluating changes in climate and their implications.

Terrestrial based temperature data and corresponding precipitation data (Mekis and Vincent 2011; Vincent et al. 2012) are summarized below for the description of trends over land. The precipitation data have been adjusted for a range of known measurement issues including wind undercatch as well as estimates of regional variation in the water equivalent of snowfall from ruler measurements. These adjustments have substantially increased the recorded solid precipitation amounts over the Arctic region.

Although limited records dating back to the 1920s are available (Skinner and Gullet 1993), consistent collection of meteorological data over the Canadian Arctic Islands did not begin until 1947 (Maxwell 1980). Daily climate

observations of temperature and precipitation are available at most communities in the region, but the length and period of observations are quite variable. For example, in the homogenized monthly air temperature dataset of Vincent et al. (2012) only Baker Lake, Kugluktuk and Cambridge Bay have more-or-less continuous temperature data available from 1950 to date. The number of stations peaked at 14-16 in the 1968-1977 and 1995-2007 periods, but fewer stations were present during other time periods - this limits the data available for characterizing the climate and examining climate trends. A total of 10 climate stations are available with more-or-less complete temperature data in the 1971-2000 climate normal period; the more recent 1981-2010 climate normal period is characterized by fewer stations with complete data.

The spatial distribution of climate stations within the IRIS region has a noticeable western bias (a major cluster of stations in the Mackenzie Delta and the Beaufort Sea coast) with most stations located in coastal communities. Coastal locations typically have cooler summer temperatures than inland locations because of the influence of cold water and sea ice (e.g. Tuktoyaktuk summer temperatures are on average almost 3°C colder than Inuvik located ~130 km inland from the coast – Table 1). A concentration of stations occurred along the DEW Line (Distant Early Warning Line – a network of radar stations across the Canadian Arctic) with only three additional widely-separated stations (Mould Bay, Sachs Harbour and Cambridge Bay) representing the climate of the Canadian Arctic Islands in the region. Some stations adjacent to the IRIS region (e.g. Baker Lake) have been included to supplement the small amount of data available.

For data over the ocean, temperature averages and trends were calculated using the National Centres for Environmental Prediction (NCEP) Reanalysis 1 monthly mean temperature (<http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html>). The spatial coverage is based on a grid with spacing of 2.5 degrees latitude by 2.5 degrees longitude (144x73). The NCEP/NCAR (National Centre for Atmospheric Research) Reanalysis 1 project uses

a forecast system to incorporate observations from 1948 to the present. The dataset is a combination and interpretation of land surface, ship, rawinsonde (weather balloons), pibal (pilot balloons), aircraft, satellite and other data.

Two gridded precipitation datasets were used to examine precipitation over the IRIS region: the Canadian Gridded Temperature and Precipitation Anomalies (CANGRD) dataset (Zhang et al. 2000) for land areas and the Global Precipitation Climatology Project (GPCP) dataset (Adler et al. 2003) for marine areas. CANGRD is considered one of the best currently available precipitation datasets over land in the Canadian Arctic. The latest version of the CANGRD dataset uses climate station data corrected for undercatch and regional variations in snowfall density following previously tested methods (Mekis and Vincent 2011). GPCP is the only observation-based data available for precipitation over the marine environment. GPCP is a merged analysis using precipitation estimates from satellite data and surface measurements. It should be noted that the accuracy of GPCP precipitation depends strongly on the quality of satellite data, which can be rather low over the Arctic (Serreze et al. 2005).

Weekly regional ice data for the Canadian Arctic were obtained from the Canadian Ice Service (CIS) using the IceGraph Tool 2.0.4 (<http://www.ec.gc.ca/glaces-ice/>). The data are from the Canadian Ice Service Digital Archive - Regional Charts collection. The tool gives regionally averaged values from the ice charts based on the predefined ice regions and the specified date range (1981-2010). The ice charts are produced for tactical planning and operational purposes and represent an estimate of the ice conditions at the time of production (MANICE 2005). Production of the ice charts integrate all the information available at the time, including but not limited to weather conditions, visual observations and satellite/aircraft imagery, to characterize the sea-ice conditions in the Arctic. Throughout the study period, the quality and quantity of information used to produce the ice charts has improved (i.e. after 1995 with the inclusion of RadarSat-1 data) and thus may impact the quality of the sea-ice information. These data have been used effectively in previous studies examining the spatial and temporal sea-ice

TABLE 1. Temperature climatologies for the 1981-2010 period from stations in and adjacent to the IRIS region with 19 years or more of complete monthly data in the dataset of Vincent et al. (2012).

STATION	LAT (°N)	LONG (°W)	ELEV (M)	MEAN ANNUAL AIR TEMP (°C)	MEAN MONTHLY MIN AIR TEMP (°C)	MEAN MONTHLY MAX AIR TEMP (°C)
Baker Lake	64.3	96.1	18	-11.1	-32.7	11.9
Lupin	65.8	111.3	488	-10.8	-31.1	11.5
Kugluktuk	67.8	115.3	23	-10.0	-29.4	11.1
Inuvik	68.3	133.5	103	-8.1	-28.8	14.2
Kugaaruk	68.5	89.8	17	-13.3	-34.9	9.4
Cambridge Bay	69.1	105.1	27	-13.7	-33.7	9.0
Tuktoyaktuk	69.4	133.0	18	-9.5	-28.1	11.5
Cape Parry	70.2	124.7	17	-11.1	-29.0	6.7
Sachs Harbour	72.0	125.3	86	-12.4	-30.1	6.9
Mould Bay	76.2	119.3	2	-16.8	-34.8	4.2

characteristics in the Arctic (e.g. Stirling et al. 1999; Agnew and Howell 2003; Barber and Iacozza 2004; Gagnon and Gough 2005; Howell et al. 2008b; Galley et al. 2008; 2013).

Winds (north-south and east-west components) were obtained from the NCEP North American Regional Reanalysis (NARR) dataset (<http://www.esrl.noaa.gov/psd/cgi-bin/data/narr/>), with a grid resolution of 32 km at the lowest latitude and a three-hour sampling interval (Mesinger et al. 2006). The NARR model is an extension to the NCEP global reanalysis project and covers 1979 to the present. Seasonal averages were generated using the online analysis tools provided by the NOAA/ESRL (Earth System Research Laboratory) Physical Science Division, Boulder, Colorado (<http://www.esrl.noaa.gov/psd/>) and were computed over the 1981-2010 period with annual anomalies computed with respect to the 1979-2001 climatological mean.

Assessment of variability and change in storm frequency and intensity over the IRIS region was based on a review of previous studies (Serreze 1995; Simmonds and Keay 2009) and analysis of cyclone tracks and characteristics using the cyclone tracking algorithm of Serreze (2009). Dataset parameters include the total number of daily cyclone systems, position and cyclone central pressure, distance traveled by

cyclone, determination of a cyclogenesis (development of a cyclone) or cyclolysis (deterioration of a cyclone) event, and the cyclone intensity.

2.3 Observed variability and change in climate

2.3.1 Air temperature

The Intergovernmental Panel on Climate Change (2013) reported that increases in surface air temperature have ranged from 1 to 3 degrees in the Arctic over the last decade. The accelerated decline in Arctic sea-ice extent and thickness highlights the impact of warming at high latitudes (IPCC 2013). Overland et al. (2008) believe that the recent Arctic warm period and the accelerated changes in sea ice are unprecedented. The Arctic ocean-sea ice-atmosphere interactions are part of a feedback loop. As the atmosphere warms, snow and ice cover will melt, leading to a decrease in surface albedo and an increase in the absorption of solar radiation at the surface (the ocean is darker and thus absorbs more radiation than the ice and snow). This will in turn increase the ocean temperature and further melt the ice. In addition, the warmer ocean then affects the atmosphere and

moderates the temperatures to promote further warming in the cold seasons (Uttal et al. 2002; Curry et al. 1996). In the subsequent sections, observed trends in temperature over terrestrial and marine areas are described separately.

Terrestrial air temperatures

The CANGRD 50-km gridded temperature and precipitation dataset (Zhang et al. 2000) was used to characterize the spatial and temporal variability in seasonal air temperature over the IRIS region. This dataset is based on the adjusted homogenized station data of Vincent et al. (2012) and the adjusted precipitation data from Mekis and Vincent (2011)

and takes account of topography and distance from the ocean in the interpolation process.

Terrestrial air temperatures in the IRIS region exhibit a strong north-south gradient, with the warmest temperatures occurring in the southwest (Mackenzie Valley) and the coldest temperatures over the uninhabited northern islands (Figure 2). The mean annual air temperature, observed across the eight climate stations in the IRIS region, and two nearby stations, with long-term data, tends to decrease with increasing latitude (to the north) and to increase with increasing longitude (to the west). Of these two trends, latitude exerts the strongest influence on the temperature.

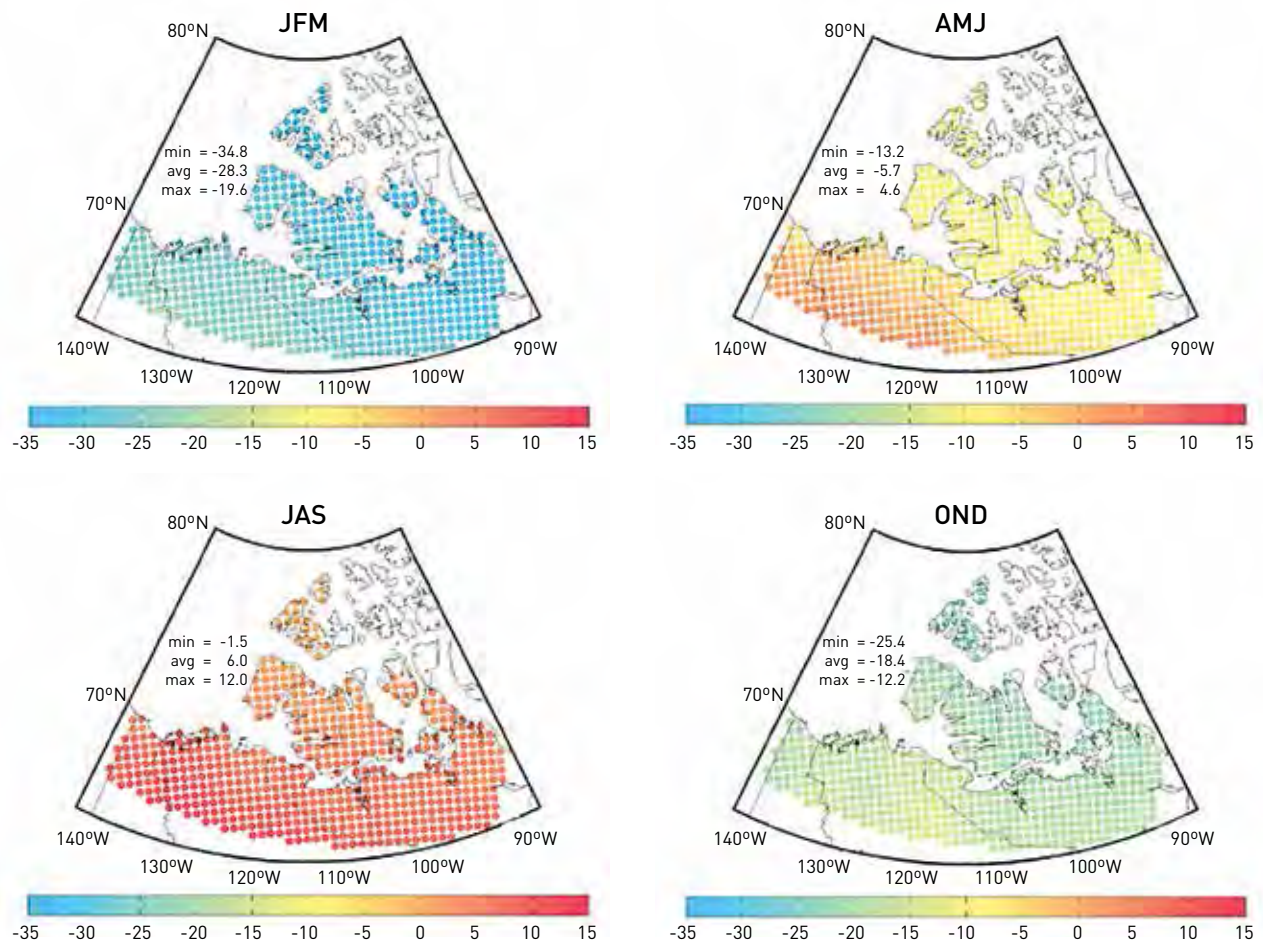


FIGURE 2. Spatial variation in 1981-2010 seasonal mean air temperatures over the IRIS region from the CANGRD dataset. The regionally-averaged mean temperatures are: winter (-28.3°C), spring (-5.7°C), summer (-1.5°C), and fall (-18.4°C).

Table 1 gives mean temperature values for the climate stations in the IRIS region with 19 years or more of complete temperature data during the 1981-2010 period in the dataset of Vincent et al. (2012). Of the stations summarized in Table 1, the warmest average annual air temperature (-8.1°C) is observed at Inuvik in the Mackenzie Delta and the coldest (-16.8°C) at Mould Bay on Prince Patrick Island. The difference in the two stations is largest during the summer period (Figure 3) with a maximum difference in mean daily air temperature of 10°C in July. The seasonal curves in Figure 3 also highlight the influence of the ocean (sea ice) on the climate of the Arctic Islands, with a much shorter period of above-freezing temperatures (June-August) at Mould Bay compared to Inuvik (May-September).

Figure 4 shows the regionally averaged seasonal air temperature over the IRIS land area for the period from 1950 to

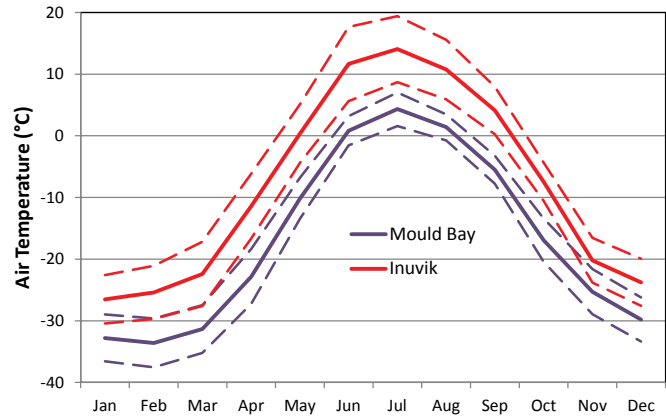


FIGURE 3. 1981-2010 mean monthly minimum, maximum and average temperatures for Mould Bay and Inuvik, the coldest and warmest stations in the IRIS region with 20 years or more of complete data in the averaging period.

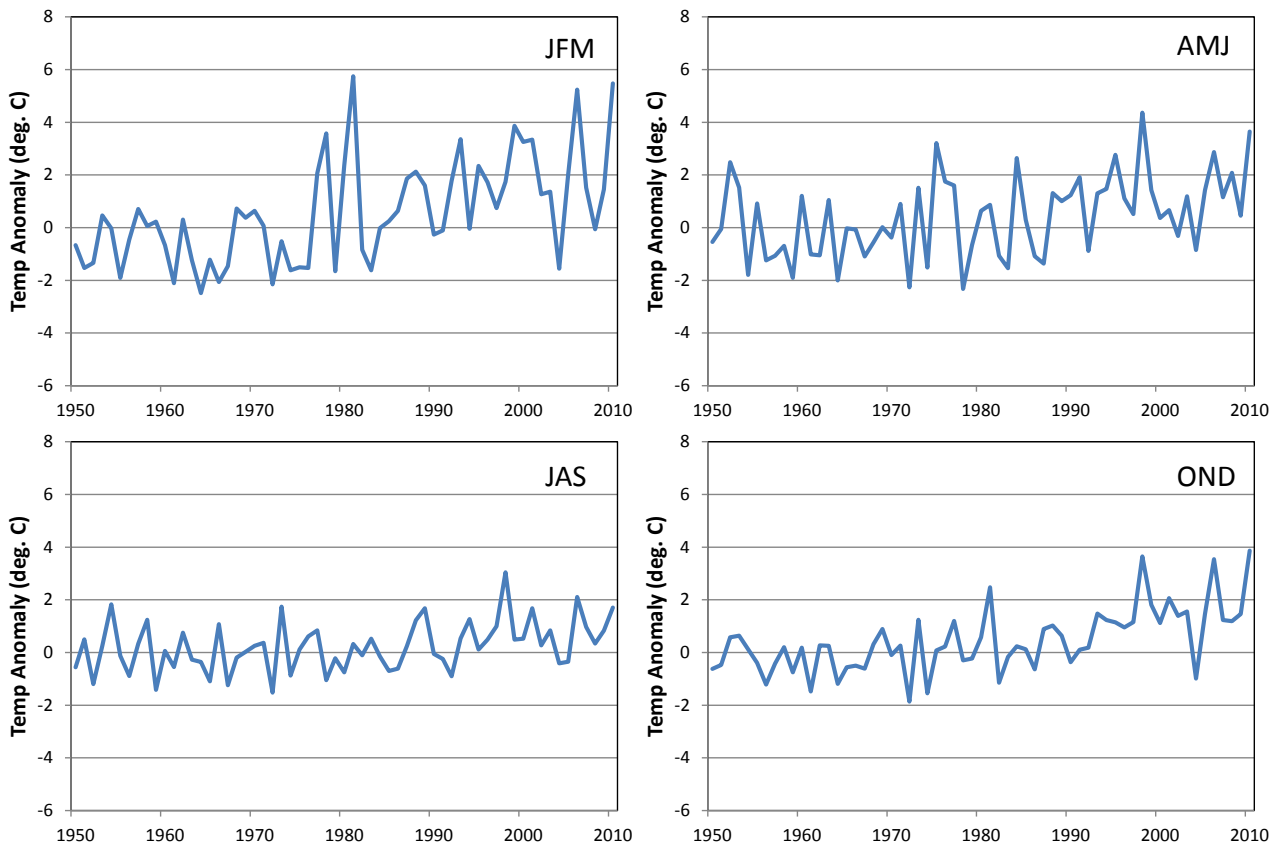


FIGURE 4. Regionally-averaged time series of seasonal mean daily air temperature over the 1950-2010 period from CANGRD. Values are anomalies with respect to a 1961-1990 reference period.

2010. The seasons were defined as follows: winter: January-March (JFM), spring: April-June (AMJ), summer: July-September (JAS), and fall: October-December (OND). The CANGRD dataset provided the data in this figure.

The results shown in Figure 4 indicate that the current warming is a relatively recent phenomenon occurring after ~1980 in winter, spring, and summer, and after ~1990 for the fall season. All four seasons have significant warming trends over the 60+ years, with the strongest warming in winter (0.63°C per decade) and fall (0.47°C per decade), followed by spring (0.35°C per decade) and summer (0.19°C per decade). Analysis of trends in the dataset of Vincent et al. (2012) shows that the coldest monthly air temperatures have increased at a much faster rate and more linearly (0.85°C per decade) than the warmest monthly air temperatures (0.27°C per decade). This contrast in the temperature changes between warm and cold months is also apparent in trend results for individual stations (Table 2).

The more rapid warming observed in the colder months, especially in winter, is consistent with Inuit Traditional Knowledge of fewer winter extreme cold temperatures at many communities in the IRIS region. The observations are also consistent with trend analysis results presented in Vincent et al. (2012) and with climate model projections of warming (Kharin et al. 2007) that show cold extremes warming faster than warm extremes over regions with snow and ice cover.

Nine of the 10 warmest monthly average air temperatures of the 1950-2012 period in the IRIS region have occurred since 1997. The 1998 extreme high temperature, which was the 2nd warmest monthly average air temperatures after 2010, was particularly noteworthy for the large changes in the cryosphere that occurred in response to the exceptionally long melt season (Atkinson et al. 2006). That year (1998) in fact had the longest period of above-freezing temperatures in the 1950-2012 period, with 140 days above freezing compared to the 116 days for the 1950-2012 average. However, 2010 was the warmest year overall. Finally, the period prior to 1975 was characterized by relatively cold

temperatures (7 of the 10 coldest years occurring prior to 1975) with the coldest monthly average air temperatures observed in 1974.

Figure 5 below illustrates the regionally averaged values of thaw- and freeze-onset dates over the period 1950 to 2012 from the temperature data of Vincent et al. (2012). The thaw-onset date was defined as the first day in the spring when the average of that day's temperature and the temperature of the seven days before and after is above zero; this type of analysis is called a "running average". The freeze-onset date is the first day that the running average is below zero. The time between thaw- and freeze-onset is often referred to as the thaw season. As can be seen in Figure 5, only small changes are observed in the thaw-onset and freeze-onset dates over the 60-year period. However, the combined influence

TABLE 2. Linear trends in average annual air temperature (the change in temperature with time) and the warmest and coldest months in the year over the 1981-2010 period for the stations in Table 1. Trends are given per decade with statistically significant trends (0.05 level) indicated with an asterisk. A station was required to have at least 20 years data in the period to compute the trend.

STATION	TREND IN AVERAGE ANNUAL AIR TEMP [°C PER 10 YEARS]	MEAN MONTHLY MIN AIR TEMP [°C PER 10 YEARS]	MEAN MONTHLY MAX AIR TEMP [°C PER 10 YEARS]
Baker Lake	0.68*	0.71	0.47
Lupin	0.86*	1.22	0.59
Kugluktuk	0.76*	1.27*	0.27
Inuvik	0.82*	2.11*	-0.19
Kugaaruk	1.21*	1.64*	0.99*
Cambridge Bay	0.69*	1.19*	0.59
Tuktoyaktuk	n/a	n/a	n/a
Cape Parry	0.52	0.68	0.26
Sachs Harbour	0.78*	0.85	0.19
Mould Bay	0.83*	0.99	0.42

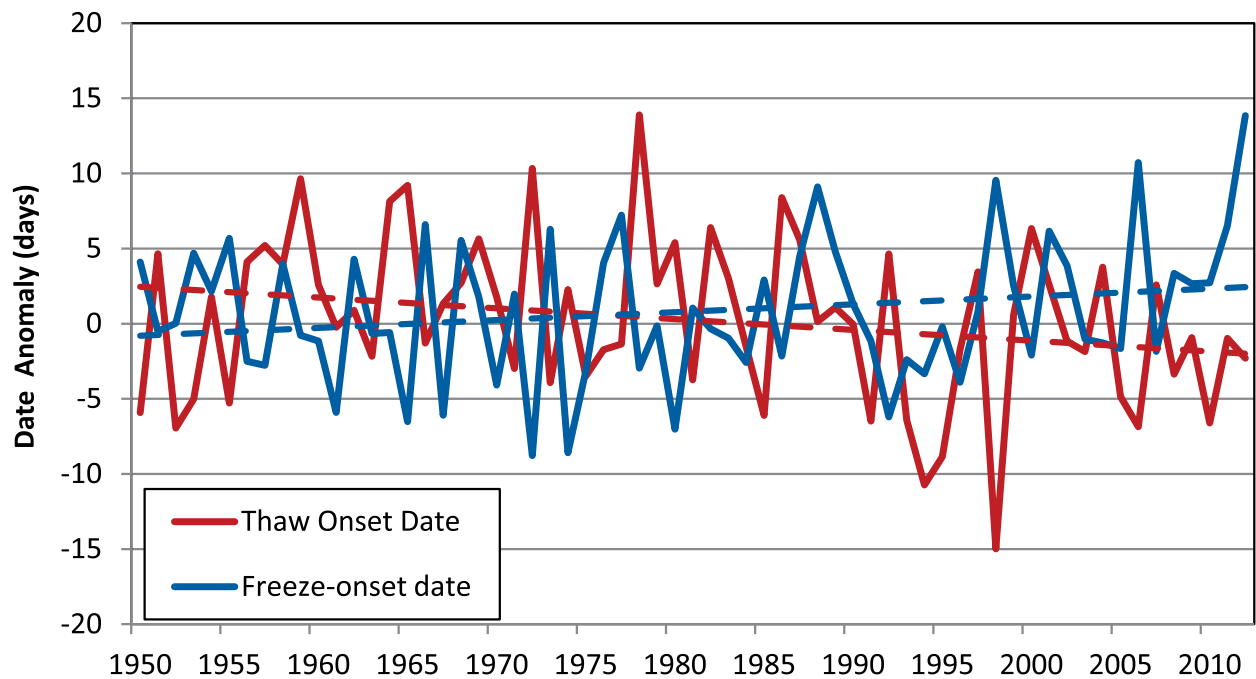


FIGURE 5. Regionally-averaged anomaly series of thaw-onset and freeze-onset date from 16 climate stations in the daily homogenized dataset of Vincent et al. (2012). Anomalies are computed with respect to a 1971–2000 reference period. The least-squares trend is shown as a dashed line.

of the earlier thaw and later freeze contributes to a statistically significant increase in the thaw season duration of 1.2 days per decade over the 1950–2012 period.

The trend results discussed above are influenced by a gradual cooling of fall and spring temperatures occurring through 1950 to the end of the 1970s (Figure 4). If the effect of this cooling period is removed and analysis is computed for the years 1980–2012, more trends can be seen. A significant trend to later freeze-onset dates of 2.0 days per decade is observed. Furthermore, while the thaw-onset date does not show any significant trend over the 1980–2012 period, it does contribute to a statistically significant increase in the duration of the thaw season of 3.3 days per decade. This observation supports the assertion that the rate of warming has accelerated since the 1980s in the IRIS region.

The spatial pattern of the warming has also changed in the period since 1980. The long-term warming trend from 1950 has the strongest warming over inland regions of

the western Arctic in winter. However, the warming since 1980 is more marked over the Canadian Arctic Archipelago (CAA) and the eastern Arctic, with the strongest warming trend observed for the fall season (Figure 6). This pattern reflects the recent rapid warming and sea-ice loss taking place across the Arctic (Serreze and Barry 2011) and the end of the 1970s cooling over the North Atlantic region (Thompson et al. 2010) that influenced temperature trends over the eastern Arctic.

Marine air temperatures

NCEP reanalysis data from 1981–2010 were obtained in order to examine maritime air temperature trends and variability. The IRIS region was divided into eight areas pre-defined by the Canadian Ice Service (Figure 7; Canadian Ice Service (CIS)). These areas are based on the local sea-ice characteristics and climatology. The eight CIS regions within the IRIS region are the Beaufort Sea, the Western High Arctic, Eastern High Arctic, the Western Parry Channel,

Eastern Parry Channel, M’Clintock Channel, Franklin and the Western Arctic Waterway (Figure 7). All data were spatially averaged to fit into the CIS regions and temporally averaged by month.

For each of the eight predefined regions the 1981-2010 monthly averages were given for surface air temperature (Table 3). The 1981-2010 average for the surface air temperatures of the Beaufort Sea region showed the moderating effect of the ocean, with the warmest temperatures in the

winter and cooler temperatures in the summer compared to the surrounding regions. During the ice-covered months even small amounts of open water influence air temperatures throughout the nearby region (Raddatz et al. 2011). The two types of open water in winter are “flaw leads” which occur between ice fastened to the land (“land fast ice”) and the ocean’s pack ice, and “polynyas” which are areas of open water surrounded by sea ice at a time and location when you expect it to be ice covered (Barber and Massom 2007).

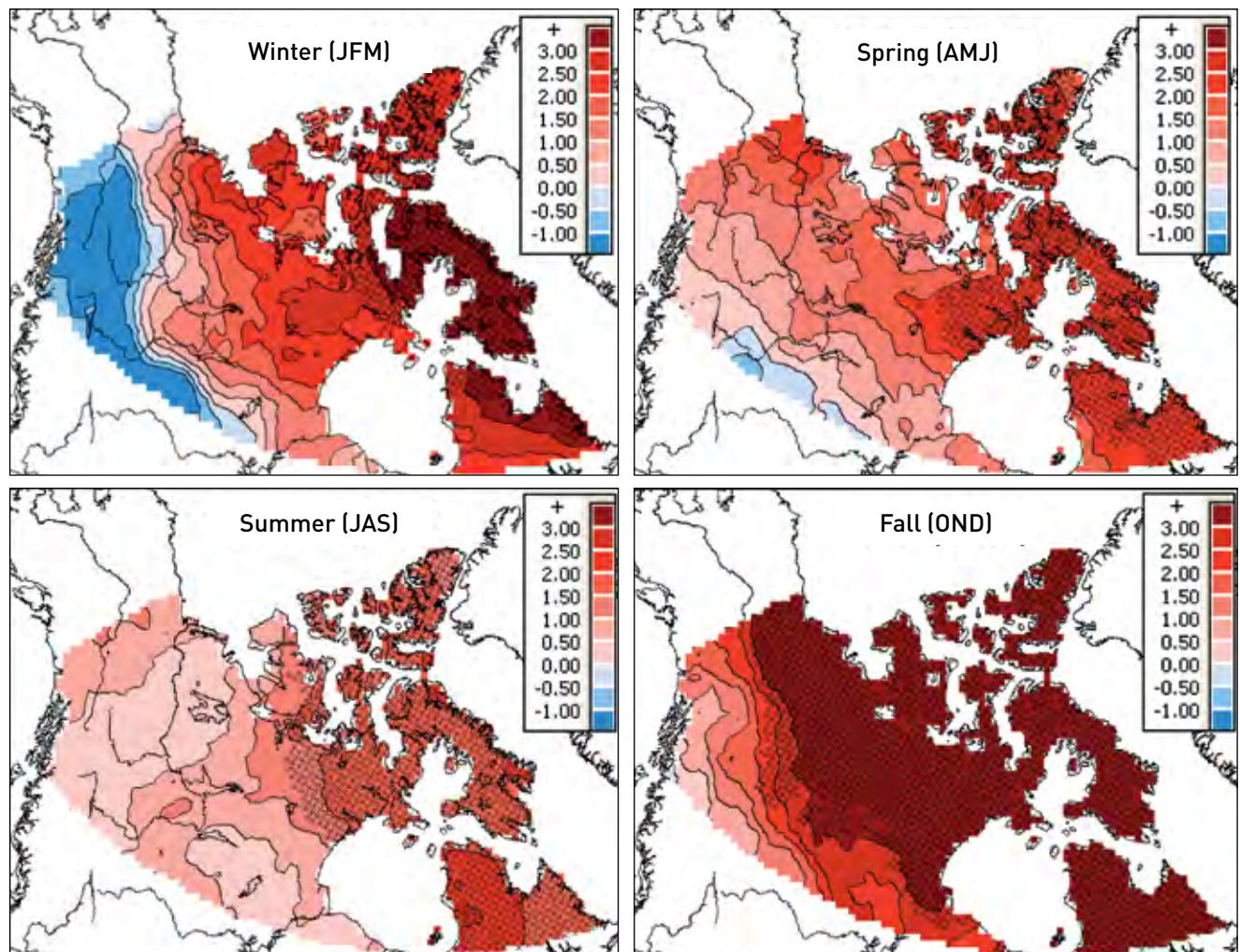


FIGURE 6. Observed warming in CANGRD seasonal air temperatures over 1981-2010 from Mann-Kendall estimates of trend. Grid points with locally significant trends are indicated with an “x”.

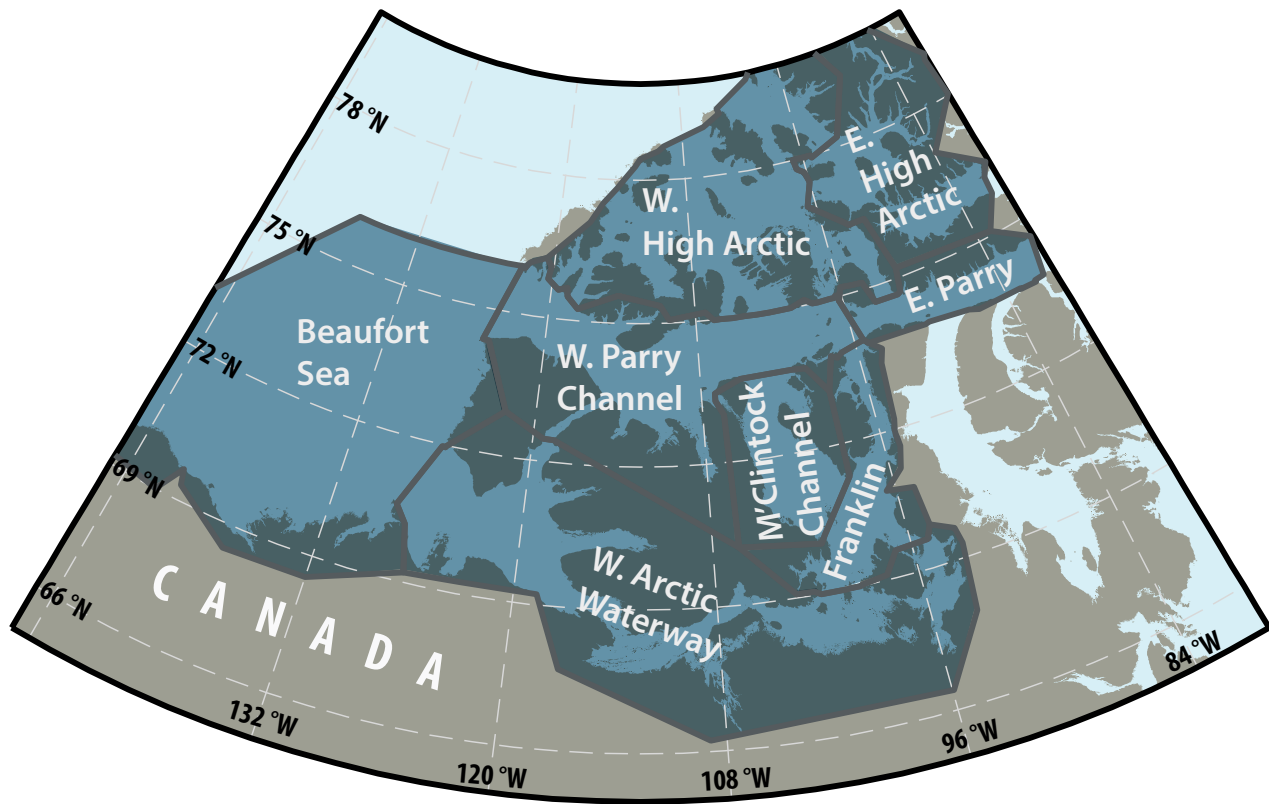


FIGURE 7. A map of the Canadian western high Arctic with the Canadian Ice Service regions highlighted. From Candlish et al. (2014).

TABLE 3. The 1981-2010 average monthly surface air temperatures (°C).

	BEAUFORT SEA	W. HIGH ARCTIC	E. HIGH ARCTIC	W. PARRY CHANNEL	E. PARRY CHANNEL	M'CLINTOCK CHANNEL	FRANKLIN	W. ARCTIC WATERWAY
Jan	-25.8	-29.6	-29.0	-29.1	-30.6	-30.6	-31.4	-28.5
Feb	-25.7	-29.9	-29.6	-29.2	-30.4	-30.4	-31.1	-28.0
Mar	-23.6	-27.8	-28.1	-26.7	-27.9	-27.3	-27.1	-23.9
Apr	-15.3	-19.5	-19.3	-18.2	-18.7	-18.7	-18.1	-14.4
May	-5.4	-8.5	-7.9	-8.0	-7.9	-8.6	-8.2	-5.4
Jun	2.8	0.8	1.3	1.0	1.1	0.8	1.3	3.5
Jul	5.4	3.2	3.8	4.1	3.7	4.8	6.7	10.1
Aug	3.2	0.7	1.1	1.4	1.7	2.4	4.3	7.1
Sept	-1.4	-6.3	-6.6	-4.3	-3.9	-3.5	-2.2	-0.1
Oct	-10.4	-16.3	-16.2	-14.1	-13.6	-14.3	-13.5	-10.3
Nov	-20.5	-23.1	-23.0	-23.4	-22.7	-23.6	-24.1	-21.4
Dec	-24.2	-26.9	-26.6	-27.8	-27.2	-28.0	-28.4	-26.2

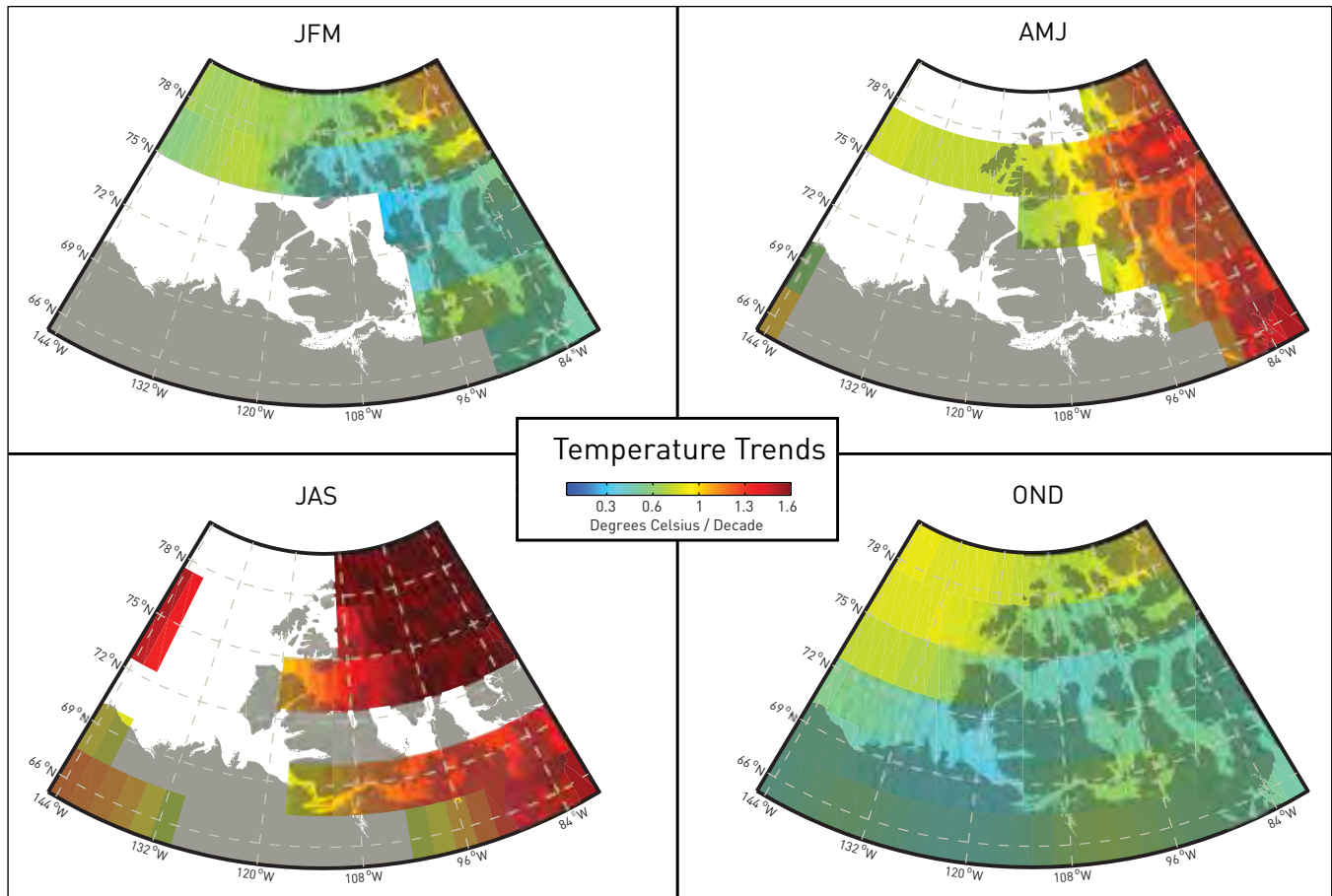


FIGURE 8. Temperature trends in the western and central Canadian Arctic. Only statistically significant trends are shown. Data from the 1981-2010 NCEP reanalysis.

The Western High Waterway region had the warmest average summers with July having normal temperatures of 10.1°C and August with 7.1°C. The Franklin Channel region had the next warmest summers. The coldest summers occurred in the Western High Arctic with normal temperatures of 3.2°C for July and 0.7°C for August. All regions had similar winters with the coldest temperatures typically in January ranging from -25.8°C in the Beaufort Sea to -31.4°C in the Franklin Strait region.

The seasonal air temperature trends for 1981-2010 are shown in Figure 8. For the winter season (JFM), only moderate increasing trends were seen in the northern and eastern part of the IRIS region. Similarly, during spring (AMJ), increasing temperatures were found in the northeast part of the IRIS region over the 30-year period from 1981 to 2010. The increasing temperature trend was more apparent in this quadrant in summer, with the largest positive trend rising nearly 6° over the 30-year period. In the fall, temperatures exhibited moderate warming trends over the general study area.

2.3.2 Permafrost and ground temperature

The term “permafrost” refers to ground (either soil or rock) which has remained at temperatures below 0°C for at least two years. Permafrost depth can range from as little as 1 metre to more than 1 kilometre below the surface. Some sections of permafrost are hundreds or even thousands of years old, while other areas are more recently frozen. There is often a ground layer between permafrost and the atmosphere that undergoes freezing and thaw on an annual basis, called the “active layer”. The active layer can moderate the interaction between permafrost and the atmosphere, influencing the condition of the permafrost. The condition of an area’s permafrost is both ecologically and socially important, as the frozen ground can be an important foundation for natural habitat and human infrastructure (see Chapter 7). Permafrost is typically classified according to its geographic continuity: “continuous permafrost” describes regions where permafrost underlies nearly all of the landscape. “Discontinuous permafrost” underlies only some fraction of the landscape while other areas are unfrozen (Anisimov et al. 1997). With the exception of the Mackenzie River Delta, continuous permafrost underlies the entire IRIS land area (Chapter 7, Figure 4).

Permafrost provides information about the recent past climate and, in some cases, climatic information going back several hundred years. The temperature-dependent condition, or “thermal state”, of permafrost is a response to air temperature, the insulating properties of the surface (snow cover and vegetation), and the flow of heat below the Earth’s surface. Precipitation (frozen and unfrozen) has also been shown to exert a strong influence on permafrost temperature (Stieglitz et al. 2003).

The thermal state of permafrost is a good indicator of its stability. Permafrost stability, both present and future, is an important climate related concern in northern societies. Because permafrost is the foundation for infrastructure (e.g. runways, roads and buildings), the monitoring of changes in its thermal state is important for community development

and sustainability (see Chapter 7). Furthermore, basic human needs are affected by changes in permafrost because increased ground temperatures and thaw depths can lead to reductions in drinking-water quality (see Chapter 8). For example, permafrost thaw slumps have increased the amount of sediment and solute in the streams (Kokelj et al. 2013). Kokelj et al. (2010) also found that an increase of shrubs in disturbed areas can trap snow, which in turn warms the ground. Changes in permafrost can jeopardize food supplies and storage sites, as traditional community freezers are highly dependent on permafrost temperature (see Chapter 8). Finally, concern is growing as tailings and other mining deposits buried in frozen ground begin to thaw (Thienpont et al. 2013).

The following sections present information on historic variability and trends in northern permafrost, the recent thermal state of permafrost in the IRIS region, and projections for ground temperatures and permafrost condition to 2050.

Historical ground thermal state

Permafrost temperature, depth, and extent have varied considerably over the pan-Arctic region during the past ten thousand years. Paleoclimatic records and permafrost observations from across the Arctic indicate that permafrost has been in a predominantly thawing state since the last glacial maximum roughly 22,000 years ago; the rate of thawing has varied based on regional climate.

Paleoclimatic records in the Canadian Arctic are in broad agreement with the observed permafrost data (Besonen et al. 2008; Kaufman et al. 2009). Summer temperature reconstruction from ice core data indicates that 1850 was the coldest year in the last 1000 years (Koerner and Fisher 1977; Kaufman et al. 2009). Other studies, using data from deep boreholes (Overpeck et al. 1997; Taylor et al. 2006), confirm that high Arctic permafrost temperatures have increased since the middle of the 19th Century. This is again shown in a study by Besonen et al. (2008), which looked at sediment cores from a lake in the Canadian Arctic Archipelago.



ISABELLE DUBOIS/ARCTICNET

Recent changes in ground thermal state

The recent ground temperature trends have been correlated with latitude: ground temperatures have tended to increase more rapidly at higher latitudes (to the north) (Derksen et al. 2010; Romanovsky et al. 2010). During the International Polar Year (2007 to 2009) several boreholes were established in the IRIS region with the results presented by Smith et al. (2010). The spatial distribution of boreholes is very uneven with most located in the Mackenzie Delta (Smith et al. 2010). Since the 1980s, ground temperatures have only modestly warmed-up in the discontinuous permafrost of the southern and central Mackenzie valley (increases of up to 0.2°C per decade). Further north, ground temperature trends of the western Arctic's continuous permafrost zone showed clear evidence of greater warming rates of 0.8°C per decade (Derksen et al. 2012).

On Garry Island in the outer Mackenzie Delta plain of the Inuvialuit Settlement Region, a ground temperature warming of approximately 1°C has been observed since the 1970s (Smith et al. 2005, 2010; Burn and Kokelj 2009). Near Inuvik, mean annual ground temperatures have increased roughly 1.6 to 3°C since 1960 from an initial temperature of roughly -4.6°C (Burn and Kokelj 2009). According to Smith et al. (2010), since the 1960s and early 1970s the greatest increase in mean annual ground temperature in the Mackenzie Delta region has occurred in the outer delta plane, where temperature changes of more than 2°C have been recorded. This temperature rise has brought the area's typical mean annual ground temperatures above -2.5°C (Smith et al. 2010).

In Tuktoyaktuk, on Richards Island and in Paulatuk a significant warming of the permafrost's upper layers has been observed and is in the range of other pan-Arctic

measurements (Smith et al. 2010). Measurements taken at greater depths (24 to 29 m) show temperature changes ranging between 0.2 and 0.6°C per decade during the 1989 to 2003 period (Smith et al. 2005). Thaw depths were also examined in the area of Tuktoyaktuk and the observed increases in ground temperature were not found to be associated with any increase in thaw depths. This is in contrast to the increased thaw depths that have been observed in Scandinavia, the Russian Arctic, and the Eastern Canadian Arctic (Smith et al. 2010; Callaghan and Johansson 2011).

Data taken from a 42 m deep borehole at Hershel Island off the Yukon coast have also shown increases in ground temperature throughout the 20th Century (Burn and Zhang 2009; Smith et al. 2010). Between 1899 and 2006 the mean annual ground temperature at a depth of 20 m increased by 1.9°C (from -10.2°C to -8.3°C). At this location, the snow cover is thin (< 25 cm) and the ground thermal response is closely tied to air temperature.

Active layer thickness has only shown progressive increases in the interior of Alaska (Viereck et al. 2008). In the IRIS region, active layer thickness appears to be relatively stable, with negligible increases or decreases compared to the maximum reached in 1998 (Burn and Kokelj 2009). In cases where permafrost is ice-rich, changes in the active layer thickness can be masked by the melting of ice lenses (water frozen into large void spaces in the ground) (Nixon et al. 2003).

Changes in air temperature, snow cover and duration, and vegetation are all interacting to influence ground temperatures in the IRIS region. On a pan-Arctic scale, studies indicate that tundra plant biomass has increased by roughly 20% over the past 30 years (Epstein et al. 2012). These results are consistent with Traditional Knowledge observations in the Inuvialuit Settlement Region (Community of Aklavik et al. 2005). It is not obvious what effect these changes in biomass will have on permafrost, as different types of vegetation exert different influences on ground temperature and the effects of plant cover can be difficult

to separate from those of air temperature and snow cover (Romanovsky et al. 2010).

There is little data available examining the spatial distribution and change in extent of permafrost over the Western Canadian Arctic. Permafrost degradation (which involves warming to the point of permafrost erosion or loss) over the last century and half has mostly affected discontinuous permafrost south of the IRIS region (Beilman and Robinson 2003; Callaghan and Johansson 2011).

Projected changes in ground thermal state

Currently, near-surface permafrost temperatures in the zone of continuous permafrost lie between -15 and -2°C. However, temperatures below -10°C are limited to the Canadian Arctic Archipelago and high-elevation areas. Permafrost temperatures along the coast of mainland Alaska and Yukon territories are typically between -10 and -5°C, while temperatures between -5 and -2°C occur farther inland towards the south (Smith et al. 2010).

Projections for the Alaskan and Canadian Arctic coasts generated in 2005 indicate that permafrost near surface temperatures could increase between 2 and 2.5°C by 2050 (with a reference period of 1981-2000). These projections rely on several assumptions, including that mean annual air temperature will increase 2 to 3°C by 2050 (Walsh et al. 2005); this assumed temperature increase is within current scientific expectations for atmospheric warming. For details about the model see Walsh et al. (2005) in Arctic Climate Impact Assessment (2005).

More recent efforts in ground thermal modeling (details in Marchenko et al. 2008, 2009) showed that ground temperature at 2 m depth on the coast of the Northwest Territories could rise about 2°C for the 2013- 2050 period compared to the 1991-2010 reference period (Callaghan and Johansson 2011). These projections assume a mean air temperature increase of approximately 2.2°C by 2050. For more details about the permafrost modelling used here see Marchenko et al. (2008, 2009)

At the Canadian scale, climate projection outputs extending as far as 2090 showed that the mean annual air temperature in the continuous permafrost zone should remain sufficiently cold to maintain the presence of permafrost despite air temperature increases. However, the extent and depth of permafrost is projected to decline during this time (Zhang et al. 2008). Moreover, increases in the active layer thickness on the order of 14-30% (relative to 1991-2010) are projected to occur in the continuous permafrost region by 2050 (Zhang et al. 2008). In absolute values, the increases are approximately 2 to 20 cm depending on the model parameters. These results are in agreement with other studies in the Canadian Arctic (Anisimov et al. 1997; Stendel and Christensen 2002). In summary, at the projected time scale of interest (2050), continuous permafrost is not projected to disappear.

Changes in ground thermal state are expected to have important impacts on climate at the regional and global scale through the release of greenhouse gases (ACIA 2005; IPCC 2007). Carbon dioxide (CO₂) and methane (CH₄) concentrations at depth have recently been revealed to be much larger than previously expected (Bockheim 2007; Bockheim and Hinkel 2007; Callaghan and Johansson 2011). Nevertheless, the net effects of permafrost thawing on CO₂ releases are not clear (Lupascu et al. 2014; Natali et al. 2014). Many factors could affect the direction of feedbacks to the climate system. Such factors are mostly related to the wetness (or dryness) of the landscape, which are highly variable at the Northern Hemispheric scale. In this context, dry and well-drained landscapes are considered likely to become sources of carbon while poorly-drained and cold landscapes will likely become carbon sinks. According to regional projections, tundra regions at the Arctic scale should remain weak carbon sinks through the 21st Century (Euskirchen et al. 2006; McGuire et al. 2009; Callaghan and Johansson 2011).

2.3.3 Precipitation

Precipitation is difficult to measure. The measurement of solid precipitation, such as the snow and hail occurring in the Arctic, is particularly difficult as measurements are subject to many systematic errors (Goodison et al. 1997). It is even more challenging in the Arctic where the winter precipitation regime is characterized by frequent trace events and high wind speeds. The measurement of precipitation in the marine environment is also a challenge and the few data sets available tend to be based on short field projects. These challenges and limitations must be kept in mind when considering conclusions made from precipitation data in the Arctic.

Precipitation over land

Total precipitation exhibits a northwest-southeast gradient over the region (Figure 9 and Table 4). The largest annual totals (~350-375 mm) were observed in the southeast (Kugaaruk and Baker Lake) and the smallest totals (~175-200 mm) are observed in the west (Tuktoyaktuk and Ulukhaktok). This pattern reflects the large-scale gradient in atmospheric water content over the Canadian Arctic, which has a low water content over the Arctic Ocean and a high content over southeastern Baffin Island (Maxwell 1980). Seasonal trends in precipitation are relatively uniform over the region, with relatively low precipitation in the colder months and higher precipitation in the summer. More than half of the annual precipitation falls in the July to October period (Figures 9 and 10).

The amount of precipitation at any location is controlled by the average moisture content of the air, the proximity to moisture sources and weather systems, and topographic influences (mountains or local terrain). The islands of the IRIS region are the farthest from moisture sources and are classified as “polar desert” (Maxwell 1980). In this environment, precipitation varies year to year and is influenced by changes in the location and number of storms and by the presence of local moisture sources such as polynyas and flaw leads in the winter ice pack.

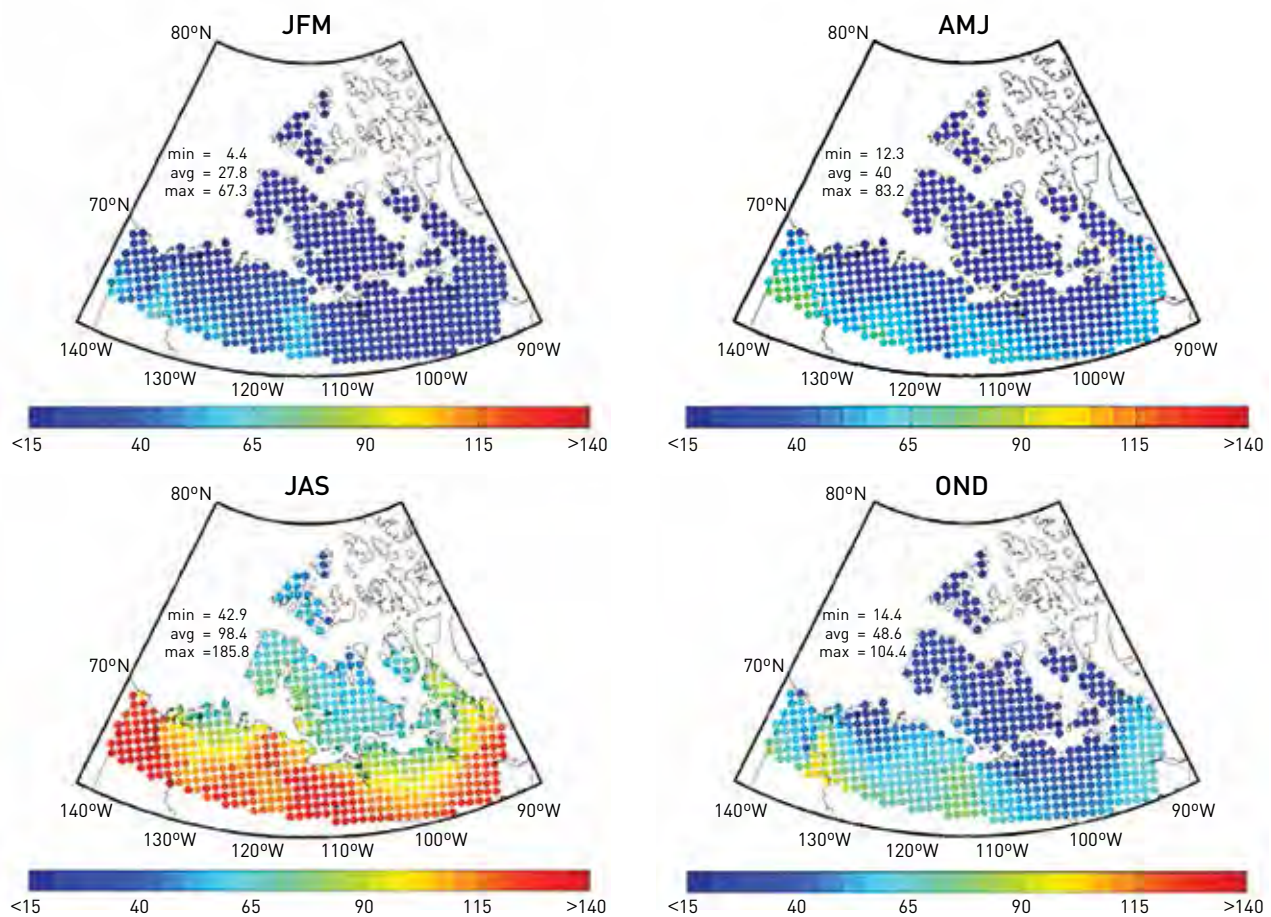


FIGURE 9. Spatial variation in 1981-2010 seasonal mean total precipitation (mm) over the IRIS region from the CANGRID dataset. The regionally-averaged mean total seasonal precipitation is: winter (27.8 mm), spring (40.0 mm), summer (98.4 mm), and fall (48.6 mm).

The CANGRID data set was used to examine trends in the IRIS region's regionally-averaged seasonal and annual precipitation totals over the longer 1950 and 2010 period as the large year-to-year variability masks trends computed over the most recent 1981-2010 period. The results showed evidence of significant increases in all seasons over the period, with the strongest precipitation increases in winter (11.5% per decade) and fall (7.3% per decade). Both snowfall and rainfall exhibit significant increasing trends over the 1950-2010 period.

- Total annual snowfall increased at 9.8% per decade.
- Total annual rainfall increased at 6.0% per decade.

Trends in annual snowfall and rainfall at individual stations within the IRIS region over the recent 1981-2010 period were examined. The results are outlined below:

- None of the climate stations had statistically significant trends in rainfall.
- The only statistically significant trend in snowfall was at Kugluktuk, which increased by 3.7 cm per decade.

When trends were calculated based on regionally averaged data and over the longer 1950 to 2010 period, the year-to-year variability was masked. However this was not the case using individual climate stations over the more

TABLE 4. Total annual precipitation averages for the 1981-2010 period from stations in and adjacent to the IRIS region with 19 years or more of complete monthly data in the homogenized precipitation dataset of Mekis and Vincent (2011). Where there were insufficient data in the period the 1971-2000 average is included and denoted with an asterisk

STATION	LAT (°N)	LONG (°W)	ELEV (M)	AVERAGE ANNUAL TOTAL RAINFALL (MM)	AVERAGE ANNUAL TOTAL SNOWFALL (CM)
Baker Lake	64.3	96.1	18	179.3	198.0
Lupin	65.8	111.3	488	174.1	160.3
Kugluktuk	67.8	115.3	23	163.5	213.8
Inuvik	68.3	133.5	103	132.8	199.7
Kugaaruk	68.5	89.8	17	133.7	215.8
Cambridge Bay	69.1	105.1	27	90.9	125.6
Tuktoyaktuk	69.4	133.0	18	81.8*	95.8*
Cape Parry	70.2	124.7	17	85.6*	161.9*
Ulukhaktok	70.7	117.8	36	82.5	113.1
Sachs Harbour	72.0	125.3	86	64.1	142.2
Mould Bay	76.2	119.3	2	39.8*	197.1

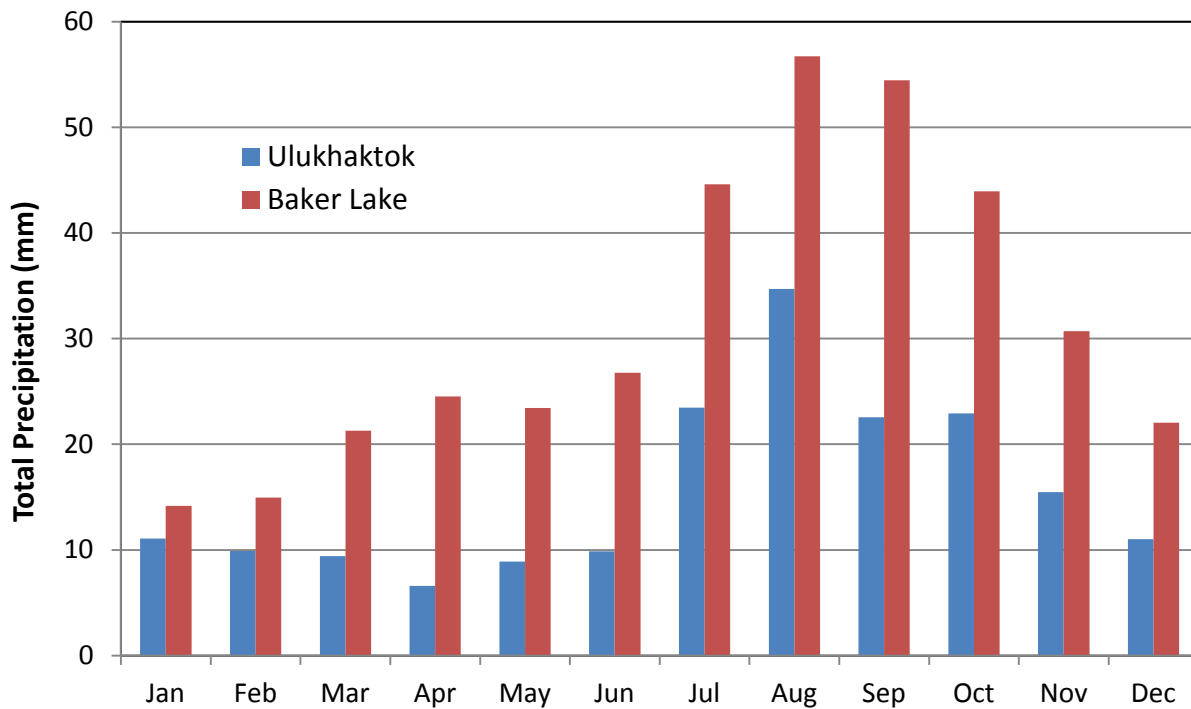


FIGURE 10. 1981-2010 monthly average total precipitation at Ulukhaktok and Baker Lake, the two stations with the lowest and highest measured precipitation amounts over the period.

recent 1981-2010 period, where there were few statistically significant trends. See Appendix B for additional figures and analysis.

Precipitation over the ocean

Seasonal precipitation trends from 1981 to 2010 are from the GPCP dataset. Figure 11 shows only those trends that were statistically significant. There is a significant decrease in spring period precipitation over the Beaufort Sea and northern islands of the IRIS region. It is not clear what is driving this decrease and there is little corroboration from

the CANGRD trend results (see Appendix B, Figure B2) as there is no data over the Beaufort Sea. The general lack of consistency in negative trends between the CANGRD and GPCP datasets is a manifestation of the potential for error and inaccuracy when working with precipitation data. There are however, several areas showing an increase in precipitation during spring, summer and a few areas during fall. There is a zone with significant increases in precipitation for spring (AMJ) over the eastern section of the region. These regions are smaller than those indicated by the CANGRD trends (see Appendix B, Figure B2).

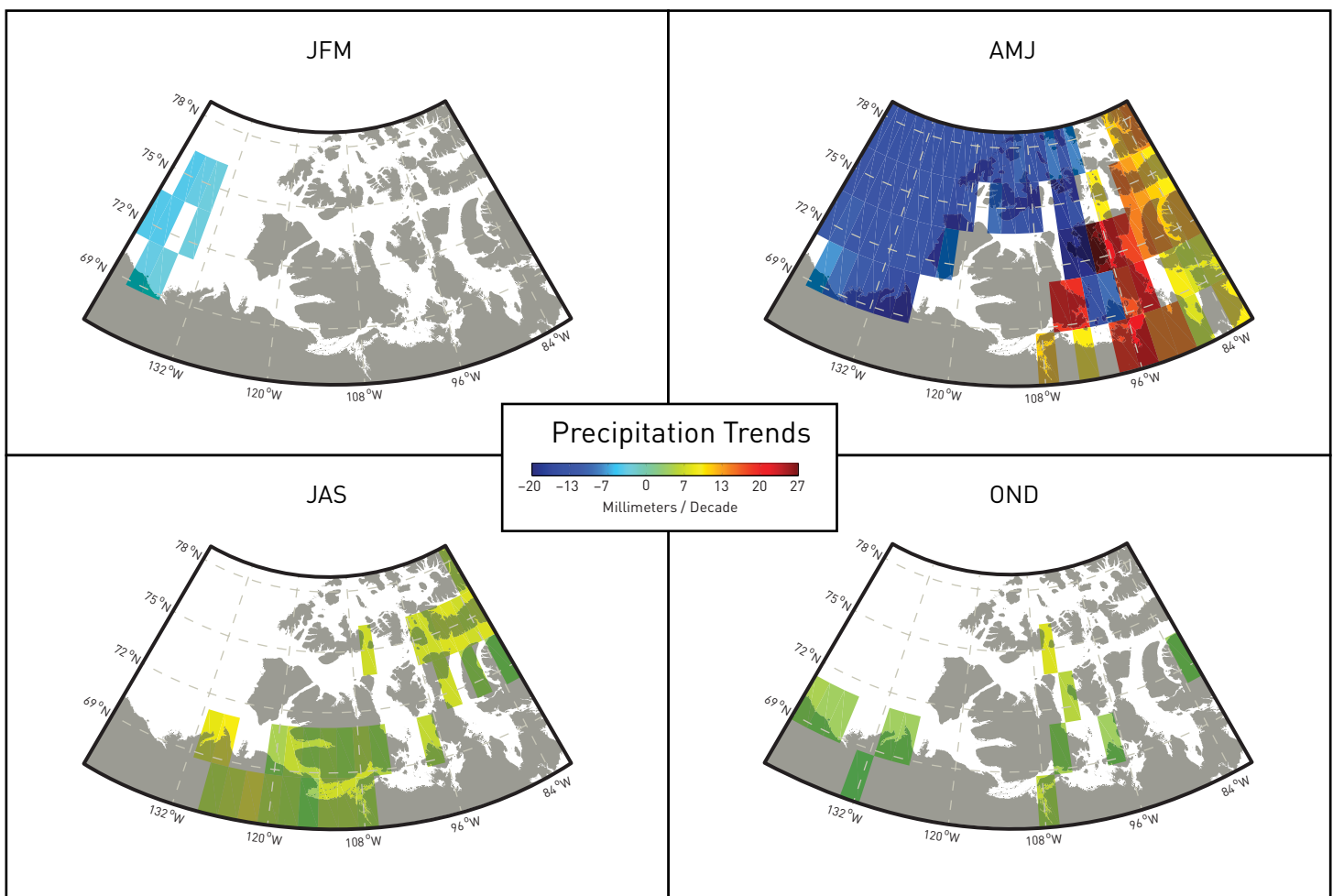


FIGURE 11. Precipitation trends in the western and central Canadian Arctic. Data from 1981–2010 GPCP reanalysis.

The increasing precipitation trends observed in the two datasets are consistent with observed long-term increases in pan-Arctic precipitation linked to global warming (Zhang et al. 2007). The relative magnitudes of the seasonal trends in precipitation mirror those of seasonal air temperature (seen in section 3.1). This is consistent with the Clausius-Clapeyron equation (a warmer atmosphere contains more water vapour) and with observed increases in atmospheric moisture over the Arctic from reduced sea-ice cover and meridional (north-south) transport of heat and moisture (Graversen et al. 2008; Screen and Simmonds 2010; Serreze et al. 2012; Koenigk and Brodeau 2014).

2.3.4 Snow

Snow is a dominant feature of the Arctic landscape and icescape. Continuous snow cover typically lasts the eight months from October to May in the IRIS region. The amount and physical characteristics of the snow cover have important influences on climate and ecology (Callaghan et al. 2012a). Snow over sea ice is also important as the insulating and reflective properties of snow influence ice growth and temperature, the amount of energy absorbed at the surface, and light penetration through the ice (Maykut 1978; Iacozza and Barber 1999; Mundy et al. 2007). Snow is particularly effective at limiting ice growth during the fall and early winter when there is fresh relatively low density snowfall on old, new or growing sea ice.

Snow characteristics also have an effect on human activities such as hunting and overland transport (Callaghan et al. 2012b). For example, the presence of perennial (year-round) snow patches in sheltered or shaded areas is particularly important to caribou for summer relief from biting insects (Lauriol et al. 1986). Moreover, snow accumulated on sea ice is important habitat for ringed seal and polar bear populations (Barber and Iacozza 2004). The caribou, ringed seal, and polar bear populations are important resources for local communities.

Snow on land

Arctic snow cover is typically shallow because of low atmospheric moisture availability. The snow's spatial distribution is primarily determined by wind interactions with the surface vegetation and terrain. Most of the snowfall arrives early in the "snow season" (Figure 12) and is continually redistributed over the landscape by wind. The shallowness of the snow, the strong temperature gradient within the snowpack, and the continual wind action give rise to a snowpack characterized by a basal layer of large crystals ("depth hoar") overlain with one or more layers of dense wind-packed snow ("wind-slab") (Derksen et al. 2009). However, several factors can generate important changes in the snow cover and its properties, including: the amount and timing of snowfall, the fraction of precipitation falling as rain and snow, the frequency of thaw and rain-on-snow events, and changes in vegetation. For example there is widespread evidence of increasing shrub growth over the Arctic tundra regions (Tape et al. 2006; Myers-Smith et al. 2011; Chapter 3) that is impacting snow accumulation, snowpack physical properties and energy exchanges (Marsh et al. 2010) as well as providing positive climate feedbacks (Loranty and Goetz 2012).

Providing reliable information on snow characteristics within the IRIS region is a challenge due to the scarcity of consistent surface observations and difficulties developing reliable satellite-based methods for monitoring snow cover over tundra regions. The following sections use the best available climate station and satellite data to provide the most accurate discussion possible for snow characteristics.

Regular daily snow depth observations have been made at Canadian Arctic climate stations with manual ruler measurements since the early 1950s and more recently with ultrasonic sensors since the early 1990s. The number of these Environment Canada stations reporting snow depth declined markedly during the mid-1990s. As a result, there are few stations with continuous snow cover observations in the IRIS region over the 1981-2010 period. The exception is

Cambridge Bay, where the climate station had a full 30-year dataset from 1981-2010.

A summary of snow cover conditions over the 1981-2010 period was able to be made for nine climate stations in the IRIS region with 15-years or more of continuous data over the period (Table 5). The results show that on average, snow cover is present for more than eight months of the year forming in early-October, reaching a maximum depth at the end of March, and disappearing in late-May to early-June. The number of days with snow cover ranges from a minimum of 201 days at Norman Wells to a maximum of 287 days in Mould Bay, although it should be noted that these estimates are likely to be on the low side as most of the measuring sites are located in open terrain near airports which may not be representative of the prevailing terrain.

Satellite data provide more detailed information on the snow cover of the IRIS region.

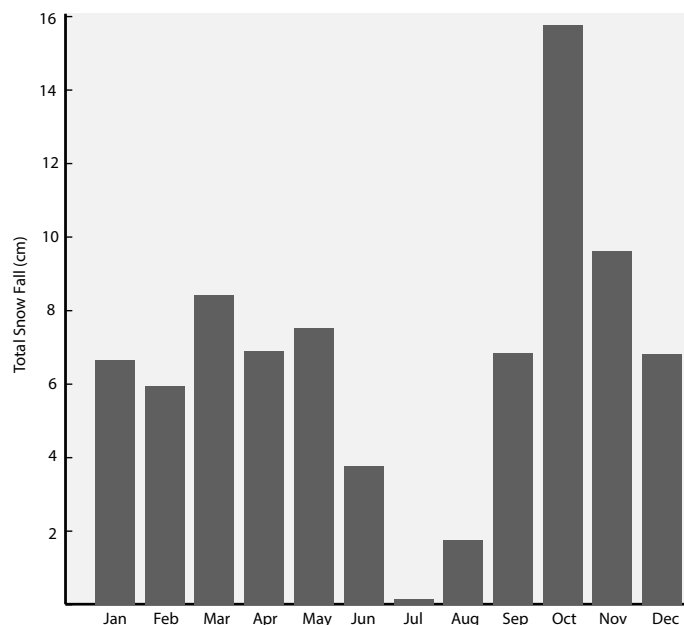


FIGURE 12. Monthly average total snowfall for Cambridge Bay. Means calculated using data from 1981–2010 taken from the Environment Canada Digital Archive of Canadian Climatological Data.

TABLE 5. Snow cover climatology for stations in and adjacent to the IRIS region with at least 15 years of complete daily snow depth data in the 1981-2010 period.

STATION NAME	LAT (°N)	LONG (°W)	AVERAGE START DATE OF CONTINUOUS SNOW COVER*	AVERAGE END DATE OF CONTINUOUS SNOW COVER*	AVERAGE ANNUAL # DAYS WITH SNOW COVER^	AVERAGE ANNUAL MAX SNOW DEPTH (CM)	AVERAGE DATE OF ANNUAL MAX SNOW COVER
Mould Bay	76.2	119.3	Sept 13	Jun 23	287	31.1	Apr 11
Uluhaktok	70.8	117.8	Oct 09	May 28	237	23.5	Mar 22
Tuktoyaktuk	69.4	133.0	Oct 09	May 31	236	38.3	Mar 29
Cambridge Bay	69.1	105.1	Oct 04	Jun 16	258	41.5	May 03
Inuvik	68.3	133.5	Oct 10	May 21	225	54.2	Apr 04
Kugluktuk	67.8	115.1	Oct 10	Jun 05	241	54.9	Mar 16
Old Crow	67.6	139.8	Oct 10	May 15	220	45.5	Mar 06
Normal Wells	65.3	126.8	Oct 14	May 01	201	42.2	Feb 18
Baker Lake	64.3	96.1	Oct 17	Jun 13	242	54.6	Apr 17
<i>Average</i>	<i>68.8</i>	<i>120.7</i>	<i>Oct 07</i>	<i>May 31</i>	<i>238</i>	<i>42.8</i>	<i>Mar 28</i>

* 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

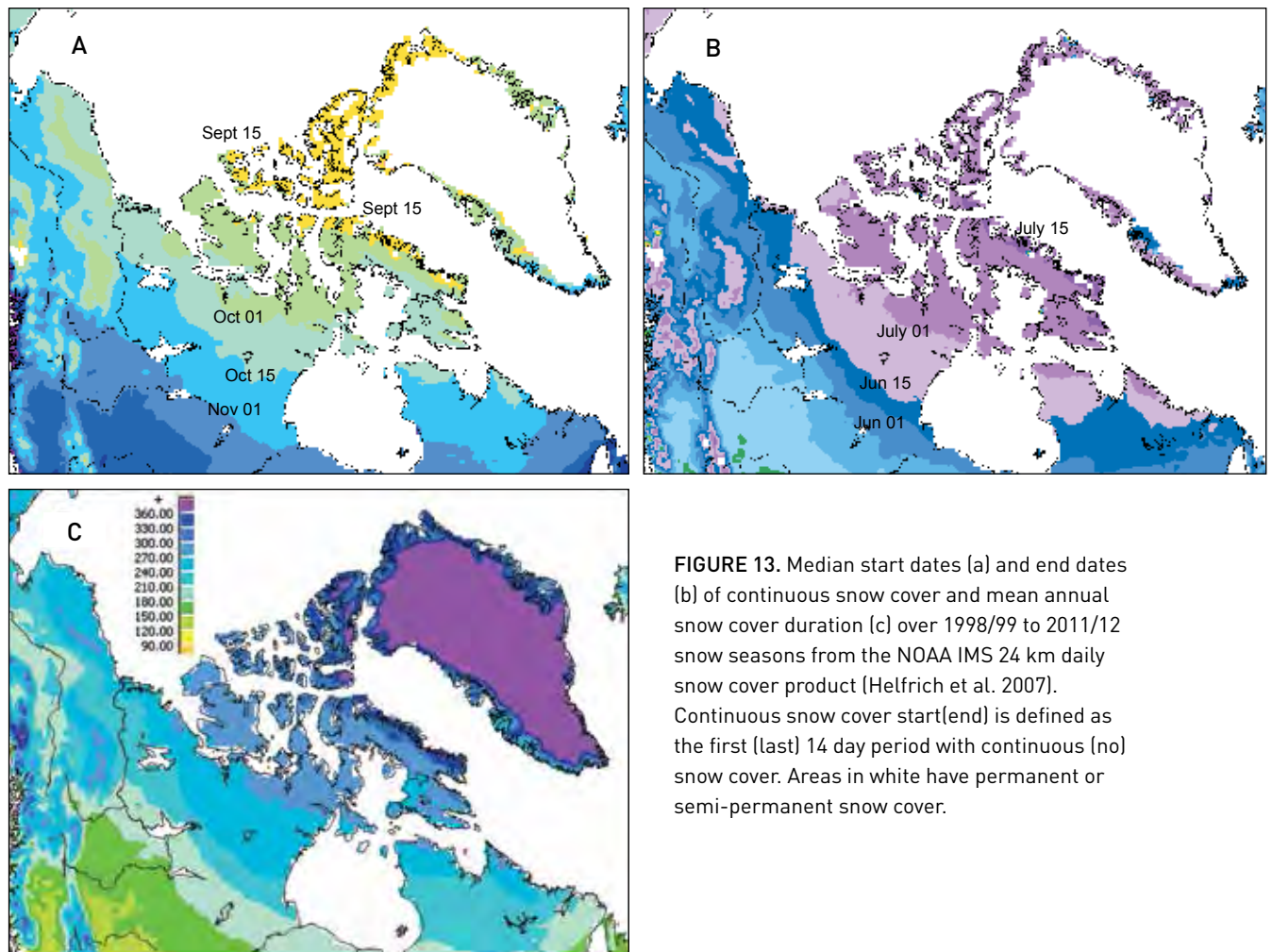


FIGURE 13. Median start dates (a) and end dates (b) of continuous snow cover and mean annual snow cover duration (c) over 1998/99 to 2011/12 snow seasons from the NOAA IMS 24 km daily snow cover product (Helfrich et al. 2007). Continuous snow cover start(end) is defined as the first (last) 14 day period with continuous (no) snow cover. Areas in white have permanent or semi-permanent snow cover.

Figure 13 was generated from NOAA daily snow cover analyses derived from manual interpretation of mainly visible satellites (Helfrich et al. 2007) over the 1998/99 to 2011/12 snow seasons. Snow-onset dates from the satellite data agree well with the climate station data (shown in Table 5), while the satellite data tends to give snow cover end dates that are about two weeks later than climate station observations. The disparity in end dates may be realistic, given that snow tends to melt earlier in the open areas where stations are typically located (Brown et al. 2007). The satellite-derived maps clearly illustrate the variation in snow cover with latitude and elevation over the region.

The main drivers of the regional pattern of snow accumulation are proximity to moisture sources and preferred tracks of winter storms, and terrain elevation. In the IRIS region the largest snow accumulations are observed on average at Inuvik and Kugluktuk (~55 cm) with the shallowest snow cover (~20-30 cm) at more northern “polar desert” sites e.g. Ulukhaktok and Mould Bay (Table 5). The depth of snow that accumulates throughout the season varies greatly with terrain, vegetation, and elevation. Snow that is deposited in open environments is affected by blowing snow processes. These processes often result in redistribution of fallen snow and have a strong influence on snow depth and stratigraphy in open terrain (Pomeroy and Gray 1995; Liston and Sturm 1998).

TABLE 6. Linear trend analysis of snow cover over 1981-2010 period for stations in or adjacent to the IRIS region with at least 20 years of data in the period. An asterisk indicates a significant result.

STATION	AVERAGE CHANGE IN START DATE OF CONTINUOUS SNOW COVER (DAYS PER 10 YEARS)	AVERAGE CHANGE IN END DATE OF CONTINUOUS SNOW COVER (DAYS PER 10 YEARS)	CHANGE IN DURATION OF PERIOD WITH CONTINUOUS SNOW COVER (DAYS PER 10 YEARS)	AVERAGE CHANGE IN ANNUAL NUMBER OF DAYS WITH SNOW COVER (DAYS PER 10 YEARS)	CHANGE IN ANNUAL MAX SNOW DEPTH (CM PER 10 YEARS)	CHANGE IN DATE OF ANNUAL MAX SNOW DEPTH (DAYS 10 YEARS)
Resolute	11.2* later	7.0 earlier	-18.2*	-2.7	0.4	24.0 earlier
Cambridge Bay	6.7 later	0.9 earlier	-7.6*	1.2	-1.4	1.1 earlier
Baker Lake	6.5* later	4.6 earlier	-11.1*	-3.3	-15.1*	4.2 earlier
Norman Wells	9.4* later	1.0 later	-8.4*	-1.2	8.3*	7.2 later

The few surface stations with long-term daily snow depth observations (five total) show significant reductions in max snow depth at three of the five stations in spite of increasing snowfall amounts. Recall that the mean maximum snow depth values shown in Table 5 are point measurements typically made at open, exposed locations near airports that may not reflect the snow cover of the region's prevailing terrain and vegetation.

Analysis of snow cover trends over the recent 1981-2010 period using data from the climate stations included in Table 5 is a challenge because only three of the stations have sufficiently continuous data for the time period: Cambridge Bay, Norman Wells, and Baker Lake. Table 6 summarizes the analysis results for these stations as well as for Resolute, which is in the Canadian Arctic Archipelago (CAA) just east of the IRIS region. These results are also outlined below:

- All the stations show significant trends toward a later onset to the snow cover season and toward a significantly shorter period of continuous snow cover.
- Rates of change range from ~10-20 days per decade.
- The number of days with any snow on the ground ≥ 2 cm depth does not show a significant decline at any station over the 1981-2010 period. This indicator includes

periods of ephemeral snow before and after the main snow cover season and is probably a less relevant indicator for Inuit than the period with continuous snow cover.

Information about the amount of water contained within the snowpack (the snow water equivalent or SWE) is important for hydrological applications like spring flood forecasting. Providing reliable information on SWE variations over the IRIS region is a challenge because of the scarcity of the surface observations and difficulties developing reliable satellite-based methods for monitoring SWE over tundra regions. An estimate of the mean annual maximum SWE over the Canadian Arctic region was obtained by merging two analysis products (Figure 14). The main conclusions are outlined below:

- Over the IRIS region, annual maximum SWE is estimated to vary between 100-150 mm over most of the mainland, with some areas of higher accumulation in the east (Kugaaruk) and west (Inuvik).
- The islands have much lower snow accumulations with the lowest SWE values (60-80 mm) observed over northern Victoria Island and adjacent islands. This pattern reflects the previously discussed spatial pattern in precipitation.

Aboriginal Affairs and Northern Development Canada carry out regular snow surveys at a number of basins in the Northwest Territories. These surveys provide values for end of winter SWE, which corresponds to the maximum SWE discussed above. The survey areas closest to the IRIS region with consistent data are Snare Basin north of Yellowknife (data begin in 1978) and the area around Inuvik (data begins in 1983). The Snare Basin data show a statistically significant increasing trend in SWE of 11 mm per decade over the period from 1978. The Inuvik surveys do not show any statistically significant trends. The Taltson Basin southeast of Yellowknife, also near IRIS, shows a statistically significant increasing trend in SWE of 8.3 mm per decade since 1965. Increases in maximum SWE are consistent with observed trends of increasing snowfall over the Canadian Arctic (Mekis and Vincent 2011) and with climate model projections (Brown and Mote 2009). Muskett (2012) shows increasing trends in mean annual SWE of 5.1 mm per decade over the IRIS region using satellite data over the period 1979-2010.

Snow on sea ice

Snow covered sea ice forms an integral part of the marine ecosystem at high latitudes, including habitat for ringed seals and polar bears (Chapter 4). Snow cover accumulation begins in the fall when sea ice is beginning to form. The maximum snowfall is reached during the late fall and early winter season (December and January), with limited accumulation occurring in the spring and summer seasons (Warren et al. 1999; Sturm et al. 2002). Not only is the amount of snowfall on the sea ice an important component, but also the spatial distribution of snow as a function of location and ice type. The surface roughness of sea ice is a critical factor in how much snow can accumulate; multiyear ice typically accumulates much thicker snow cover than smoother first year ice (Iacozza and Barber 1999). Webster et al. (2014) concluded that on-ice snow depths had decreased over the western Arctic and Beaufort-Chukchi Sea regions by 37% and 56%, respectively, based on a comparison of recent field observations with historical data from Soviet drifting stations. The thinner snow

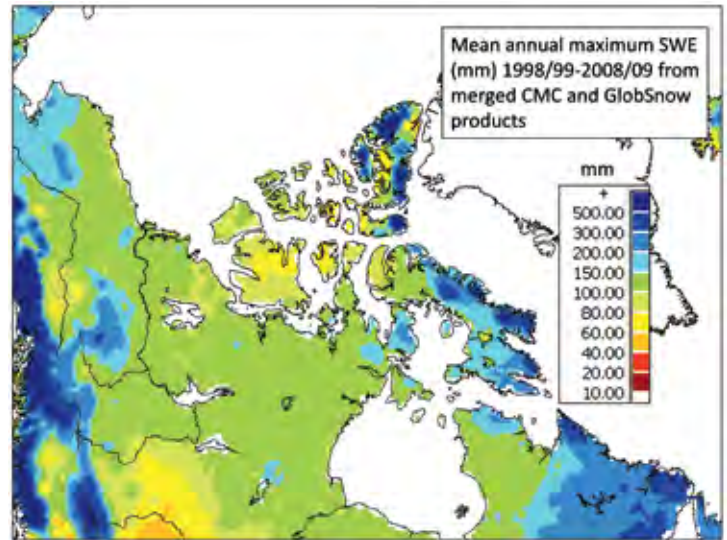


FIGURE 14. Mean maximum snow water equivalent (mm) for snow seasons 1998/99 to 2008/09 from merged Canadian Meteorological Centre (CMC) (Brown and Brasnett 2010) and GlobSnow (Takala et al. 2011) datasets. The maximum value of CMC or GlobSnow SWE was used to create the merged product.

accumulations are linked to delayed onset of sea ice freeze-up during the autumn.

Snow on sea ice can play an important role for ice growth and formation (Thomas and Dieckmann 2010). If snow accumulates on newly formed sea ice, it will create a thermal barrier between the atmosphere and the sea ice. During the fall and winter, when the air temperatures are colder than the ocean, the accumulation of snow on new and young sea ice will hinder the growth of sea ice. In the late spring and summer, when the air temperatures are warmer than the ocean, fresh snow on sea ice can delay the melting of the sea ice. Generally, sea ice that is older than a few days has snow on it formation (Thomas and Dieckmann 2010). Deeper snow will generally be found on older first year and multiyear sea ice, since there has been more time for snow to accumulate (Massom et al. 2001). The pattern of snow distribution is controlled by the sea-ice surface; sea ice with large ridges or hummocks will have deeper snow cover near the hummocks, while smooth first year ice will have a relatively uniform layer of snow (Iacozza and Barber 1999).

The distribution of snow on sea ice is heavily affected by the winds; snow can be blown over sea ice and redistributed by winds as light as 4.5 m s^{-1} for loose snow (Budd et al. 1966; Schmidt 1982).

Long term measurements of snow over sea ice are limited. A study conducted by Iacozza and Barber (2010) compared land-based measurements of winds, temperature and precipitation to nearby measurements located on sea ice. They determined that due to significant changes in topography there was little agreement for winds and precipitation. Trends and analysis of snowfall over the ocean can be approximated from the precipitation over the ocean (see section 3.2 and Figure 11), with the assumption that the precipitation falling in the fall and winter will be snow. Due to a limited number of in situ measurements for snow over sea ice and because of our inability to accurately estimate snow thickness over space using remote sensing techniques, limited research has focused on snow over sea ice and how it has been changing over the past 30 years.

Future possibilities

Climate model projections indicate that precipitation will continue to increase over the ocean due to an increase in air temperature (and associated increase in moisture holding capacity) and changes in storms (Carter et al. 2000; Rinke and Dethloff 2008). Over the Arctic Basin, an increase in snowfall of 1-2 cm is projected by the middle of this century (Walsh 2008), while doubling of winter precipitation is expected by the end of the 21st Century (Rinke and Dethloff 2008). The greatest change in precipitation is estimated to occur during the autumn and winter seasons (period of maximum snowfall) in the Arctic Basin (Walsh 2008; Rinke and Dethloff 2008). If the temperatures remain below zero during these periods, this projected increase in precipitation will occur as snowfall, potentially increasing the snow depth on the sea ice. Projected changes in snowfall amount depend on the interplay between the increased precipitation and a shortening of the period with below-freezing temperature. Current climate models only project increased snow accumulations over the coldest sectors of the Arctic region

inside the -20°C isotherm in late 20th Century November–March mean air temperature (Räisänen 2008). This includes most of the CAA. Interannual variability is also expected to increase, with more variability in the winter precipitation compared to the summer season (Rinke and Dethloff 2008).

Brown and Mote (2009) show that the response of snow cover to warming and increased precipitation depends on the interplay between the rate of change in the snow accumulation period and the rate of change in snowfall. This interplay means that changes in snow cover over the Arctic can occur at different rates and possibly in different directions depending on region, elevation, and the snow cover characteristic examined.

2.3.5 Sea ice

Arctic sea ice is a relatively thin cover that separates the ocean from the atmosphere, limiting and reducing the exchange of energy, momentum and mass between the two. The Arctic climate is closely tied to the state of the cryosphere. Increasing atmospheric and oceanic temperatures lead to (or are created by) reductions in sea-ice thickness, sea-ice volume, and average age of ice, as well as an increase in melt season length (Rothrock et al. 1999; Maslanik et al. 2007; Markus et al. 2009; Kwok and Cunningham 2010). These changes in sea-ice cover can release large heat and moisture fluxes into the Arctic atmosphere throughout the cold season, thus modifying the regional climate.

Here we define sea-ice extent as the total ocean area that is at least 15% covered with ice (referred to as 15% ice concentration) (NSIDC 2009). In the Arctic, the maximum extent occurs in March when sea ice covers approximately 15 million km^2 (Comiso 2003). The minimum sea-ice extent occurs in September when sea ice covers approximately 7 million km^2 . In recent years the summertime minimum sea-ice extent has undergone a dramatic decline. Record Arctic sea-ice minimum extents were observed in 1979, 2000, 2005, 2007, and 2012 indicating a gradual decline

in sea-ice extent from 1979-2000 shifting to a rapid (yet highly variable inter-annual) decline since 2000.

Multiyear ice (MYI) is a term typically applied to sea ice that has lasted for at least one freeze and thaw cycle, freezing in one fall or winter and surviving the thaw in the ensuing spring and summer. MYI has different properties than new “first year” ice, tending to be thicker, stronger, and less salty. The extent and location of MYI are an important concern for the Arctic environment, as MYI has a significant influence on ocean reflectivity, chemistry, and temperatures (Cosimo 2012).

Recent changes have also been documented with the export and drift of sea ice in the Beaufort Sea; Babb et al. (2013) documented the first observations of ice being exported through the Bering Strait, with ice drift speeds being significantly faster than historic measurements. Another study has shown that for regions surrounding Tuktoyaktuk, Kugluktuk, Cambridge Bay, Gjoa Haven, Arctic Bay and Pond Inlet there is a shorter land fast ice season, which can have significant social, cultural and economic impacts of the communities (Galley et al. 2012). Another resulting factor of the decline in sea ice and increased air temperatures in the Arctic is the increase in ice hazards. A recent study documented ice hazards from glacial or thick MYI having keels of more than 30 m thick and moving faster and can move in opposing directions to that of the ice pack (Barber et al. 2014). There are also occurrences of glacial ice features being incorporated into the pack ice of the Beaufort Sea due to the decay of ice shelves along the west coast of Ellesmere Island (Copland et al. 2007).

The average ice thickness in the Arctic has been decreasing (Rothrock et al. 1999). The thinning and reduction of the sea ice in the Beaufort Sea has resulted in many instances where the ice pack was mischaracterized by satellite data and rather than having thick, strong multiyear ice there was rotting sea ice (where the ice is weak and permeable) (Barber et al. 2009). In 2009 when the ice pack was relatively weak and thin, a strong cyclone event created long waves that propagated deep into the pack ice, thereby

causing swells and the eventual break-up of the sea ice pack (Asplin et al. 2012). This process reduced the floe size into smaller more mobile pieces and increased floe surface area, and thereby affected sea ice dynamic and thermodynamic processes (Asplin et al. 2014). Smaller more mobile ice floes can result in ice motion that has more inertial oscillations (loops), which are harder to forecast or model over short time periods (Barber et al. 2014). These changes in the sea ice have not only been observed and documented by scientists (Barber et al. 2010; Barber et al. 2012) but have been observed by northern communities and passed down through traditional knowledge (Barber and Barber 2009).

Only one coastal station in the IRIS region (Cambridge Bay) has maintained roughly constant weekly ice thickness measurements over the period from 1958. Ice data for Cambridge Bay indicate that the land fast ice (ice attached to the land, also referred to simply as “fast ice”) grows to an average maximum thickness of around 200 cm by around the third week in May. Over the period of record, annual maximum depth at Cambridge Bay has varied over a range of 170-246 cm. Prior to the mid-1990s there was a much more extensive network of fast ice thickness observations. The Canadian Ice Centre (now called the Canadian Ice Service) (1992a) published 1961-1990 period ice thickness data for 135 stations in Canada, including five coastal stations located in the IRIS region. The data indicate that maximum ice thickness is relatively uniform across these locations, only varying 15 cm around an average value of 190 cm for the region. Brown and Cote (1992) showed that the on-ice snow accumulation was a key factor influencing the variability of maximum fast ice thickness over the Canadian High Arctic. The difference in snow accumulation between Cambridge Bay and Mould Bay is likely playing a role in the comparatively thinner ice at Mould Bay, which has a colder winter climate and higher freezing degree-day totals than Cambridge Bay.

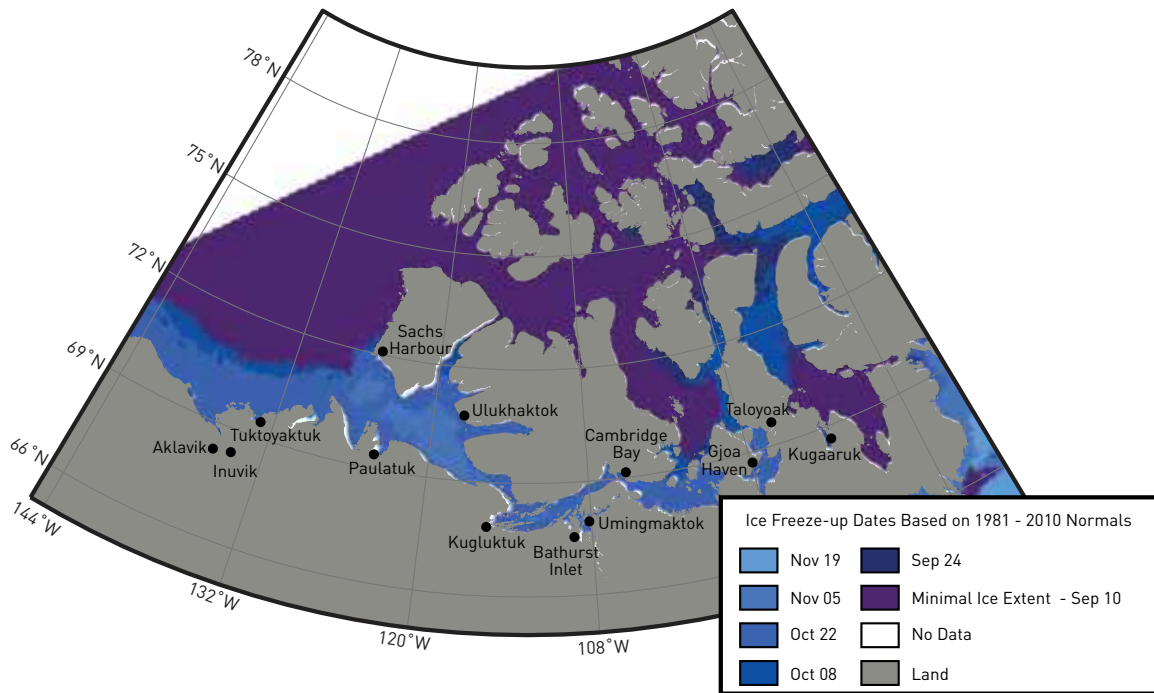


FIGURE 15. Median ice freeze-up date, based on the 1981–2010 normals provided by Canadian Ice Service. From Candlish et al. (2014).

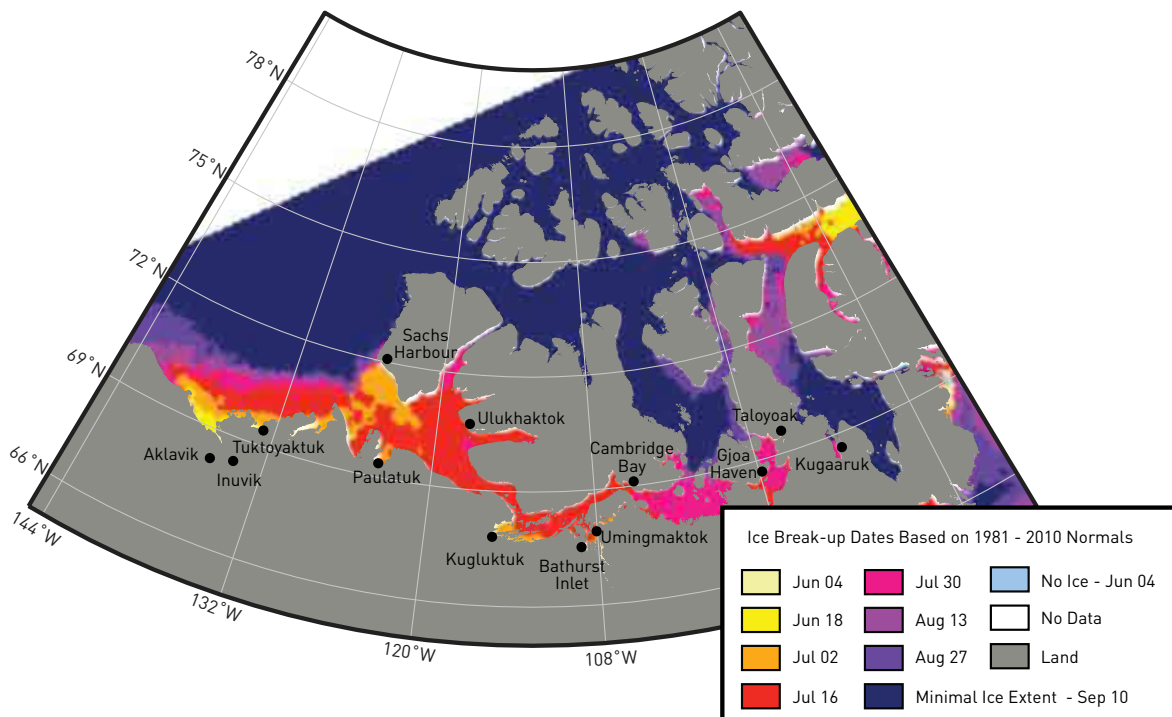


FIGURE 16. Median ice break-up date, based on the 1981–2010 normals provided by Canadian Ice Service. From Candlish et al. (2014).

The freeze-up dates and break-up dates for the IRIS region are shown in Figure 15 and Figure 16. The data are from the Canadian Ice Service (CIS) and are based on the 1981-2010 averages. Some key points from the figure are outlined below:

- The deeper northern waters of the Beaufort Sea are covered in sea ice throughout the year (see the minimal ice extent shown in purple).
- The Amundsen Gulf has ice freeze-up dates ranging from early October to late November.
- The ice break-up dates range from early June in the Mackenzie Delta to July in the eastern Amundsen Gulf.

The length of the “open water” season was also analyzed. Open water is typically defined as ocean area with ice concentration below 10 or 15%; however, because the sea-ice extent remains very high in the IRIS ocean region throughout the year, “open water” was defined as ice concentrations below 50% for this analysis. The main results of this analysis are described below. In this discussion, the areas are named in keeping with those shown in Figure 7.

The open water analysis allowed a characterization of the open water season in the IRIS regions (Candlish et al. 2014):

- The regions with the shortest open water seasons were the Western High Arctic, Western Parry Channel and M’Clintock Channel, where the average length was zero weeks, one week, and one week, respectively.
- The Western High Arctic was the only region with zero weeks of open water in as many as 29 of the 30 years examined.
- The Eastern Parry Channel and Western Arctic Waterway had the longest average open water season, 13 and 14 weeks respectively.
- The Beaufort Sea, Franklin and the Eastern High Arctic had open water seasons of five, six, and four weeks, respectively.
- Although the Arctic Ocean has significant increases in open water (Barber et al. 2015), the only region with a statistically significant trend in open water season length was Eastern Parry Channel, where the open water season increased by approximately one week per decade.

Table 7 shows the average monthly total sea-ice concentrations and MYI concentrations for each of the regions shown in Figure 7 (also see Figure B3 in Appendix B). Some key points from the table are listed below:

- The total sea-ice concentrations were consistently high (>95%) from approximately November through to May in all of the regions.
- The Western Arctic Waterway had the lowest total ice concentration with <10% during August and September.
- During the summer the minimum monthly average sea-ice concentration was generally still high (>50%) for all regions except the Western Arctic Waterway and Franklin.
- The region with the most consistently high concentrations of MYI was the Western High Arctic; however, the Beaufort Sea, Western and Eastern Parry Channel, and M’Clintock Channel also had relatively high amounts of MYI.
- On average the Western Arctic Waterway had very little MYI (<5%). The Eastern High Arctic and Franklin Strait also had low concentrations (<25%).

TABLE 7. The 1981–2010 monthly total sea-ice concentration (%) top, and the 1981–2010 average monthly multiyear ice concentrations (%) bottom. Adapted from Candlish et al. (2014).

	BEAUFORT SEA	W. HIGH ARCTIC	E. HIGH ARCTIC	W. PARRY CHANNEL	E. PARRY CHANNEL	M'CLINTOCK CHANNEL	FRANKLIN	W. ARCTIC WATERWAY
Jan	97	100	99	99	97	100	100	99
	45	65	25	44	45	50	20	2
Feb	97	100	99	100	97	100	100	99
	45	65	25	42	45	49	20	2
Mar	97	100	100	100	97	100	100	99
	46	65	25	42	46	49	20	2
Apr	97	100	100	100	97	100	100	99
	44	65	25	42	44	50	21	2
May	94	99	98	99	94	100	100	94
	41	64	25	42	41	49	21	2
Jun	86	99	97	97	86	100	100	84
	40	65	25	41	40	50	21	2
Jul	73	95	88	94	73	99	95	53
	42	64	25	42	42	50	21	2
Aug	57	80	48	74	57	81	54	7
	39	62	20	42	39	47	16	2
Sep	48	80	50	65	48	65	31	3
	37	62	19	41	37	41	13	2
Oct	71	96	93	94	71	92	78	37
	43	69	29	48	43	52	22	2
Nov	95	99	99	98	95	98	98	95
	44	67	28	47	44	51	22	2
Dec	97	100	100	98	97	99	99	99
	45	66	26	45	45	49	21	2

Trends in sea-ice concentration and multiyear ice

The analysis by Candlish et al. (2014), shown in Figure 17, provides insight into trends in the monthly sea-ice concentrations:

- For the 1981–2010 period there were no statistically significant trends in total sea-ice concentrations for the months of January, March, May and June.
- There was only one area with an increasing trend: the Eastern High Arctic had a slight increase in total sea-ice concentration for the month of April.
- The most dramatic decreases in ice concentration occurred during late summer and early fall (August, September and October) (Figure 17):
 - During August the Beaufort Sea, Eastern Parry Channel, M'Clintock Channel and Franklin region

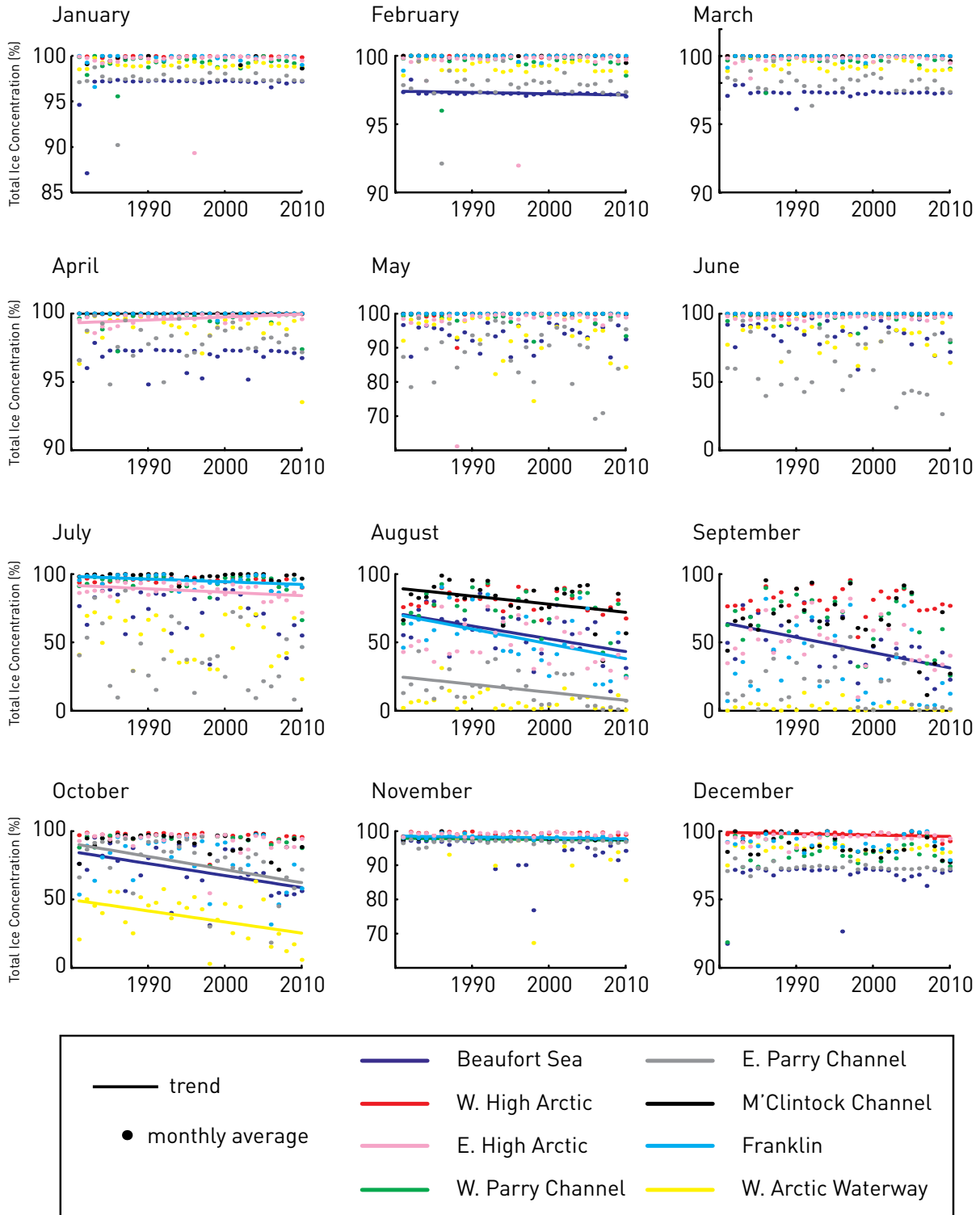


FIGURE 17. The monthly total sea-ice concentration with statistically significant trends. From Candlish et al. (2014).

(Figure 7) all showed a statistically significant decrease in total sea-ice concentration.

- Looking at the most recent decade 2001-2010, the total sea-ice concentration had significant declines during August for the Western High Arctic, Eastern High Arctic, Western Parry Channel, Eastern Parry Channel and the Beaufort Sea.
- The most significant decline over the past decade was during September, the typical sea-ice minimum, where six of the eight regions had a decline in sea ice, only excluding M'Clintock Channel and the Franklin Strait region.

These results, indicating a decline in summer sea ice, are in agreement with a study done by Tivy et al. (2011). These authors examined 1968-2008 trends in summer sea ice and determined a decline of 2.9% per decade within the Canadian Arctic Archipelago, and 5.4% per decade in the Beaufort Sea (Tivy et al. 2011).

Monthly MYI concentrations for the entire IRIS region from 1981-2010 are illustrated in Figure 18, and key points are discussed below:

- There were no statistically significant trends for the months of January through to April.
- The Western Arctic Waterway showed a slight decreasing trend for MYI in May, June, and July.
- There was a significant decrease in MYI from September to December in the Beaufort Sea region.
- There was a significant decrease in MYI the M'Clintock Channel in October.
- Looking at the most recent decade (2001-2010):
 - The August MYI concentration showed significant declines in the Western High Arctic, Eastern High

Arctic, Western Parry Channel, Eastern Parry Channel, Western Arctic Waterway, and the Beaufort Sea.

- There were also significant declines over the past decade during September, October, and November for the Western High Arctic, Western Parry Channel and the Beaufort Sea.

2.3.6 River and lake ice

Lake and river ice are integral components of the northern environment that influence ecosystems and numerous ecological and water quality characteristics (Beltaos and Prowse 2009; ArcticNet 2010; Prowse et al. 2011a). Ice is also a critical component of cold-regions hydrologic systems affecting extreme floods and low winter flow (Beltaos and Prowse 2009).

Within the IRIS region there are numerous rivers, lakes and wetlands (Figure 19). However, the freshwater system is dominated by the Mackenzie River with a drainage basin of almost 2 million km² and a mean annual discharge of 325 km³ (Chapter 3, Box 1). The large north-south gradient in air temperature along the river affects ice formation, dynamics and ice jam flooding (Prowse et al. 2010) and is an important factor in the ice regime response to warming.

There is clear evidence that the climate of northern Canada is changing (sections 3.1 and 3.2). Ice cover formation, melt and dynamics are sensitive to a range of meteorological variables (e.g. wind speed, temperature, precipitation (rain and snow), cloudiness, solar radiation and humidity) and changes in any of these can influence ice composition, thickness, stability and the complex interactions between hydrodynamic, mechanical and thermal processes (Beltaos and Prowse 2009). Lake and river ice regimes also respond to non-climatic controls such as lake morphology (shape) and depth (Brown and Duguay 2010) and changes in the terrestrial hydrologic regime (Prowse et al. 2011a, b). Deltas and large river mouths where settlements tend to be located are ecologically rich environments that are

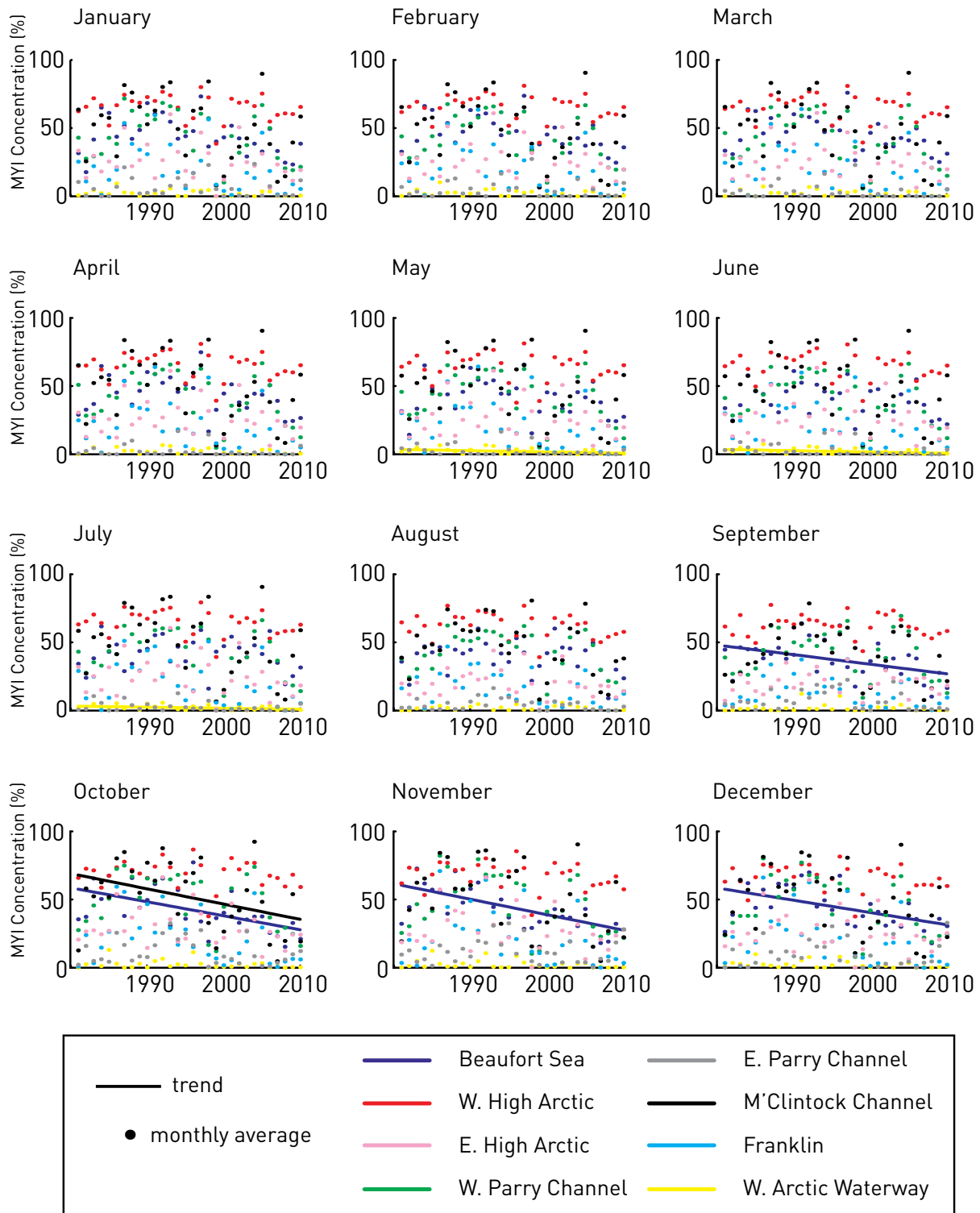


FIGURE 18. The monthly multiyear ice concentration with statistically significant trends. From Candlish et al. (2014).

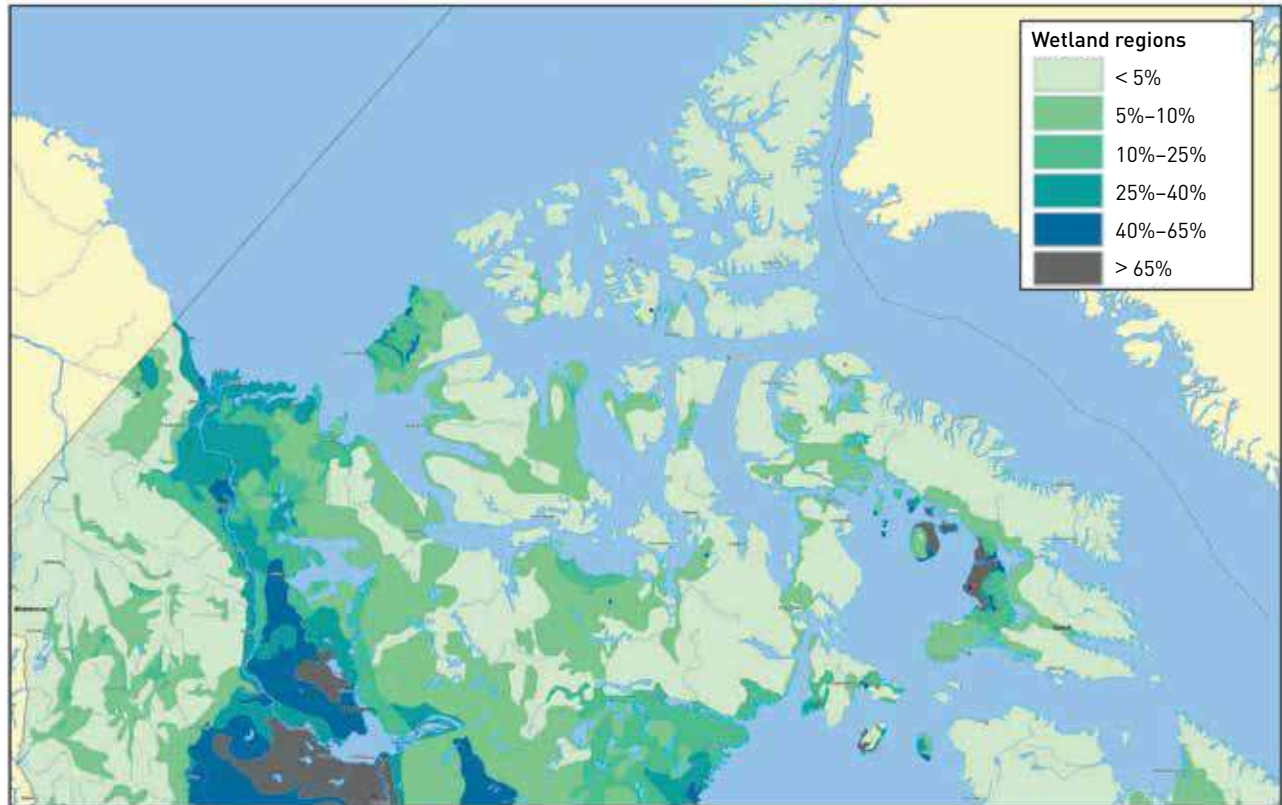


FIGURE 19. Fractional coverage of wetlands in northern Canada. From the Atlas of Canada, 6th Edition (www.atlas.gc.ca).

particularly sensitive to warming climate influences on ice conditions and hydroclimatic controls of break-up and ice-jam flooding (Goulding et al. 2009; ArcticNet 2010). High Arctic lake ice regimes are shifting from perennial to seasonal ice (Brown and Duguay 2011) suggesting that the response of northern ice regimes is highly threshold-dependent (Mueller et al. 2009).

Historical variability

There are a number of challenges for monitoring the fresh water ice climate over the IRIS region: there are few in situ records, and satellite observations have various limitations related to resolution, frequency, consistency and length of coverage (Duguay et al. 2006; Latifovic and Pouliot 2007; Prowse et al. 2011a, b). 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). This program was reinstated at 11 Arctic stations in the early-2000s. The data are archived at the Canadian Ice Service (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 nine stations located in the IRIS region with more-or-less complete data in the 1961-1990 averaging period (Table 8). Four of these stations have measurements in freshwater bodies: Yellowknife (Great Slave Lake), Norman Wells and Inuvik (Mackenzie River) and Baker Lake. Corresponding information on ice cover state (dates of freeze-up and break-up) for the 1961-1990 period was published by the Canadian Ice Centre (1992b) and is summarized in Table 9. The freeze-up/break-up observing program was terminated in the mid-1990s and has not been reinstated. A volunteer ice observing network *ICEWATCH* was established in 2001 that builds on the

TABLE 8. Average ice thickness values published by the Canadian Ice Centre (1992a) for stations in and adjacent to the IRIS region with 25 or more years of data in the 1961-1990 averaging period. Freshwater sites are indicated with an asterisk.

STATION NAME	LAT (°N)	LONG (°W)	PERIOD OF DATA	AVERAGE MAX ICE THICKNESS (CM)	AVERAGE DATE OF MAX ICE THICKNESS (CM)	AVERAGE MAX ON-ICE SNOW DEPTH (CM)
Yellowknife*	62.4	114.4	1961-1990	129.4	April 23-29	25.4
Norman Wells*	65.3	126.8	1961-1990	156.1	April 16-24	21.0
Inuvik*	68.3	133.5	1961-1990	120.1	April 23-29	27.8
Baker Lake*	64.3	96.1	1961-1990	222.5	May 14-20	5.3
Cape Parry	70.2	124.7	1961-1990	183.1	May 21-27	19.1
Kugluktuk	67.8	115.1	1961-1988	174.5	May 7-13	29.5
Cambridge Bay	69.1	105.1	1961-1990	208.1	May 21-27	12.6
Sachs Harbour	72.0	125.3	1961-1986	186.2	May 7-13	14.3
Mould Bay	76.2	119.3	1961-1990	198.6	June 11-17	47.1

TABLE 9. Average freeze-up/break-up values for sites in and adjacent to the IRIS region published by the Canadian Ice Centre (1992b). Freshwater sites are indicated with an asterisk.

STATION NAME	YEARS	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
Yellowknife*	1956-1990	Oct 29	Nov 19-May 17	May 07	May 31
Norman Wells*	1957-1990	Nov 11	Nov 24-Apr 25	May 11	May 26
Inuvik*	1961-1985	Oct 19	Dec 16-Apr 29	May 09	Jun 01
Baker Lake*	1956-1989	Oct 23	Nov 15-May 28	Jun 14	Jul 20
Cape Parry	1961-1985	Oct 30	Nov 04-Jun 18	Jun 05	Jul 25
Cambridge Bay	1951-1990	Oct 09	Oct 08-May 22	Jun 07	Jul 19
Gladman Pt.	1962-1990	Oct 14	Insufficient data	Jun 26	Aug 01
Mould Bay	1955-1990	Sep 20	Oct 14-Jun 07	Jun 19	Infrequent clearing

Canadian Lake Ice Database developed by Lenormand et al. (2002). Summary information from all the ice thickness monitoring sites in the IRIS region is presented here as this is relevant to the various communities. However, the different environments of the weekly ice thickness measuring sites (river, lake and coastal fast ice) must be kept in mind when comparing sites (e.g. river sites such as Inuvik will have thinner ice than a nearby lake site due to the influence of flowing water). It should also be noted that the 1961-1990 period was on average $\sim 1^{\circ}\text{C}$ cooler than the recent 1981-2010 period. However, the summaries still provide

useful information on past ice cover conditions at the communities in 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 8 shows:

- The thinnest ice in the region is observed at Inuvik and Yellowknife (~ 1.2 m) with the maximum ice thickness of over 2 m at Baker Lake.

- The average date of maximum ice thickness varies ~2 months over the region from mid- to late-April at Yellowknife, Inuvik and Norman Wells, to mid-June at Mould Bay.

The freeze-up/break-up summary in Table 9 shows:

- A complete ice cover is established relatively rapidly over most of the region by the end of October with the latest complete freeze-over at Norman Wells in mid-November.
- The spring period shows much greater regional variability with average dates of water clear of ice ranging from late-May at Yellowknife and Norman Wells to late-July at more northern communities.
- In the 1961-1990 period Mould Bay did not have regular clearing of ice during the summer period.
- The period when ice is considered safe for traffic by observers exhibits considerable variability between sites reflecting local climate conditions and ice dynamics. The shortest ice safe period (~4 months) is observed at Inuvik and the longest (7-8 months) at Cambridge Bay and Mould Bay.

Observed trends

While there is a lack of consistent freeze-up/break-up data over the region for trend analysis over the past 30-40 years, the available evidence (Duguay et al. 2006; Lafitovic and Pouliot 2007; de Rham et al. 2008; Prowse and Brown 2010) suggests that most of the Canadian Arctic has experienced a trend to earlier spring break-up while trends in dates of freeze-up are characterized by strong regional variability. The magnitude of the reported trends is more difficult to get a handle on because of different time periods and locations. For example, trends to earlier spring break-up in the IRIS region span an order of magnitude from 1 day per decade earlier spring break-up in upstream portions of the major tributaries of the Mackenzie River over the period 1970–2002 (de Rham et al. 2008) to 9.9 days per

decade earlier break-up of lakes over the CAA over the 1970-2005 period (Lafitovic and Pouliot 2007). Bonsal and Prowse (2003) and Duguay et al. (2006) showed that lake freeze-up/break-up trends are consistent with trends in the date when air temperature crosses 0°C (0°C-crossing date). Analysis of regionally-averaged 0°C-crossing date series from 16 stations in the IRIS region with the homogenized dataset of Vincent et al. (2012) showed evidence of only small non-significant changes to earlier thaw and later freeze over the period (see section 3.1, Figure 5) that are of about a similar magnitude.

Some key trends are:

- An increase in thaw season duration (or conversely a significant decrease in the duration of the period with freezing temperatures) over the 1950-2012 period of 1.2 days per decade.
- Since 1980 thaw season duration has increased 3.3 days per decade.
- Analysis of trends in snow cover-onset and snow-off dates from stations reporting daily snow depths in the IRIS region (see section 3.4) show stronger trends in the spring period with an average decrease of spring snow cover duration of 2.5 days per decade over the period from 1950.

Some idea of the spatial variability in the sign and strength of recent trends in the spring response of the cryosphere over the IRIS region can be obtained from trends in dates of melt-onset obtained with passive microwave satellite data (Wang et al. 2013). Passive microwave is very sensitive to the presence of liquid water in the snowpack and the timing of the main melt-onset period was found to be closely linked to when temperature warmed above 0°C (Wang et al. 2008). Figure 20 shows that melt-onset trends over the IRIS region are earlier in the area west of the Mackenzie River with values ~5 days per decade. This pattern is consistent with May-June temperature trends for the same period from the a second data set (NCEP1 Reanalysis, not shown)

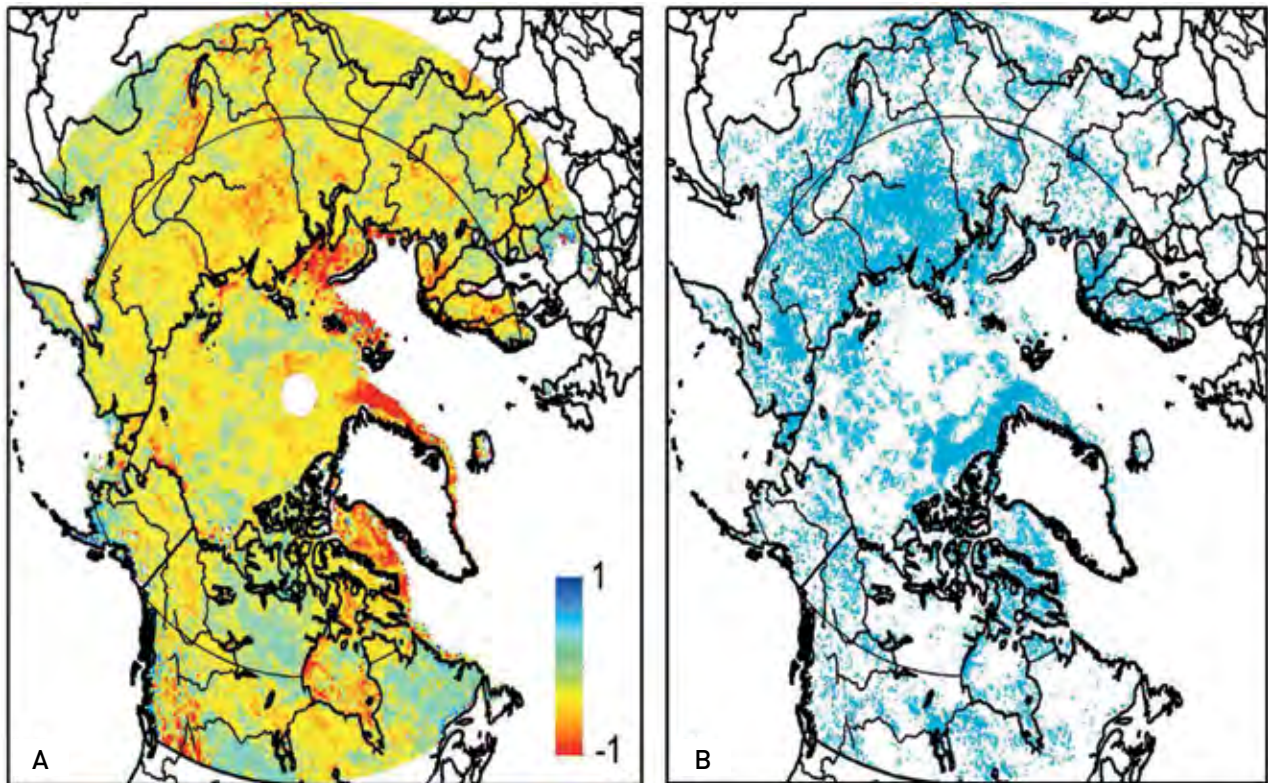


FIGURE 20. (a) Linear least squares trend (days yr⁻¹) and areas where the trend is locally significant at the 0.05 level (b) for 1979–2011 change in melt-onset date derived from passive microwave satellite data. From Wang et al. (2013).

which indicated cooling over the central Canadian Arctic and warming over Alaska and Yukon.

Information about variability and trends in observed maximum ice thickness was obtained from four stations with more-or-less complete measurements from ~1960 (Yellowknife, Inuvik, Cambridge Bay, and Baker Lake) (Figure 21).

Trends from Figure 21 are summarized, with all four stations showing statistically significant decreases in maximum ice thickness over the period:

- -3.5 cm per decade at Cambridge Bay
- -4.3 cm per decade at Baker Lake
- -5.4 cm per decade at Yellowknife

- -7.4 cm per decade at Inuvik

These trends are consistent with traditional knowledge reports of thinner ice from nearly all the communities in the region (Chapter 1, Table 1).

Projected changes

The first published estimates of changes in fresh water ice cover over northern Canada in response to global warming were obtained using observed temperature sensitivities of freeze-up/break-up with projected changes in air temperature provided by global climate models. Prowse et al. (2002) provided an 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 per °C estimated by Magnuson et al. (2000) and projected increases of 3–7°C in spring air temperatures by

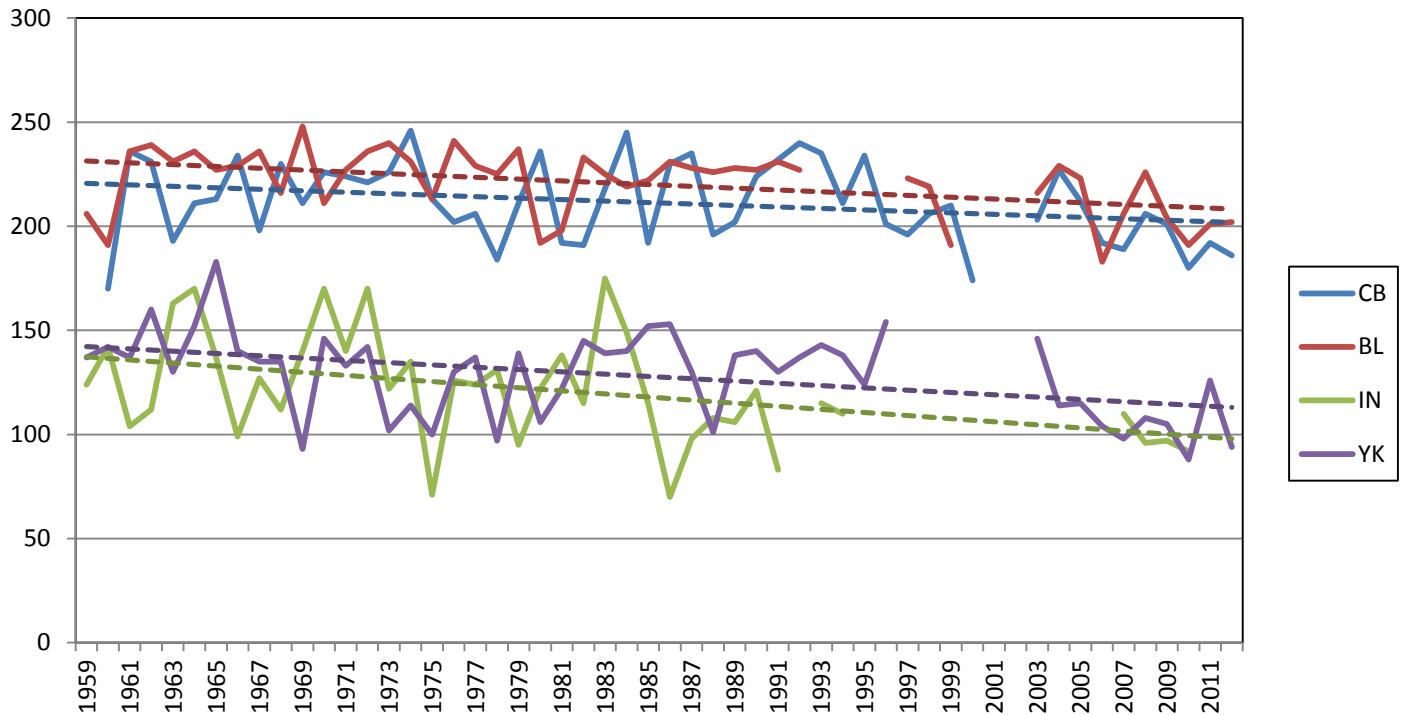


FIGURE 21. Annual series of maximum ice thickness (cm) at four sites in and adjacent to the IRIS region with the longest period of record: Cambridge Bay (CB), Baker Lake (BL), Inuvik (IN) and Yellowknife (YK). The dashed line is the trend from least squares linear regression.

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 (Brown and Duguay 2011; Dibike et al. 2011, 2012). White ice is formed when surface slush refreezes and is incorporated into the ice layer. Key results from these studies are listed below:

- Projections show an earlier break-up over the IRIS region in the 10-25 day range and a later freeze-up in the 0-10 day range for 2050.
- Ice thickness is projected to decrease by about 20-50 cm over the western part of the IRIS region with an increased potential for white ice formation.

These model simulations are based on an “idealized lake” of fixed depth. In reality, lake response will vary with lake size and depth and with local factors affecting snow accumulation (Brown and Duguay 2011).

Warming impacts on river ice dynamics and ice-related flooding is more complex than lakes particularly over the Mackenzie River, which will be subjected to a warming gradient. Prowse et al. (2010) show that under projected warming scenarios, the outlet regions of northward flowing rivers in the Arctic warm faster than the head-water regions. This results in a decrease in the latitudinal gradient in zero-crossing date along with thinner ice. This impacts the relative occurrence of thermal versus dynamic break-up events with important implications for ecology. There is some evidence that break-up severity has declined in recent decades near the Mackenzie Delta (Goulding et al. 2009) linked to reductions in

winter snow accumulation associated with spring warming (Lesak et al. 2014).

Understanding still remains poor on how climate change will alter other freshwater-ice processes other than freeze-up/break-up and thickness such as ice-cover composition and break-up dynamics (Prowse et al. 2007; Beltaos and Prowse 2009).

2.3.7 Wind and storms

There is a prevailing weather system of atmospheric high pressure above the Beaufort Sea region. This high pressure leads to a roughly clockwise (anticyclonic) wind circulation in the area. The wind averages illustrated in Figure 22 indicate the inter-season variability in this anticyclonic circulation. Noteworthy in the winter season are the predominantly

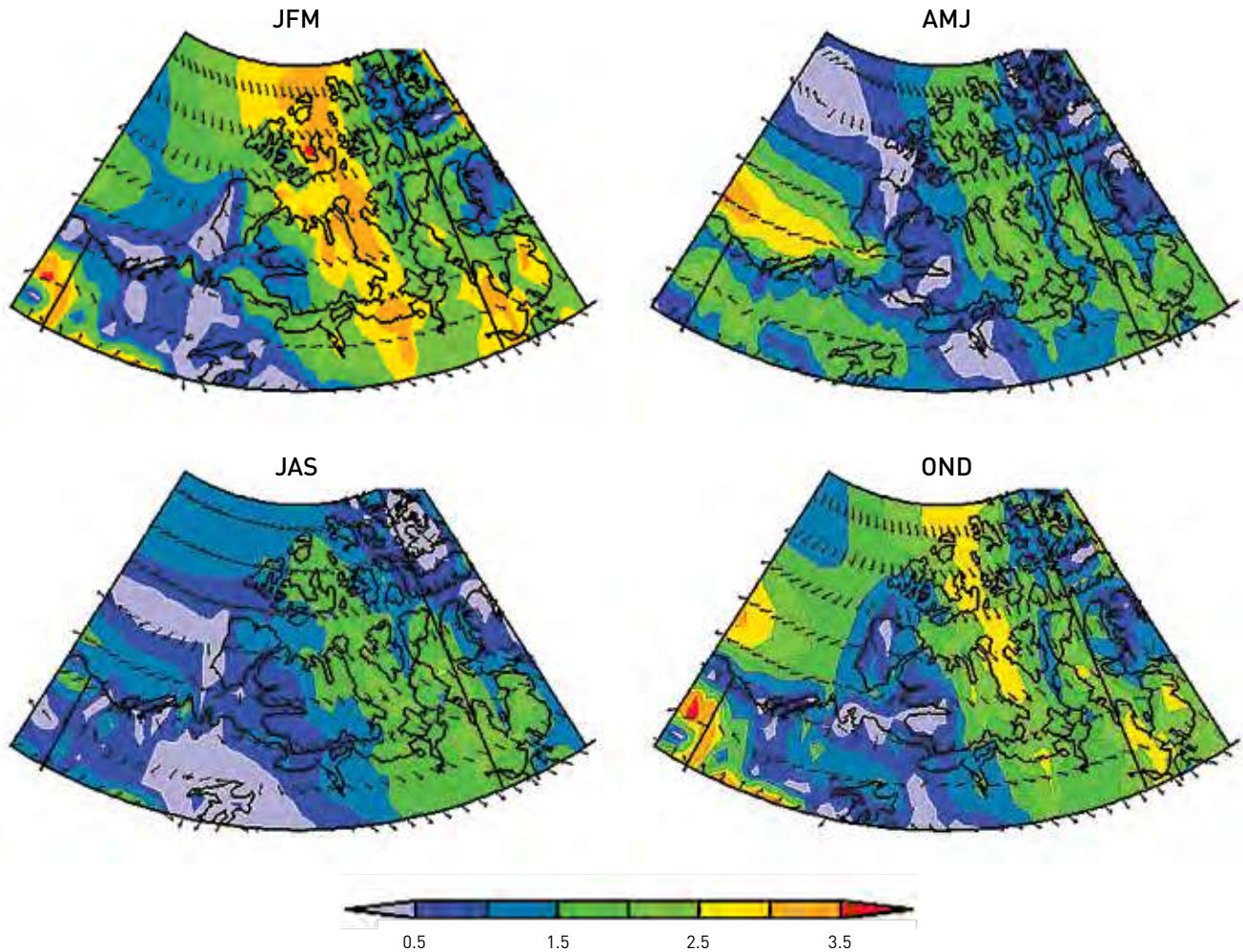


FIGURE 22. Seasonal means of NARR winds (vector and speeds) in the western and central Canadian Arctic during a) winter (JFM) b) spring (AMJ) c) summer (JAS), and d) fall (OND) from 1981 to 2010 (units in m s^{-1}). Data from NOAA/ESRL Physical Sciences Division.

north-easterly flow to the west of Banks Island and the easterly flow along the coast, with maximum speeds over the Canadian Archipelago (Figure 22, top left hand corner). In spring, easterly flow dominates in the Beaufort Sea region and northerly flow dominates in the Canadian Archipelago, with maximum values along the Beaufort coast. In the summer, comparatively weak easterly and north-easterly winds are observed over the Beaufort Sea while extrema on the order of 2.5 m s^{-1} exist over the Canadian Archipelago. Finally, in fall the wind patterns are comparable to those

found in winter, with dominant easterly winds along the Beaufort coast and northerly winds exceeding 3 m s^{-1} over the Canadian Archipelago.

Any recent changes in regional wind patterns can be examined by comparing the patterns from 2007-2010 to the average wind patterns in the same area between 1981 and 2010. This analysis provides the wind “anomalies”, which are the departures from the long-term average. These anomalies are illustrated in Figure 23.

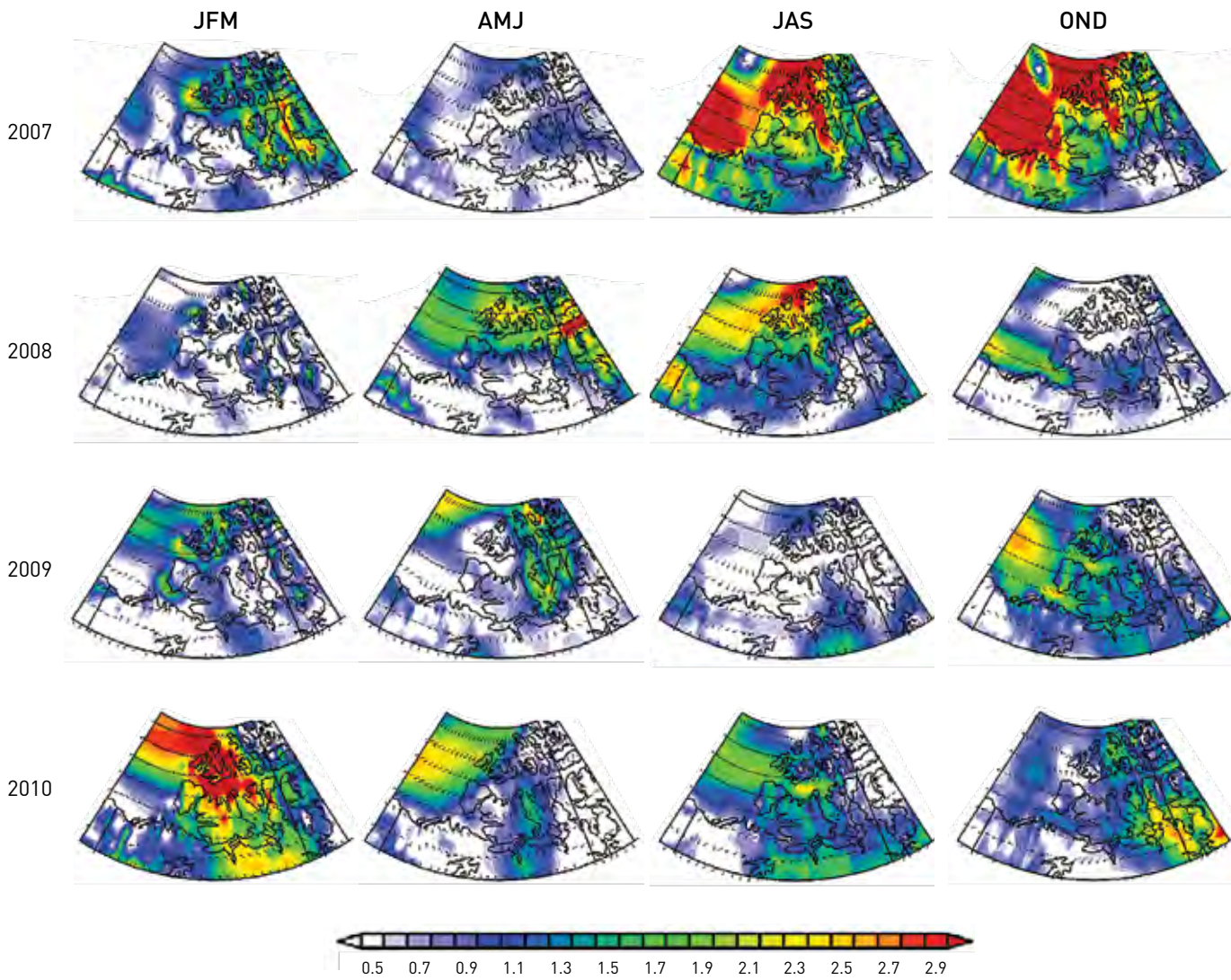


FIGURE 23. Seasonal NARR wind (vector and speeds) anomalies in the western and central Canadian Arctic during winter (JFM; first column), spring (AMJ; second column), summer (JAS; third column), and fall (OND; fourth column) from 2007 to 2010 (units in m s^{-1}). Data from NOAA/ESRL Physical Sciences Division.

Although there was some regional and temporal variation, overall the wind anomalies from 2007 to 2010 relative to the 1981-2010 period indicate enhanced winds throughout the Beaufort Sea region. Of particular interest is the strengthening of the characteristic north-easterly and easterly winds associated with the persistent high pressure over the Beaufort Sea. These strong winds contributed to the record minimum in sea-ice extent in late summer and early fall of 2007; these winds also contributed to enhanced meridional (north-south) flow over the Canadian Archipelago associated with what is referred to as the dipole anomaly (Wu et al. 2006; Wang et al. 2009). Enhanced westerly flow was observed along the Beaufort coast during the fall of 2008. By contrast, the Beaufort Sea region was distinguished by predominantly easterly flow in the fall of 2009 with a poleward retreat in maximum easterly winds in winter of 2010. Enhanced easterly winds were also present in the fall of 2010.

Regional averages for surface winds were calculated for zonal (east-west) and meridional (north-south) components (shown in Table 10 and Figure B4 in Appendix B). In general, fall and winter had the strongest winds for all areas within the IRIS region; the weakest winds were during the spring and summer. M'Clintock Channel was the region with the strongest winds while Eastern Parry Channel and the Western Arctic Waterway had the weakest.

There were very few regions with significant trends in wind magnitude over the 1981-2010 period. During March, July, and October the magnitude of the winds in the Eastern High Arctic increased by 1.1, 1.3 and 1.5 m s^{-1} per decade respectively. The only other region with a statistically significant increase in wind magnitude was the Beaufort Sea region during October, with an increase of 0.83 m s^{-1} per decade.

There was little change in the wind direction during the colder and transition (fall/spring) months. However, during the warmer months there was a shift in direction for most regions (see Figure B4 and B5 in Appendix B), with the exception of the Franklin and Western Arctic Waterway regions. During August there was a decreasing zonal

(east-west) component of the wind for the Beaufort Sea, Western High Arctic, Eastern High Arctic, Western Parry Channel, and Eastern Parry Channel.

Also of interest are the contributions of reduced ice cover and increased surface warming to storm activity in the Arctic (Simmonds et al. 2008). An assessment of storm occurrence in the Beaufort Sea region from 1979 to 1995 documented numbers between six and twenty-seven per year with no significant trend in frequency. The Beaufort Sea is characterized by a comparatively high frequency of anticyclones relative to other Arctic regions due to the high-pressure ridge at sea level established between the Chukchi and Beaufort seas (Colucci and Davenport 1987; Serreze et al. 1993; Simmonds et al. 2008). The climatology of the Beaufort Sea was characterised by atmospheric pressure patterns over the Beaufort Sea into 12 different regimes or synoptic types (Asplin et al. 2009). The regimes were categorized by cyclonic or anticyclonic circulation with the Beaufort High being dominant in seven of the twelve types. They found that for three of the twelve classifications there was strong cyclonic activity over the Beaufort Sea region. However, during the winter months, there was a higher frequency of anticyclonic activity. A more recent assessment of storm activity based on the cyclone tracking algorithm by Serreze (2009) demonstrated maximum cyclone frequencies in fall, 2007 in a manner consistent with studies by Hudak and Young (2002).

Cyclones, which are counter-clockwise rotating weather systems, also occur in the Beaufort Sea region. Investigation of storm intensity and frequency for the IRIS region from 1981 to 2008 showed a shift in cyclone intensity from winter to fall in recent years and a slight increase in cyclone frequency in spring over the past several decades (Figure 24) (Serreze 2009). Analysis of cyclone frequencies over the Beaufort Sea region indicates an increase in winter storms over the Beaufort Sea in recent years (not shown in figures), most likely once again due to an increase in open water extent in fall. Recent studies of trends in storms based on cyclonic activity from 1948-2002 further highlighted an increase in frequency of incoming cyclones through Bering

TABLE 10. The 1981-2010 monthly surface wind (m s^{-1}) averages for local areas within the IRIS region. Zonal winds (east-west) are listed on top, and meridional (north-south) are listed on the bottom. Negative values refer to easterlies (east to west) listed on top, and northerlies (north to south) listed on the bottom. Data from Candlish et al. (2014).

	BEAUFORT SEA	W. HIGH ARCTIC	E. HIGH ARCTIC	W. PARRY CHANNEL	E. PARRY CHANNEL	M'CLINTOCK CHANNEL	FRANKLIN	W. ARCTIC WATERWAY
Jan	-0.29	0.61	-1.60	1.83	0.86	1.88	2.32	2.00
	-0.31	-2.24	-2.05	-2.15	-1.24	-3.11	-1.73	-0.51
Feb	-0.27	0.63	-1.51	1.64	0.76	1.85	2.26	1.73
	-0.23	-1.95	-1.76	-1.86	-1.12	-2.78	-1.53	-0.33
Mar	-0.46	0.42	-1.51	1.37	0.38	1.45	1.72	1.10
	-0.56	-1.35	-0.92	-1.70	-0.46	-2.25	-1.12	-0.40
Apr	-1.85	0.29	-1.20	0.45	0.40	1.05	1.15	-0.47
	-0.43	-1.34	-1.13	-1.23	-0.72	-2.19	-1.40	-0.12
May	-1.88	0.45	-1.27	0.67	-0.04	1.17	1.11	-0.43
	-0.55	-1.51	-0.87	-1.57	-0.91	-2.30	-1.68	-0.48
Jun	-1.69	0.61	-0.85	0.85	-0.30	1.24	1.12	-0.38
	-0.44	-1.08	-0.31	-1.33	-0.66	-2.05	-1.41	-0.50
Jul	-0.40	0.75	-0.89	1.49	-0.25	1.68	1.32	0.29
	-0.21	-0.77	0.22	-1.32	-0.34	-2.03	-1.44	-0.91
Aug	0.06	0.72	-1.13	1.53	-0.22	1.71	1.57	0.70
	-0.09	-0.43	0.09	-1.08	-0.74	-2.24	-1.70	-0.74
Sep	-1.16	0.32	-1.33	0.58	-0.23	0.79	0.84	-0.08
	-0.07	-0.51	-0.31	-1.16	-0.80	-2.53	-1.55	-0.31
Oct	-2.02	-0.06	-1.79	0.27	-0.35	0.74	0.83	-0.35
	-0.63	-1.17	-0.71	-1.64	-0.68	-2.90	-1.51	-0.29
Nov	-1.36	-0.02	-1.90	0.92	0.07	1.32	1.66	0.68
	-0.46	-1.63	-1.28	-1.71	-0.93	-2.66	-1.34	-0.25
Dec	-1.17	0.33	-1.89	1.43	0.47	1.65	1.99	1.17
	-0.57	-2.23	-1.63	-2.12	-0.95	-3.03	-1.57	-0.45

Strait and western Canada (Sepp and Jaagus 2011). Studies using a measure of cyclone intensity, frequency and duration known as the cyclonic activity index documented an increase in frequency and intensity of storms entering the Arctic from 1979 to 2002, particularly in the North Atlantic and Eurasian sectors of the Arctic (Zhang et al. 2004). A recent study of correspondence between sea-ice loss and enhanced cyclonic activity indicated dominant contributions from cyclone strength (depth) rather than frequency in the Arctic (Simmonds and Keay 2009). Furthermore, an

assessment of precipitation minus evaporation indicative of convergence and uplift associated with increased cyclonic activity was shown to dominate in the Beaufort Sea region in summer (Serreze and Barrett 2008).

Recently there has been a significant amount of research into the interactions between winds, storms and sea ice (e.g. Barber and Hanesiak 2004; Lukovich et al. 2009, 2011 2014; Asplin et al. 2012, 2014, 2015; Raddatz et al. 2014). Lukovich et al. (2014) used case studies to show

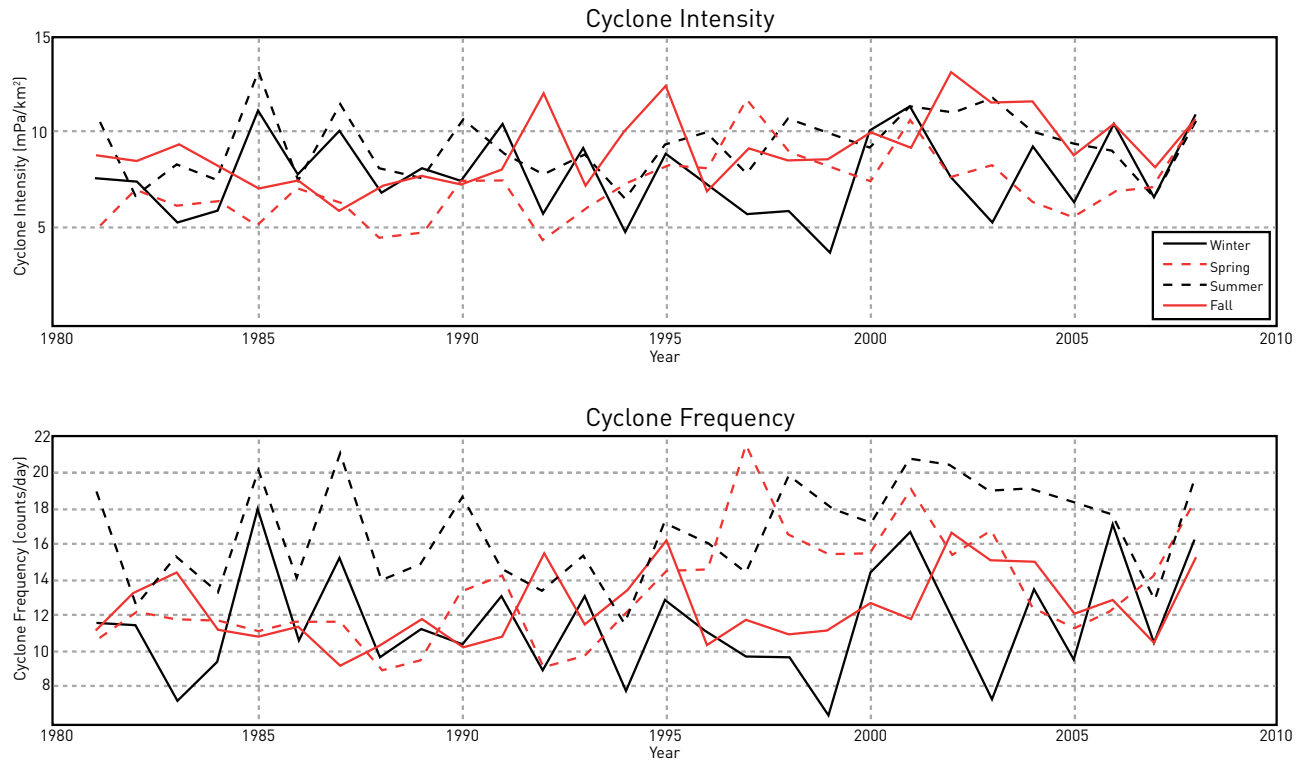


FIGURE 24. Time series of seasonal means for cyclone intensity (defined as the local laplacian of the pressure system) (upper panel) and cyclone frequency (lower panel). Data obtained from tracking algorithm by Serreze (2009).

that strong coincident winds and ocean currents can induce reversals in sea-ice motion for periods of time (or time intervals) longer than 12 hours. Another case study documented in 2009, by Asplin et al. (2012), observed long waves from a strong cyclone that propagated deep into the pack ice, thereby causing swells in the ice and the eventual rapid break-up of the sea-ice pack. This process reduced the floe size into smaller more mobile pieces and increased floe surface area, and thereby affecting sea-ice dynamic and thermodynamic processes (Asplin et al. 2014). With the increase in storm strengths, and the shifting of wind directions during the summer months, modeling of small-scale, high-frequency processes of sea-ice motion will prove to be more difficult.

2.4 Climate change projections

The climate change scenarios used in this assessment were provided by Ouranos, a non-profit climate change consortium based in Montreal (www.ouranos.ca). The climate change projections for the IRIS region were built by dynamically downscaling Global Climate Model (GCM) outputs with spatial resolutions of ~200-400 km to a higher resolution (45 km at 60°N) using the Canadian Regional Climate Model (CRCM4) (Music and Caya 2007; de Elía and Côté 2010; Paquin 2010) run at Ouranos. The projected change information was computed for the 2050 time period using the difference between 30 year averages for “future climate” (2041-2070) and “reference climate” (1971-2000) assuming the Special Report on Emissions Scenarios (SRES) A2

scenario for future greenhouse gas emissions (Nakicenovic et al. 2000). Please see Appendix A for a complete description of the model and the parameters.

Air temperature and total precipitation

Projected changes in air temperature and total precipitation over the IRIS region are summarized in Figure 25 and Figure 26. The main characteristics of the projected changes over the region are:

- The largest changes are projected to occur during fall and winter seasons (~5-6°C increase in air temperature and ~20-30% increase in total precipitation).
- The spatial pattern in air temperature change shows a south-to-north gradient over the region (greater relative increases to the north).
- The largest temperature increases are projected to occur over marine areas where sea-ice extent is projected to decrease.

A summary of the projected changes in several climate-related variables is presented in Table 11. Some key points from this table are listed below:

- An earlier summer season-onset (~4-12 days) and end (~6-10 days) extends the length of the season with above-freezing temperatures by about 10 to 22 days.
- A shorter winter season (10 to 22 days) reduces the snow covered period about a month.
- A projected increase in solid precipitation (14-30%) results in increased maximum snow depths (~1 to 10 cm) despite the shorter snow cover season.

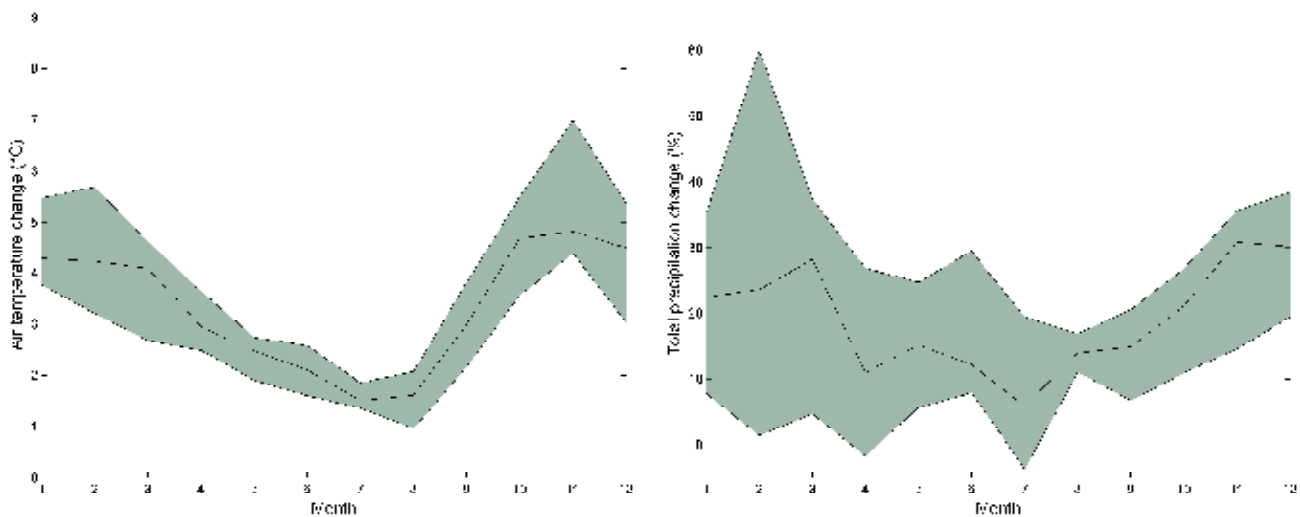


FIGURE 25. Seasonal median and range of projected changes in monthly mean air temperature (left panel) and total seasonal precipitation (right panel) from eight CRCM runs for 2050 averaged over all the grid cells of the IRIS region. The outer lines represent the range of the eight simulations.

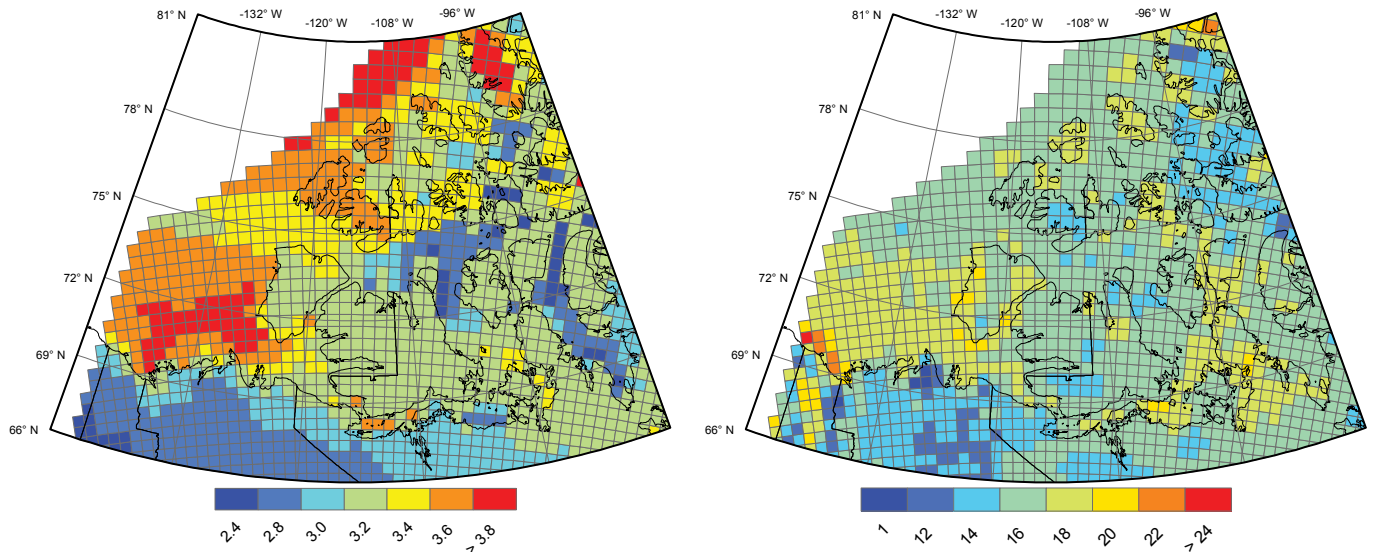


FIGURE 26. Projected change in mean annual air temperature (left panel) (°C) and in mean annual total precipitation (right panel) (%) from eight CRCM runs for horizon 2050.

These projected changes for the summer and winter season duration were supported by similar results for projected changes in lake ice duration and thickness estimated using a study by Dibike et al. (2012). The lake ice projections predicted later onset of lake ice by about six to eight days and earlier break-up of about eight to sixteen days over the Western and Central Arctic Region. Furthermore, ice thickness was projected to decrease ~20 to 35 cm by 2050.

2.5 Summary and conclusions

This chapter highlighted the current climatology and trends for air temperatures, permafrost and ground temperatures, precipitation, snow, sea ice, river and lake ice, and wind and storms. Projections for key variables were made for the next 20-50 years; these projected changes can be used to estimate the impact and vulnerability of the natural system, ecosystem and human activities. Below is a summary of the key points and projections.

Air temperature

The climate of the western and central Canadian Arctic is currently experiencing a period of rapid climate warming that is likely unprecedented in the last 44,000 years (Miller et al 2013). The stronger warming of cold temperatures is consistent with Inuit traditional knowledge of fewer winter extreme cold temperatures at many communities in the region and is also consistent with climate model projections that show cold extremes warming faster than warm extremes over regions with snow and ice cover. The following summarizes some of the other key points for air temperatures in the IRIS region:

- The warmest mean annual air temperature (-8.1°C) was observed at Inuvik in the Mackenzie Delta and the coldest (-16.8°C) at Mould Bay on Prince Patrick Island.
- Between 1981 and 2010 the climate stations in the IRIS region have had an observed average annual temperature increase $0.7\text{--}1.2^{\circ}\text{C}$ per decade.

TABLE 11. Summary of projected changes in climate variables for the IRIS region for 2050. Maps showing the spatial patterns of the projected changes are shown in Appendix A.

CLIMATE VARIABLE	PROJECTED CHANGE OVER REGION	COMMENTS
Annual air temperature	+3 to +5°C	NW-SE gradient with strongest annual temperature increases is projected over the northern part of the region.
Seasonal air temperature	+1 to +7°C	Winter change is fairly uniform over land ranging from 4 to 5°C. Winter strong warming is projected over most northern part of ISR (Prince Patrick, Mackenzie King, Brock and Borden islands). Strongest summer warming occurs over the northern part of the ISR and Banks Island. Over all seasons, the strongest warming is located over the sea area, north of Tuktoyaktuk and west of Banks Island.
Thawing degree days	4 to 240 degree days	Changes are largest on land (145 to 240 DD). Lowest values occur over ocean areas.
Growing degree days	0 to 179 degree days	Changes are largest on land. Lowest values occur over ocean areas.
Summer-onset date	4 to 12 days earlier	Changes toward earlier summer-onset dates are more pronounced over the northern and eastern parts of the IRIS region.
Summer end date	5.9 to 10 days later	Change is more pronounced over the most northern islands and on coasts.
Summer duration	10 to 22 days longer	Strongest change in summer duration is projected over the most northern part of the ISR. A clear SW-NE gradient is visible.
Number of winter thaw (Nthaw) events	-0.7 to +1.2 events per year	Increasing Nthaw events occur on a SW-NE gradient.
Total precipitation rate (rainfall + snowfall)	10 to 22% increase	Largest increase occurs over the southern part of the IRIS region with daily average changes between 0.1 to 0.2 mm.
Seasonal total precipitation (rainfall + snowfall)	2 to 36% increase	Largest relative changes occur during winter and fall, mostly north of the IRIS region (23 to 29%). Large changes (>30%) appear to be fairly marginal.
Annual total precipitation (rainfall + snowfall)	22 to 68 mm per year	Largest change is projected over the southern part of the IRIS region. Decreasing projected change toward the northern part of the region.
Rain-on-snow frequency (ROS days per year)	-0.39 to +0.35 days per year	ROS days are rare. Projected changes for the IRIS region are small with slight increases in ROS frequency (trend not significant) over the western part of the region.
Annual solid precipitation (snowfall)	14 to 30%	No clear pattern. Changes projected over land regions are generally between 14 and 26%.
Annual maximum snow depth on land and on islands	1 to 10 cm	Increases projected over terrestrial sectors of the IRIS region range between +3 and +10 cm.
Onset of snow season	From 5 days earlier to 24 days later	Western part of the IRIS region (>110°W) shows more variability with both earlier and later values in starting dates of snow period. In general, the IRIS region shows later snow season-onset dates with few early dates.
End of snow season	1 to 13 days earlier	Change occurs on a SW-NE gradient.

- Nine of the ten warmest monthly average air temperatures of the 1950-2012 period in the IRIS region have occurred since 1997. The 1998 extreme high temperature was the 2nd warmest monthly average air temperature after 2010.
- When looking at air temperatures over the ocean:
 - Winter showed warming trends of 0.3–1.1°C per decade over the northern and eastern part of the region.
 - Spring showed warming trends of 0.5–1.3°C per decade over most of the Archipelago.
 - The summer had warming trends of up to 1.6°C per decade over the northern Archipelago.
 - The fall showed warming trends over most of the region ranging from 0.3–1.1°C per decade.
 - For the month of September the temperatures from 1981-2010, for all of the defined regions, increased by 2-4°C.

Projections for 2050 by the Canadian Regional Climate Model (CRCM4) show that the largest changes in air temperature for air temperatures indicate the largest changes occur during the fall and winter seasons (~5-6°C increase in air temperature).

The largest relative temperature increases are projected to occur over marine areas where sea-ice extent is projected to decrease.

Permafrost and ground temperature

Strong regional variability in warming response is a consistent theme in all the cryospheric variables analysed in this chapter and permafrost is no exception. Permafrost temperatures in the region are estimated to have warmed ~2°C since the 1960s and 1970s in the outer Mackenzie Delta.

However, the rate and timing of warming shows important regional variability with the largest warming observed in the cold tundra environments of the western Arctic. The largest changes in active layer depth and permafrost thickness have occurred south of the IRIS region in the discontinuous permafrost region. Some additional key points about permafrost are listed below:

- Permafrost and paleoclimatic data show the Inuvialuit Settlement Region and the Kitikmeot region have experienced a period of sustained warming over the last ~200 years.
- Analysis of historical climate data show the warming is most marked in the winter period with warming of ~4°C over the region since 1950.
- There was recent rapid warming of permafrost over the North American Arctic during the 1980s and 1990s with warming rates since 1970 averaging from a few tenths of a degree up to 1°C per decade.
- Different projections for the region indicate that permafrost near surface temperatures could increase between 2 and 5°C for the timeframe of 2041-2070.

Precipitation and snow

The observed warming has been accompanied by significant increases in precipitation in all seasons with the largest increases in winter (~10% increase since 1950). Warming and increased precipitation play competing roles in snow depth; warming shortens the accumulation period, which may or may not be offset depending on the rate of snow-fall increase. This helps explain the strong variability in observed trends in snow depths over the IRIS region with decreased maximum snow depths reported at some communities (e.g. Baker Lake) but increased snow accumulation at others (e.g. Norman Wells). The following summarizes some additional key points and projections for snow and precipitation:

- Analysis of in situ daily snow depth observations illustrate that the period of snow on the ground has decreased an average of ~15 days over the region since 1950 with most of the decrease coming from earlier snow melt.
- Both snowfall and rainfall exhibit significant increasing trends over the 1950-2010 period.
 - The strongest total precipitation increases were observed for winter (11.5% per decade), followed by fall (7.3%), spring (3.7%), and summer (2.9 %).
 - Total annual snowfall increased at 9.8% per decade.
 - Total annual rainfall increased at 6.0% per decade.
 - All the climate stations had significant trends toward a later onset to the snow cover season and toward a significantly shorter period of continuous snow cover.
 - Rates of change range from ~10-20 days per decade.
- The CRCM4 model shows a projected increase (for the timeframe 2041-2070) in solid precipitation (14-30%) which results in increased maximum snow depths (~1 to 10 cm) despite the shorter snow cover season.
- The CRCM4 model also projects a 20-30% increase in total precipitation for the timeframe 2041-2070.
- Annual total precipitation is projected to increase by 22-68 mm per year. The largest change is projected over southern part of IRIS region. Decreasing projected change toward northern part of the region.

Sea ice

Ice observations from the Canadian Ice Service Digital Archive show that the summer sea-ice cover (all ice types) has decreased significantly over the period since 1968 at a rate of ~3% per decade in the Canadian Arctic Archipelago and ~5% per decade in the Beaufort Sea. However, there

is considerable variability in trends within the IRIS region with some regions such as the north-western Parry Channel route to the Northwest Passage showing no trend. The area of multiyear ice is also decreasing but at a slower rate due to the continuous import from the Arctic Ocean. The following summarizes the main points and key trends for sea ice in the IRIS region:

- The regions with the shortest open water seasons were the Western High Arctic, Western Parry Channel and M'Clintock Channel, where the average length was zero weeks, one week, and one week, respectively.
- The Eastern Parry Channel and Western Arctic Waterway had the longest average open water season, 13 and 14 weeks respectively.
- Although the Arctic Ocean as a whole has an increasing open water season (Barber et al. 2015), the only part of the IRIS region with a statistically significant trend was Eastern Parry Channel, where the open water season increased by approximately one week per decade.
- The total sea-ice concentrations were consistently high (>95%) from approximately November through to May in all of the regions.
- The region with the most consistently high concentrations of MYI was the Western High Arctic; however, the Beaufort Sea, Western and Eastern Parry Channel, and M'Clintock Channel also had relatively high amounts of MYI.
- During the timeframe 1981-2010, the amount of multi-year sea ice in the Beaufort Sea declined nearly 9% per decade during late summer and fall (September through to December), while the other regions showed little or no trends in multiyear sea ice.
- The most dramatic decreases in ice concentration occurred during late summer and early fall (August, September and October).

- The most significant decline of total sea-ice concentration occurred from 2001-2010 and occurred during September, the typical sea ice minimum. The most dramatic decreases for the 2001-2010 during September are given based on the Canadian Ice Service defined sub-regions:
 - Western Parry Channel showed a decline of 53% for the September monthly average total sea-ice concentration during 2001-2010.
 - M'Clintock Channel showed a decline of 50% for the September monthly average total sea-ice concentration during 2001-2010.
 - The regions Eastern High Arctic and Eastern Parry Channel both showed a decline of 38% for the September monthly average total sea-ice concentration during 2001-2010.
 - The Beaufort Sea showed a decline of 26% for the September monthly average total sea-ice concentration during 2001-2010.
 - The Franklin Strait region showed a decline of 27% for the September monthly average total sea-ice concentration during 2001-2010.

River and lake ice

River and lake ice cover duration is declining over the region; it is unclear how fast this is taking place and what the relative contributions are from changes in freeze-up and break-up. Trends in freeze and thaw dates from surface air temperature data suggest warming is taking place at approximately the same rate over the freeze-up and break-up periods. The available freshwater ice thickness observations in the region all show statistically significant decreases in maximum ice thickness ranging from 20-40 cm since 1960. These trends are consistent with traditional knowledge reports of thinner ice from nearly all the communities in the region. Some of the key points from the river and lake ice section are summarized below:



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- The thinnest lake ice in the region was observed at Inuvik and Yellowknife (~1.2 m) with the maximum ice thickness of over 2 m at Baker Lake.
- The average date of maximum river/lake ice thickness varies ~2 months over the region from mid to late-April at Yellowknife, Inuvik and Norman Wells, to mid-June at Mould Bay.
- The period when ice is considered safe for traffic by observers exhibits considerable variability between sites reflecting local climate conditions and ice dynamics. The shortest ice safe period (~4 months) is observed at Inuvik and the longest (7-8 months) at Cambridge Bay and Mould Bay.

- Over the years 1960–2010 the annual maximum ice thickness decreased by:
 - -3.5 cm per decade at Cambridge Bay
 - -4.3 cm per decade at Baker Lake
 - -5.4 cm per decade at Yellowknife
 - -7.4 cm per decade at Inuvik
- Ice thickness is projected to decrease by about 20-50 cm over the western part of the IRIS region with increased potential for white ice formation.
- Studies show that under projected warming scenarios, the outlet regions of northward flowing rivers in the Arctic warm faster than the headwater regions.
- During the warmer months there was a shift in direction for most regions. During August there was a decreasing zonal (east-west) component of the wind for the Beaufort Sea, Western High Arctic, Eastern High Arctic, Western Parry Channel, and Eastern Parry Channel.
- The Beaufort Sea region had an increase in winter storms in recent years, most likely due to an increase in open water extent in fall.

The climatology of the western and central Canadian Arctic is undergoing considerable change. The cryosphere and icescape are rapidly changing, due in part to changes in the atmosphere and ocean. The above sections summarized the observed and projected changes over the IRIS region that vary seasonally, regionally, and with different time scales e.g. permafrost temperature has a much longer time response to warming than snow cover or sea ice. The chapter also highlighted some of the complex linkages and interactions in a changing climate e.g. the numerous (predominantly positive) feedbacks involving snow cover, ground temperatures and carbon cycling associated with shrub expansion in tundra regions. One important take-home message from this is that climate change is not expected to be uniform over the region, which reinforces the need for continued scientific and community-based monitoring to document and understand the observed rates of change and the associated processes and interactions.

Winds and storms

Recently there has been a significant amount of research into the interactions between winds, storms and sea ice. The wind and storm section summarized this research in the western Canadian Arctic and found that although there is an increase in storm intensity there is little evidence to indicate any change in the number of storms that will go through the area. Some of the more complex interactions from the change in storm intensity however is that the more intense storms, with an increased amount of open water, can change the amount of precipitation a region will receive. The following summarizes some of the other key findings from the wind and storm section:

- The strongest winds typically occur during the fall and winter with seasonal averages of 3 m s^{-1} .
- There were very few regions with significant trends in wind magnitude over the 1981-2010 period. During March, July, and October the magnitude of the winds in the Eastern High Arctic increased by 1.1, 1.3 and 1.5 m s^{-1} per decade, respectively.

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Appendix A

Climate change projections for the western and central Canadian Arctic

Climate change scenarios are “coherent, internally consistent and plausible descriptions of possible future states of the world” (IPCC 1994) that provide a means to assess the potential impacts of climate change on the environment. Scenarios can be constructed from various methods (e.g. Mearns et al. 2001) and those presented here come from dynamical downscaling of GCM simulations using the CRCM.

This appendix presents climate change scenarios for a number of key climate indicators (see Table 11) for the western and central Canadian Arctic IRIS region. This set of climate indicators is based on the one provided for the eastern sub-Arctic IRIS final report (Barrette et al. 2012; Brown et al. 2012).

As a result of the increasing concentration in greenhouse gases (GHG) significant changes to the climate are likely to occur over the Northern Hemisphere for the 2040-2070 period and further by the end of the century (Christensen et al. 2007). As many factors can influence the path of the projected changes in numerical models, scenario users need to be aware of what is called the “cascade of uncertainty” (Jones 2000). According to Jones (2000) the sources of uncertainty in climate models are related to: greenhouse gas emissions, greenhouse gas cycles, radiative forcing and climate sensitivity. From these, the radiative forcing appears to be the key source of uncertainty in models (Visser et al. 2000). Moreover, other sources of uncertainty are attributed to the formulation of the GCM, the natural variation of the climate system and the ability of regional climate models (RCMs) to down-scale global projections to finer scales (Rowell 2006). An evaluation of uncertainties of the CRCM simulated climate (de Elía et al. 2008) concluded that the internal climate variability and configuration set-up errors are smaller than those related to the choice of driving GCM

and are not a major obstacle to downscaling projections (Brown et al. 2012). Other means of evaluating uncertainty can be obtained by the Rowell-type analysis (Rowell 2006). However, a relatively large number of GCM and RCM runs are necessary to perform this type of analysis. The number of CRCM runs used here is insufficient to perform a Rowell-type analysis. The method used to evaluate the uncertainty in this study is outlined in the following section.

Methodology

The climate change scenarios for the IRIS region are based on output from the Canadian Regional Climate Model, CRCM, version 4.2.3 (Music and Caya 2007; de Elía and Côté 2010; Paquin 2010). The CRCM provides dynamically downscaled GCM simulations at a spatial resolution of ~45 km (higher than most GCMs which typically have horizontal resolutions in the ~200-400 km range).

A set of eight CRCM runs were used to construct scenarios. Two driving GCMs were used as input sources at the lateral boundaries: the third generation Coupled Global Climate Model (CGCM3) (Flato and Boer 2001; Scinocca et al. 2008) at a T47 spatial resolution (~400 km) and the ECHAM5 global climate model of the Max Planck Institute for Meteorology (Jungclaus et al. 2006). All CRCM future climate runs are forced using the Special Report on Emissions Scenarios (SRES) A2 greenhouse gas emission scenario (Nakicenovic et al. 2000). These particular runs were selected to insure a direct continuity with the previous climate change projections made for the eastern sub-Arctic IRIS assessment report (Allard and Lemay 2012) and were determined to have acceptable seasonal biases in temperature and precipitation compared to other climate models (Grenier 2013). The spatial pattern of the standard deviation (STD) of the eight runs was plotted along with the mean projected change (seasonal or annual) to provide some indication of the level of agreement (uncertainty) between simulations and how it varied over the study region.



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Because of the unequal number of CRCM runs driven by CGCM3 (five runs) versus ECHAM5 (three runs) both groups were assumed to be of equal weight when computing the mean and STD of the ensemble. Climate change scenarios were provided as the difference or “delta” in the 30-year mean values for the 2041-2070 “future climate” period minus the 1971-2000 “current climate” period. This method is effective at removing model bias, assuming the bias is relatively constant over time. The climate indicators are either:

expressed as an absolute change

$$\Delta_{\text{diff}} = \text{Value}_{\text{fut}} - \text{Value}_{\text{ref}}$$

and/or as a percentage change

$$\Delta_{\text{pct}} = 100 * (\text{Value}_{\text{fut}} / \text{Value}_{\text{ref}}) - 1$$

where $\text{Value}_{\text{fut}}$ and $\text{Value}_{\text{ref}}$ are respectively the future and reference 30 year normal average of a given simulation member.

Evaluation of CRCM for the IRIS region

Since its implementation at Ouranos, the CRCM has been used in a number of assessment reports and studies at the North American scale (Caya and Laprise 1999; Langlois et al. 2004; Plummer et al. 2006; Sushama et al. 2006; Music and Caya 2007; Sushama et al. 2007; Dibike et al. 2012).

Because of the limited number of CRCM simulations available over the IRIS region an assessment was made of the projected changes in seasonal air temperature and precipitation from the CRCM runs versus the projected changes from an ensemble of 71 GCMs to ensure that the CRCM results were representative (Figure A1). The results showed that the different CRCM runs (blue squares and diamonds

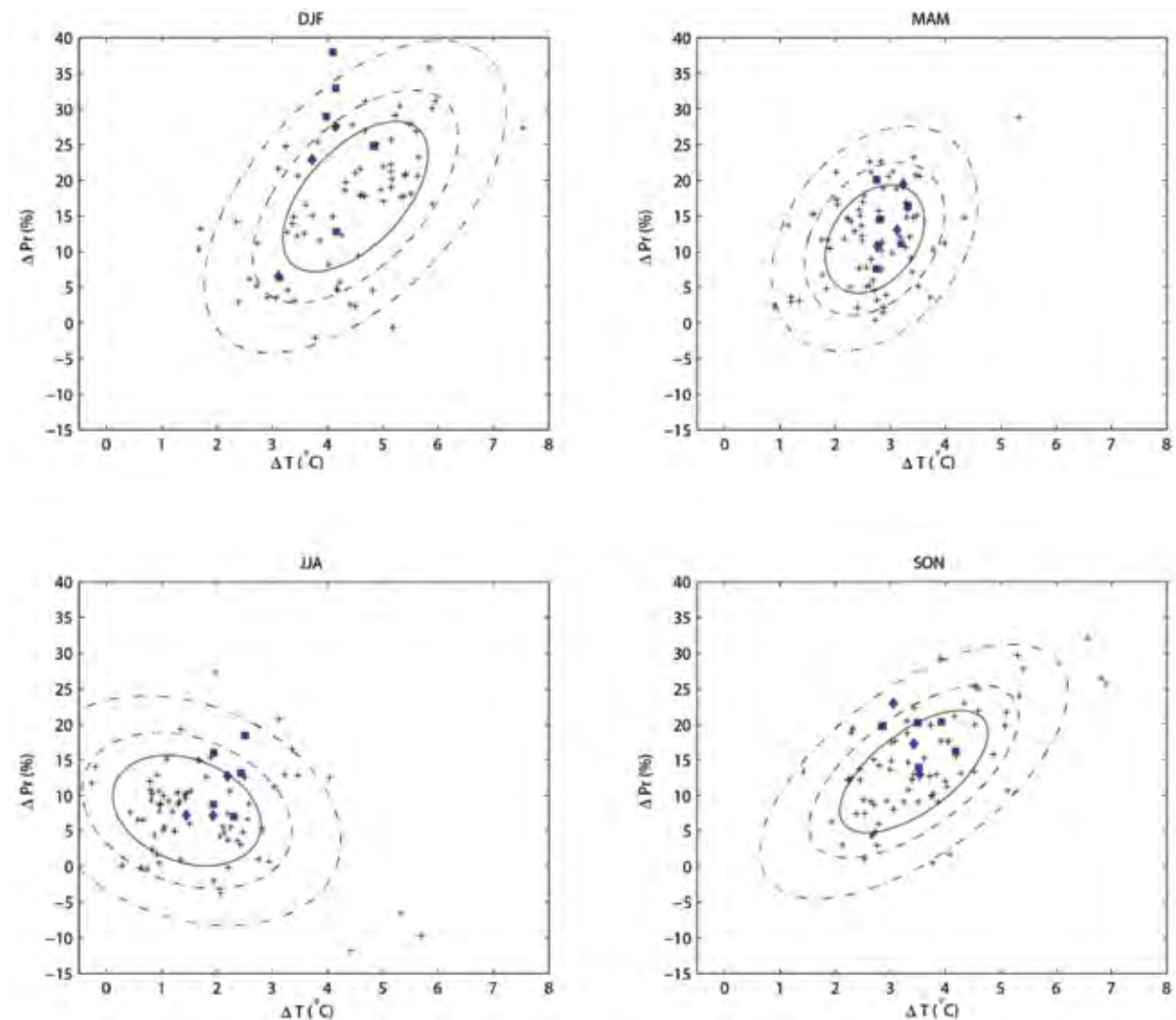


FIGURE A1. Seasonal mean precipitation (ΔPr in %) and mean temperature change (ΔT in Celsius) between 1976-1995 and 2046-2065 for the IRIS region by seasons. The '+' signs represent GCM, the squares represent CRCM runs piloted by CCCma-CGCM3 and the diamonds represents CRCM runs piloted by Max Planck Institute ECHAM5. DJF-December, January, February; MAM-March, April, May; JJA-June, July, August; SON-September, October, November

in Figure A1) are generally close to the GCM ensemble average (inside the ~50 and 75 percentiles). The exception was winter precipitation where the CRCM results are in the high range of the projected changes from the GCM ensemble. The CRCM results compare well with previously published estimates of Arctic climate change (Kattsov et al. 2007; Chapman and Walsh 2007).

Description of the climate indicators

This section is mostly taken from the Appendix of chapter 2 (Barrette et al. 2012) of the eastern sub-Arctic IRIS report *Nunavik and Nunatsiavut: From Science to Policy* (Allard and Lemay 2012). The readers can refer to this section for a detailed description of the indicators and method of calculation. Some of these methods were refined and may differ from the original text by Barrette et al. (2012).

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

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

An index of plant growth can also be obtained from the sum of degree-days above a threshold temperature corresponding to a plant's physiology e.g. the sum of daily mean air temperatures above 5°C is used to estimate growing degree days (GDD) in Arctic environments. Inversely, degree-days

can be used to calculate indices related to cooling e.g. freezing degree days (FDD) calculated as the sum of degree-days under 0°C are closely linked to ice growth (see USACE 2002). Degree-day indicators are also linked to ungulate population dynamics as they influence the amount of forage through the length of the growing season and the amount of primary production (Sharma et al. 2009).

Summer season length (SSL): The duration of the period with above-freezing air temperatures affects a wide range of environmental processes such as evaporation, precipitation type, and plant growing conditions. The duration of the summer season was computed from 0°C crossing dates using a centered 20 day moving average of daily mean air temperature.

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

Precipitation: Mean annual total precipitation (P_t) and annual solid precipitation (P_s) were obtained from 6-hourly averaged precipitation rate (mm per day) output from the CRCM. Calculations are made over a calendar year for P_t and from October to May for P_s . Precipitation was assumed to be solid when surface air temperature was $<0^\circ\text{C}$.

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

Snow cover duration (SCD): SCD is important for transportation, ground thermal regime and ecology. The snow cover season was defined here as the period with at least 2 cm snow depth which was found to correspond well with satellite observations of snow cover (Brown 2000). The start (end) date of the snow season was defined as the first (last) 5 consecutive days with snow depth above (below) the defined threshold.

Study area

A shape-file of the IRIS region boundaries was used to define the CRCM grid points within the region. An additional mask was applied to eliminate some points in regions of the CAA where the model simulated permanent or

semi-permanent snow cover. Snow cover change values computed at these points were unrealistic because CRCM does not include any physics for glacier ice formation

It is important to note that some of the projected change fields are quite noisy over the Canadian Archipelago because of grid cells overlapping land and ocean areas.

Results

Projected change in air temperature and related indices

Figure A2 presents the projected change in mean annual air temperature from an ensemble of eight CRCM runs. The projected increase in regionally-averaged annual temperature ranges from about 3 to 5°C with the largest projected warming over the northernmost islands (Borden, Brock, Mackenzie King, Prince Patrick, Eglinton). Warming is projected to be largest (4-7°C) in the fall (October through December) and winter (Figures A3 and A4) with a clear north-south gradient in the warming. Projected changes are relatively small in the spring and summer periods ranging

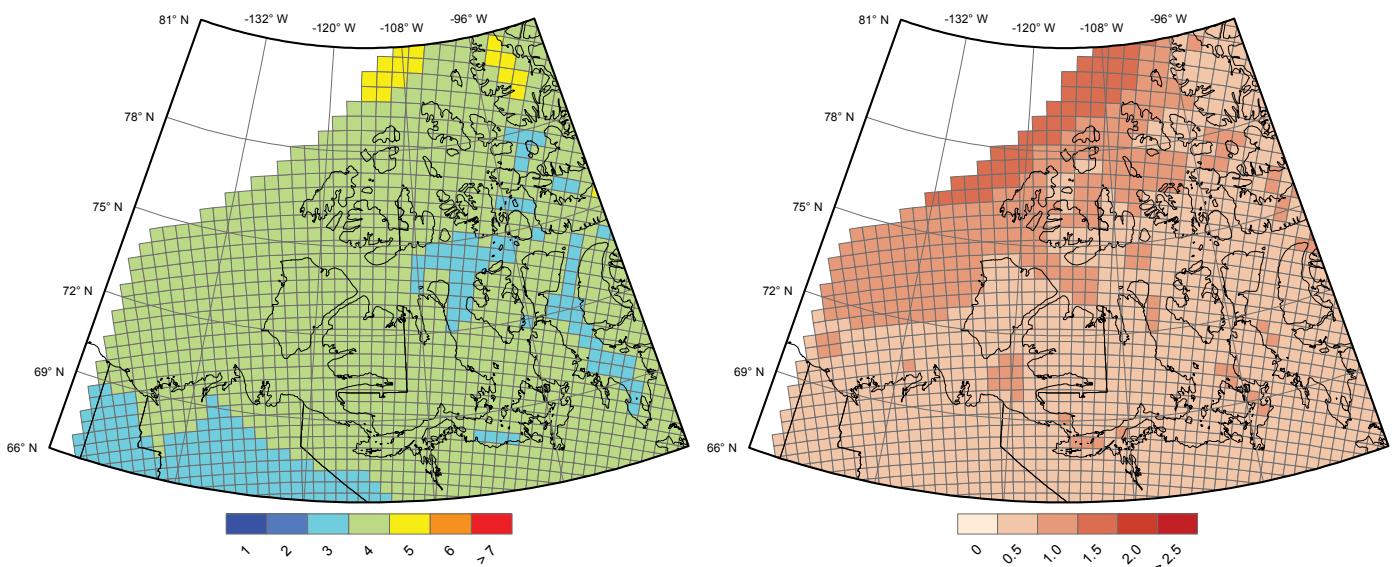


FIGURE A2. Projected change in mean annual air temperature from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

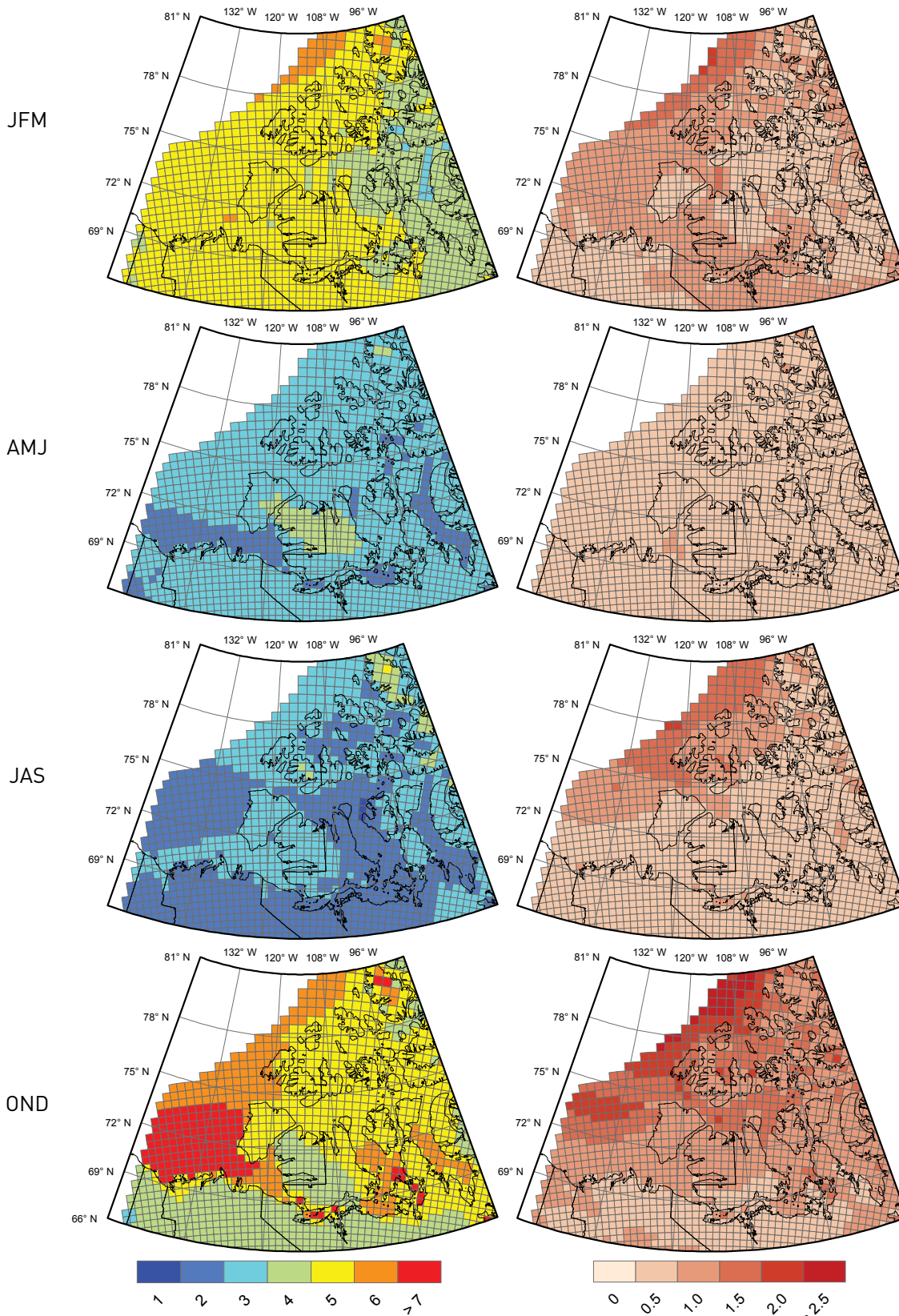


FIGURE A3. Projected change in mean seasonal air temperature from eight CRCM runs for 2050 (left panels) and the corresponding STD (right panels).

from about 1 to 3°C with no clear spatial pattern. The STD in projected air temperature change is largest over the Arctic Ocean in the fall season (Figure A3).

Figures A5 and A6 show respectively the projected change for thawing degree days (TDD) and growing degree days (GDD) (in absolute values). The TDD projected change shows a clear south to north gradient with the strongest changes over the southern part of the IRIS region (values >250 degree days). The STD for TDD is fairly low and uniform over the land areas (mostly between 30 and 45 thawing degree days). Projected change in GDD is strongest in the southern part of the IRIS region and on Banks and Victoria islands. North of these locations the projected changes are fairly small (mostly <100 degree days). The STD for the projected change in GDD is strongest over the south-western part of the IRIS region.

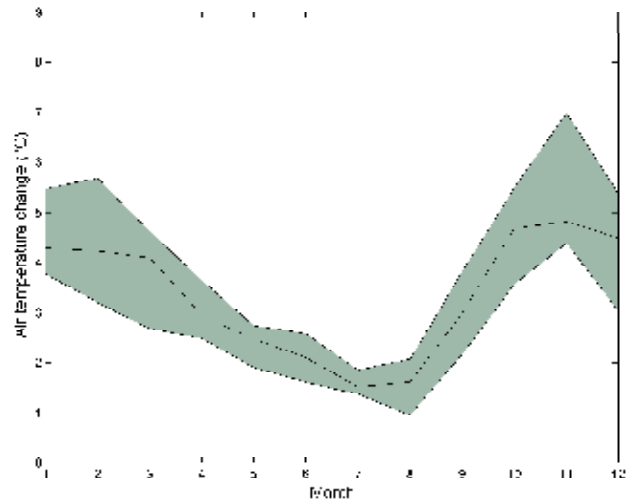


FIGURE A4. Seasonal median and range of projected changes in monthly mean air temperature from eight CRCM runs for 2050 averaged over all the grid cells of the IRIS region. The outer lines represent the range of the eight simulations.

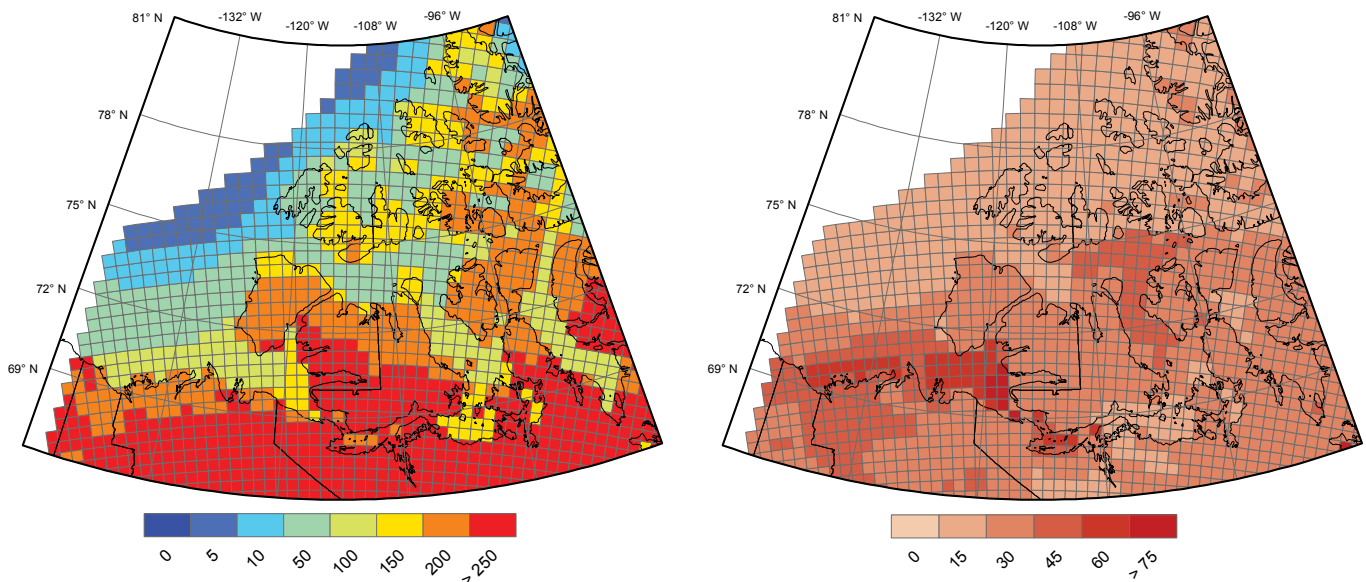


FIGURE A5. Projected change in thawing degree days (TDD) (Celsius) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

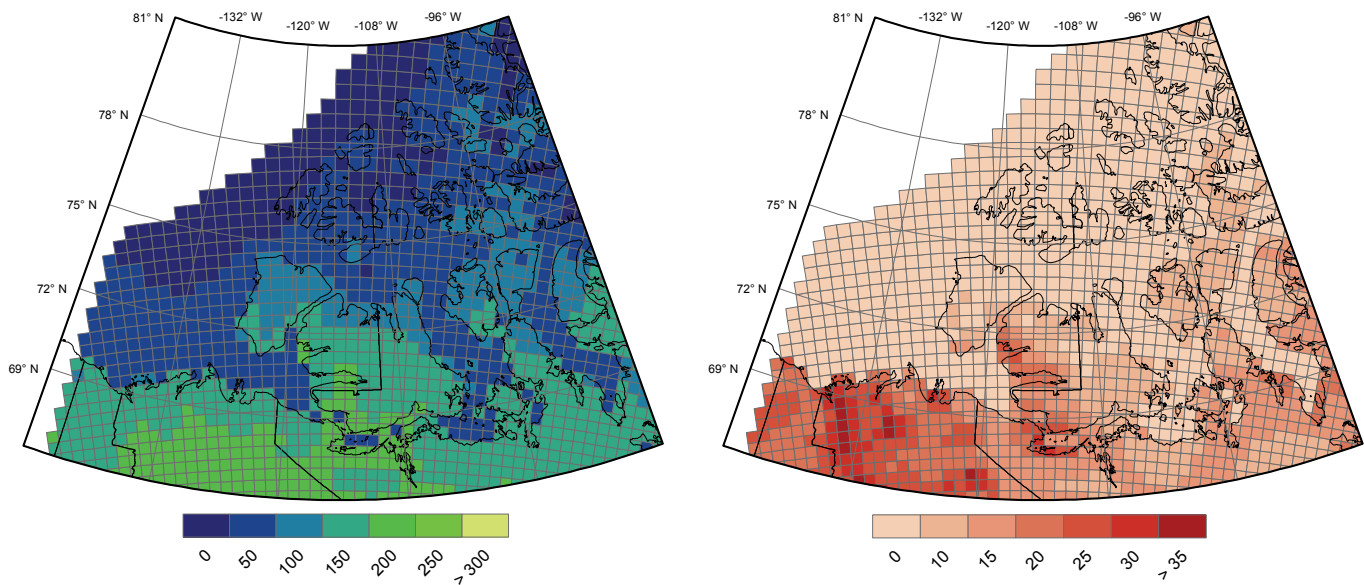


FIGURE A6. Projected change in growing degree days (GDD) (Celsius) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

Figures A7 through A9 present projected changes in summer season-onset and end dates and summer season duration. A land/sea mask was applied to summer season related indices. Projected change in summer season-onset date ranges from about 2 to 15 days earlier (Figure A7, left panel) with the largest changes over the northern part of the IRIS region. The projected changes follow a south-west to north-east gradient (Figure A7, left panel) with the largest changes in the north-east. Figure A8 (left panel) shows projected change in summer season end date with values mostly ranging between about 6 and 12 days later. A few points in the northeastern part of the region yield higher values up to about 17 days later. The STD (Figure A8, right panel) is relatively heterogeneous apart from an area of higher values over the Mackenzie Delta. Projected changes in summer season duration (Figure A9) range from 11 to 29 days longer with the largest changes projected over northern regions. STD values are more uniform with the exception of the northern most islands which are noisy.

Projected change in winter thaw events (Figure A10) show small increases over the northeastern part of the IRIS region of about 0.5 to 1 events per year compared to the regional average which shows an increase of only ~ 0.15 events per year. Slight decreases are projected over the southwestern part of the IRIS region. To place these changes in context, winter thaw events are relatively rare events in the Arctic and the mean annual number of events ranges from 1 to 3 events per year over the region. Most of the air temperature-related indicators have low STD values with exceptions generally occurring over marine areas or over the small islands of the Archipelago (see *Study area* in previous section).

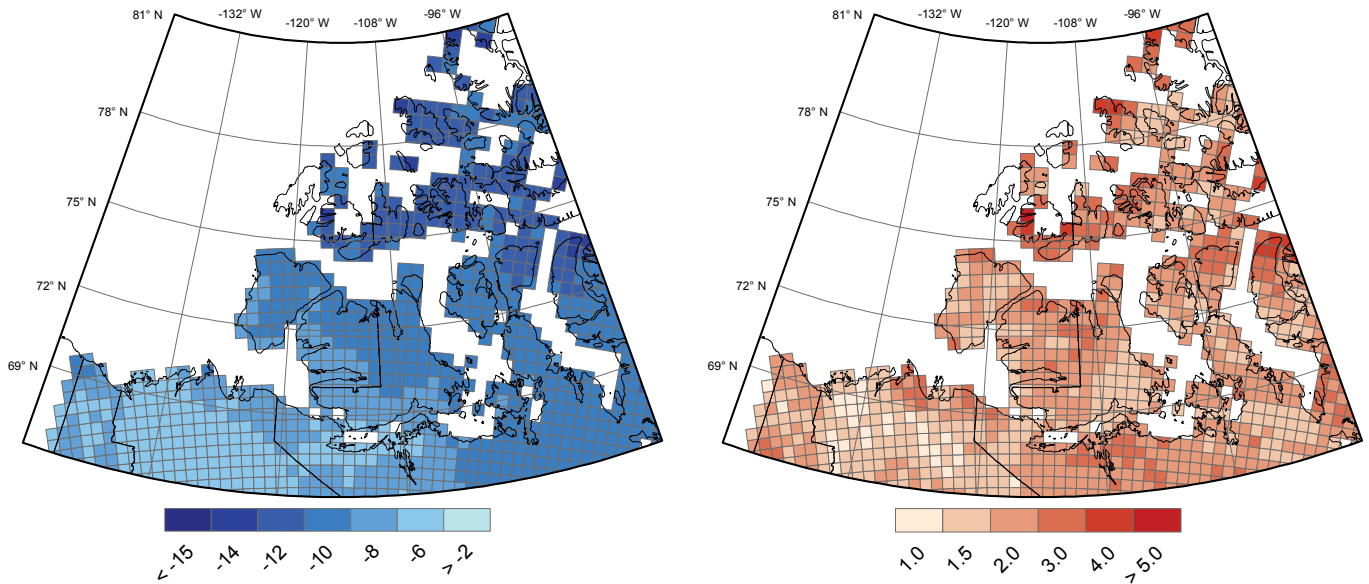


FIGURE A7. Projected change in summer season-onset date (days) for 2050 from an ensemble of eight CRCM runs (left panel) and the corresponding STD (right panel).

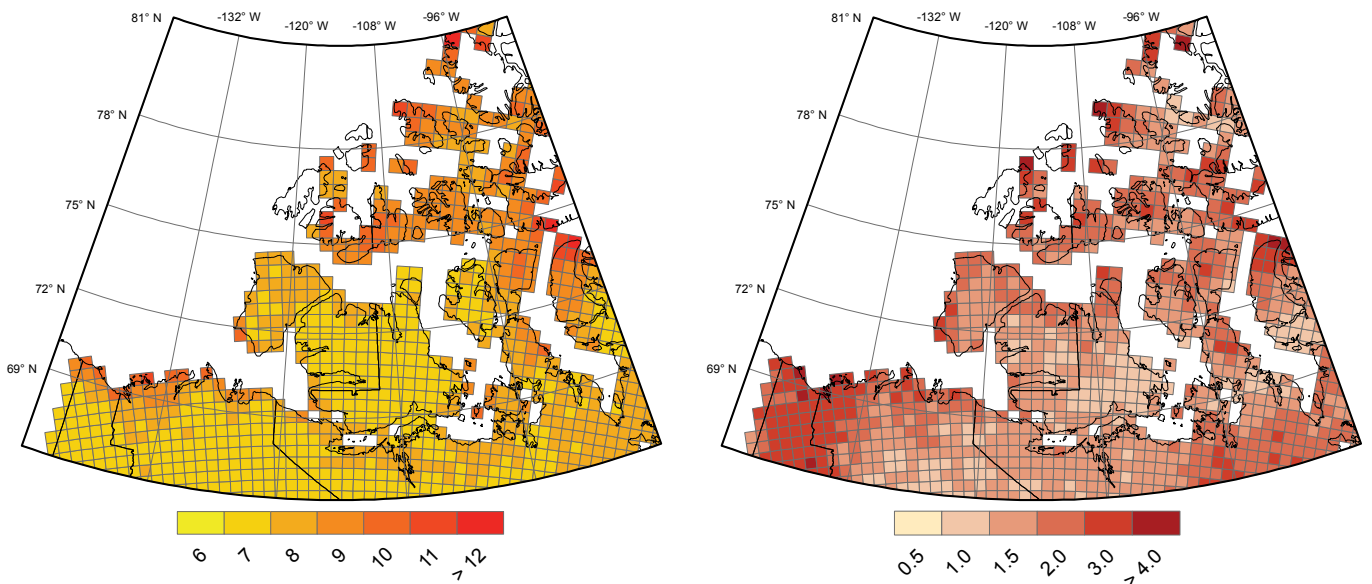


FIGURE A8. Projected change in summer season end date (days) for 2050 from an ensemble of eight CRCM runs (left panel) and the corresponding STD (right panel).

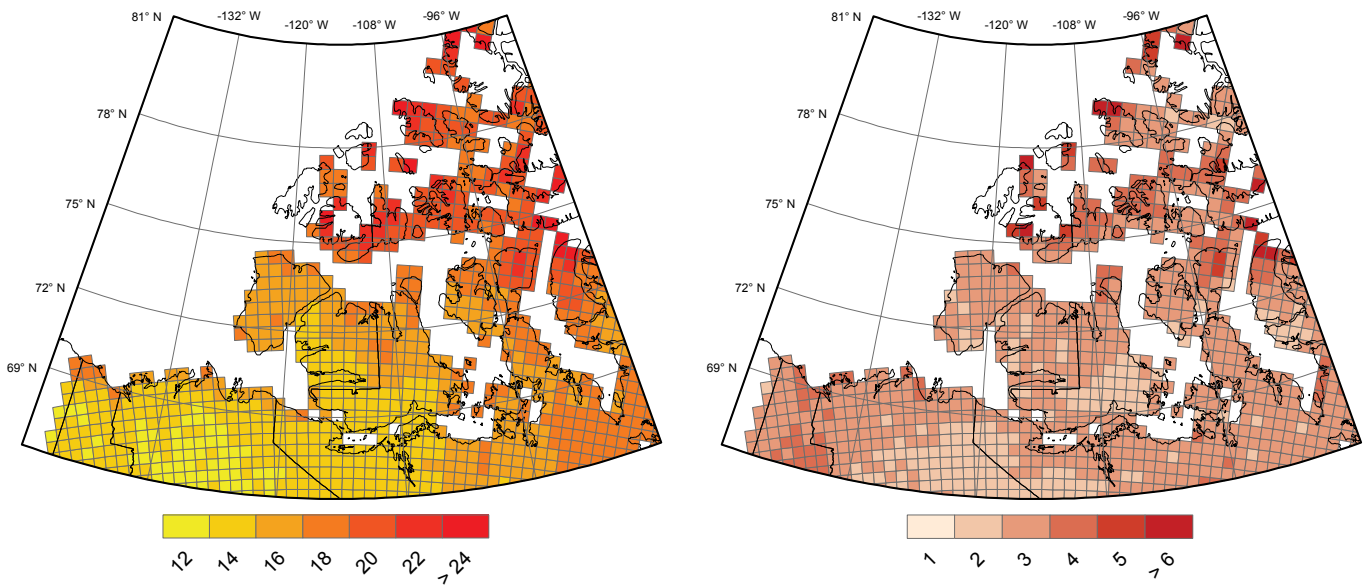


FIGURE A9. Projected change in summer season length (days) for 2050 from an ensemble of eight CRCM runs (left panel) and the corresponding STD (right panel).

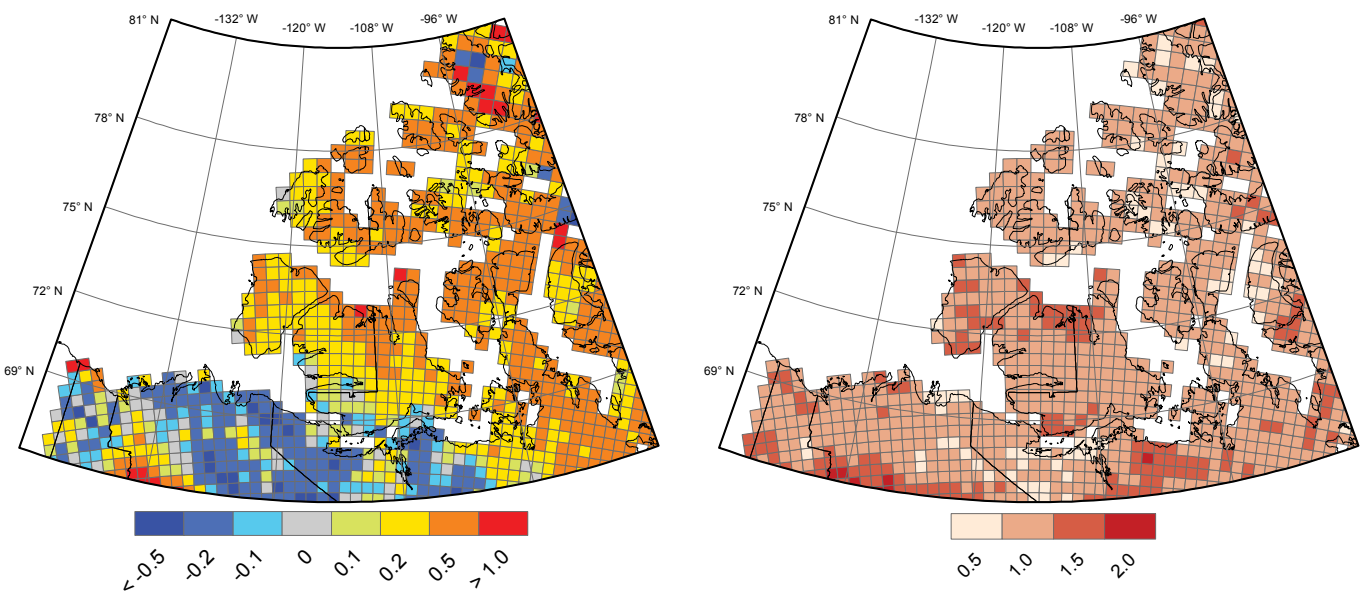


FIGURE A10. Projected change in the mean annual number of thawing events (N_{thaw}) (events per year) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

Projected change in precipitation and related indicators

Projected change in mean annual total precipitation is presented in Figure A11 with values ranging from 10 to 30%. No clear spatial pattern is visible. Standard deviation values of mean annual total precipitation are fairly low ranging between 5 and 10%. On a seasonal basis (Figure A12), the changes in mean total precipitation are projected to be strongest during winter (JFM) and fall (OND) with values up to about 30%. No clear spatial pattern is visible with the exception of the winter season where there is evidence of a south-west to north-east gradient with the largest increases (>30%) projected over the northeast.

Figure A13 shows the amplitude and seasonal pattern of the projected change in monthly total precipitation for the regional average in both millimeters and percentage. The left panel of Figure A13 shows that changes in monthly total precipitation (mm) are relatively small with the largest changes projected during the summer months (JJA). In relative values (Figure A13, right panel), the monthly regional

precipitation change is projected to be most important during the winter season. However, as shown on the right panel of Figure A13 the five first months of projected changes have a fairly wide range indicating there is substantial variability in the model projections over this period. The projected change of the annual total precipitation (Figure A14) shows the largest increases over the southern part of the IRIS region with values ranging from 30 to 60 mm. Standard deviation values are generally <10mm with no apparent spatial pattern (Figure A14, right panel).

Figure A15a and A15b compare rain on snow event (ROS) climatologies computed with air temperature and precipitation from the ERA-Interim reanalysis (Dee et al. 2011) and from the CRCM ensemble for the 1979-2000 period, respectively. The ERA-Interim results show higher values in the high Arctic when compared to the CRCM which is likely linked to a warm/wet bias in ERA-Interim compared to surface observations (Rapaic et al. 2015). Projected changes in ROS event frequency (Figure A15c) are small (-0.35 and 0.35 events per year) with no spatial pattern visible.

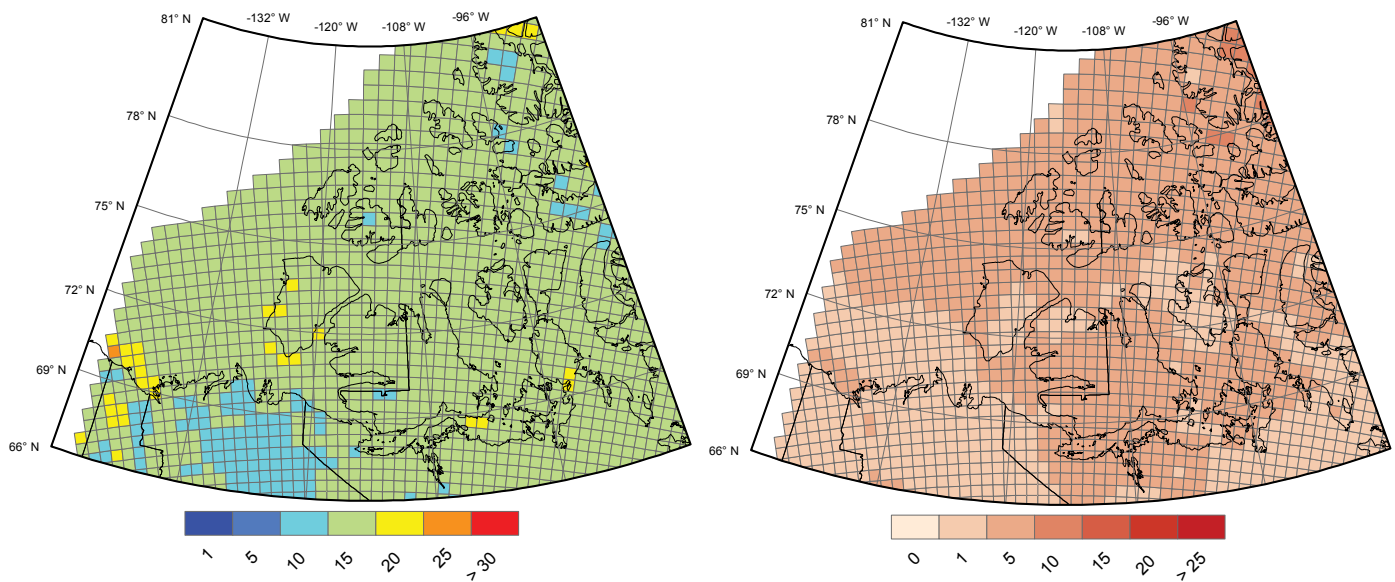


FIGURE A11. Projected change in total precipitation rate (%) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

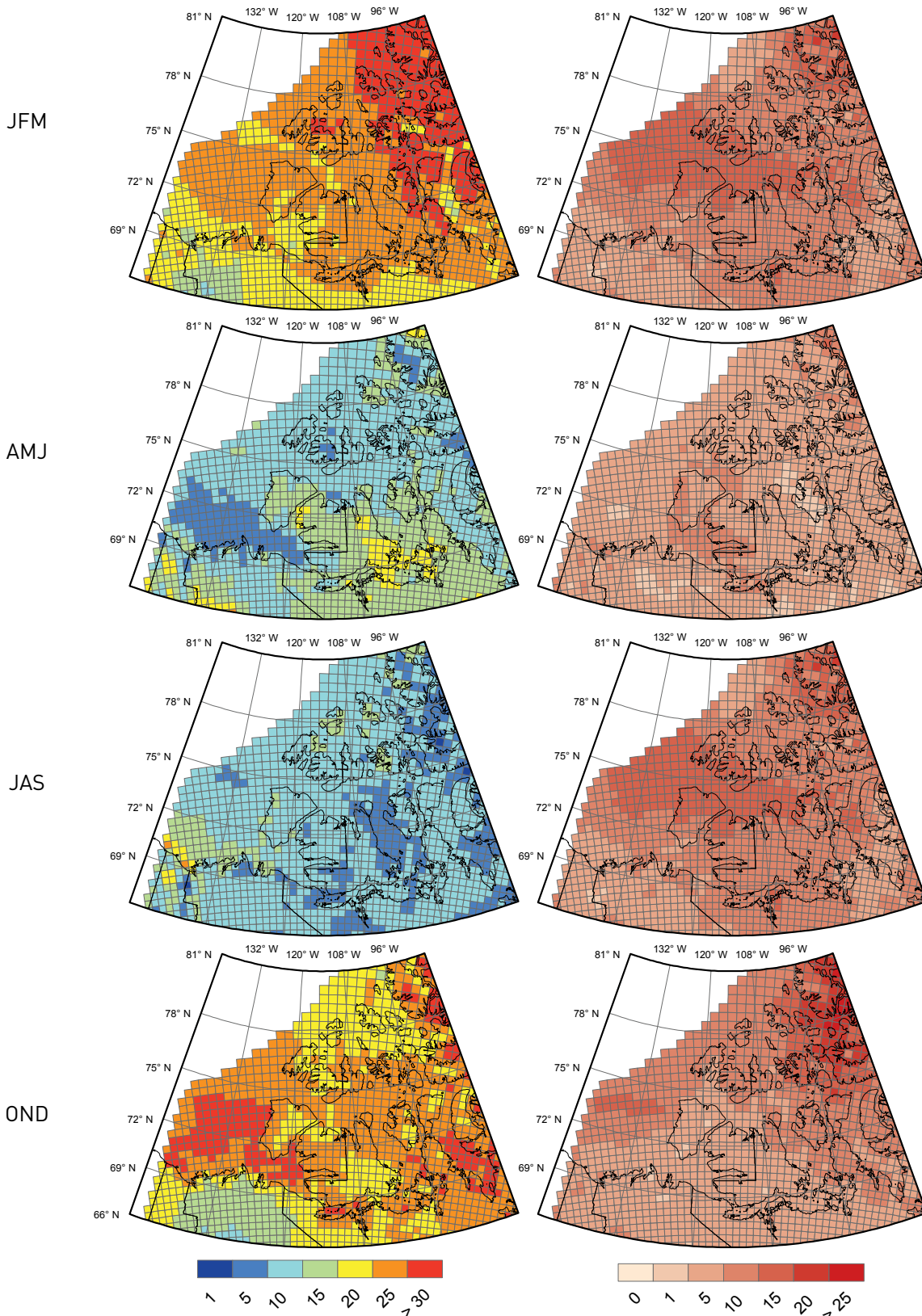


FIGURE A12. Projected change in seasonal total precipitation (%) from eight CRCM runs for 2050 (left panels) and the corresponding STD (right panels).

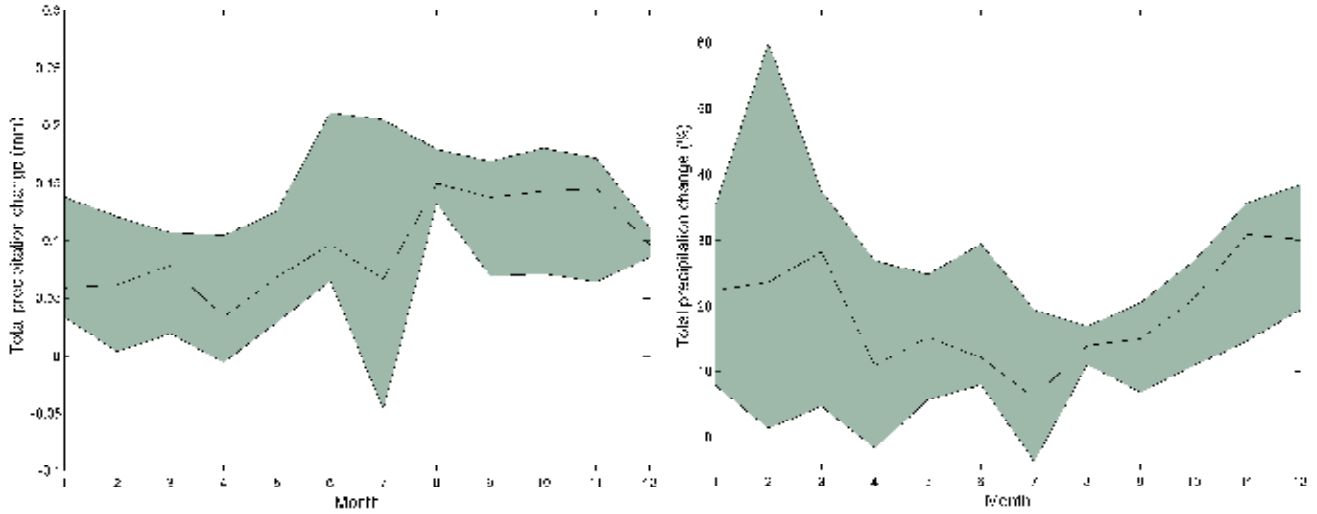


FIGURE A13. Seasonal median and range of projected changes in monthly total precipitation rate in mm (left panel) and % (right panel) from eight CRCM runs for 2050 averaged over all the grid cells of the IRIS region. The outer lines represent the range of the eight simulations.

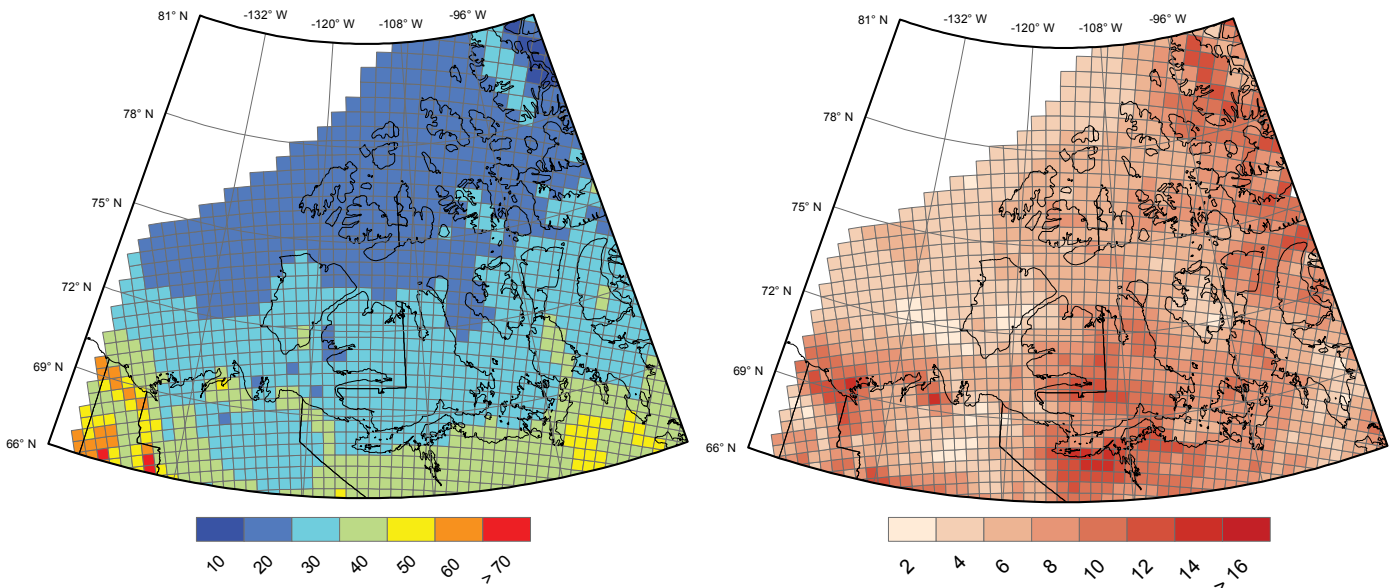


FIGURE A14. Projected change in total annual precipitation rate (mm) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

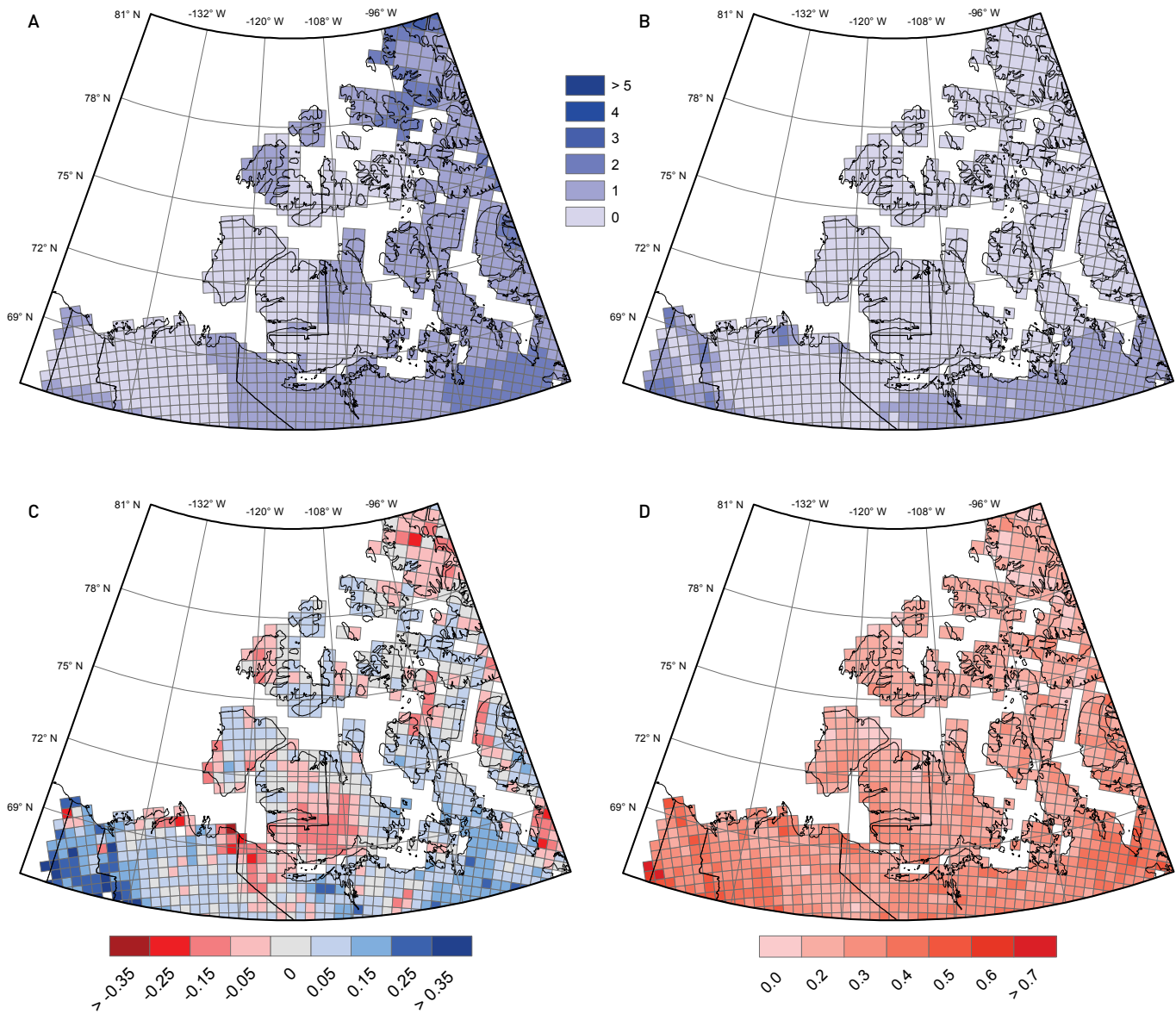


FIGURE A15. Comparison of mean annual rain on snow frequency (days per year) estimated from the ERA-interim reanalysis product [Dee et al. 2011] for 1979-2000 a) with simulated ROS frequency from the CRCM ensemble of eight runs for 1979-2000 period b). Projected change in annual frequency of ROS days for 2050 c) and STD of the projected ROS days d).

Projected changes in solid precipitation and snow cover

Figure A16 shows projected percent change in mean annual total solid precipitation. The whole region is projected to have increased solid precipitation with the largest increases over the south ranging between 25 and 30%. The STD pattern (Figure A16, right panel) has some spatial structure with bands of higher between-run variability present with values $>8\%$.

The projected absolute change in total annual solid precipitation (Figure A17) shows a similar spatial pattern to Figure A16 with the largest increases over the south-eastern part of the IRIS region (values ranging between 25 and 30 mm). The previously mentioned land ice mask was applied to mean annual maximum snow depth and snow season related indices (Figures A18 through A20). Projected change in mean annual maximum snow depth (\max_{zn}) is mostly positive over the IRIS region with values ranging from 1 to 10 cm (Figure A18). The largest increases are projected in coastal areas around the Beaufort Sea and Amundsen Gulf,

and the smallest changes are over the northern islands of the Archipelago. The STD field shows low values of about 2-3 cm with no clear evidence of any spatial pattern.

Figure A19 shows the projected change in snow cover-onset dates with values mostly ranging between 4 and 16 days later. The smallest changes are projected to occur in the western part of Banks Island with the largest projected changes over the Arctic islands north of 75°N . The latter are associated with relatively higher STD values (>5 days) (Figure A19, right panel). The projected change in snow cover end date shows values ranging between about 4 and 14 days earlier (Figure A20). The smallest changes are projected over the south-west part of the IRIS region (Mackenzie Valley and Delta) with the largest changes located over the Arctic islands in the north-eastern part of the region. The between model variability is noticeably lower and smoother for snow-off compared to snow-on (Figure A20, right panel). This is consistent with stronger snow-albedo feedbacks in the spring period (Déry and Brown 2007).

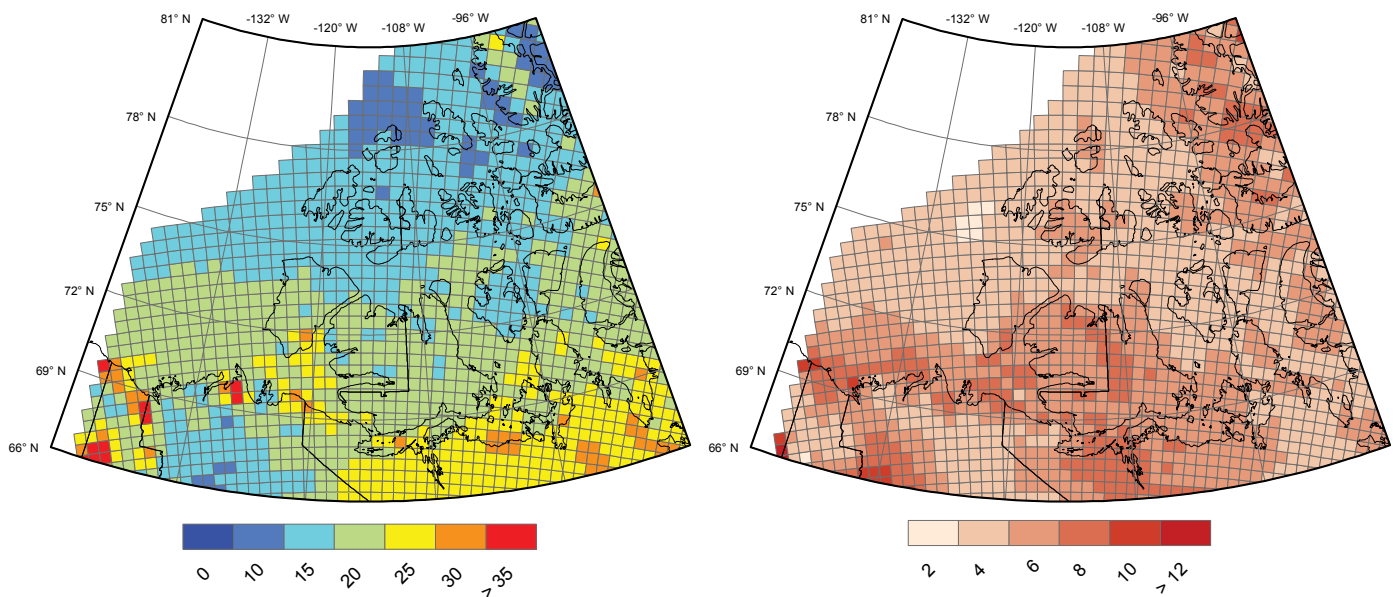


FIGURE A16. Projected change in total solid precipitation (%) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

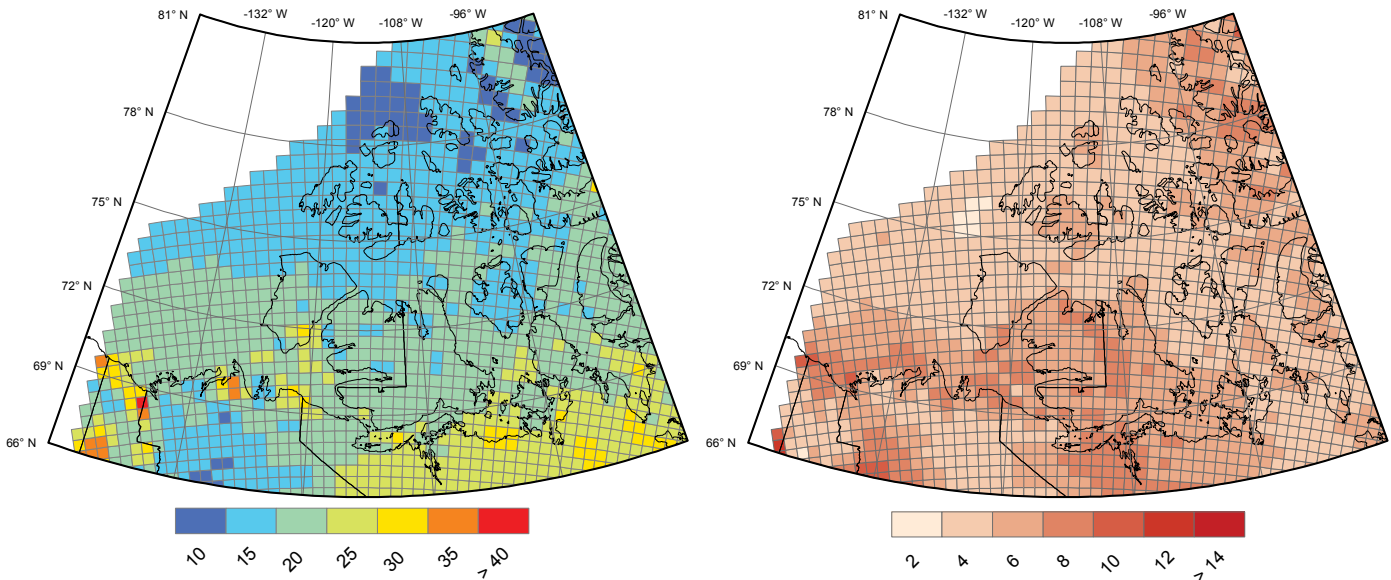


FIGURE A17. Projected change in total annual solid precipitation (mm) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

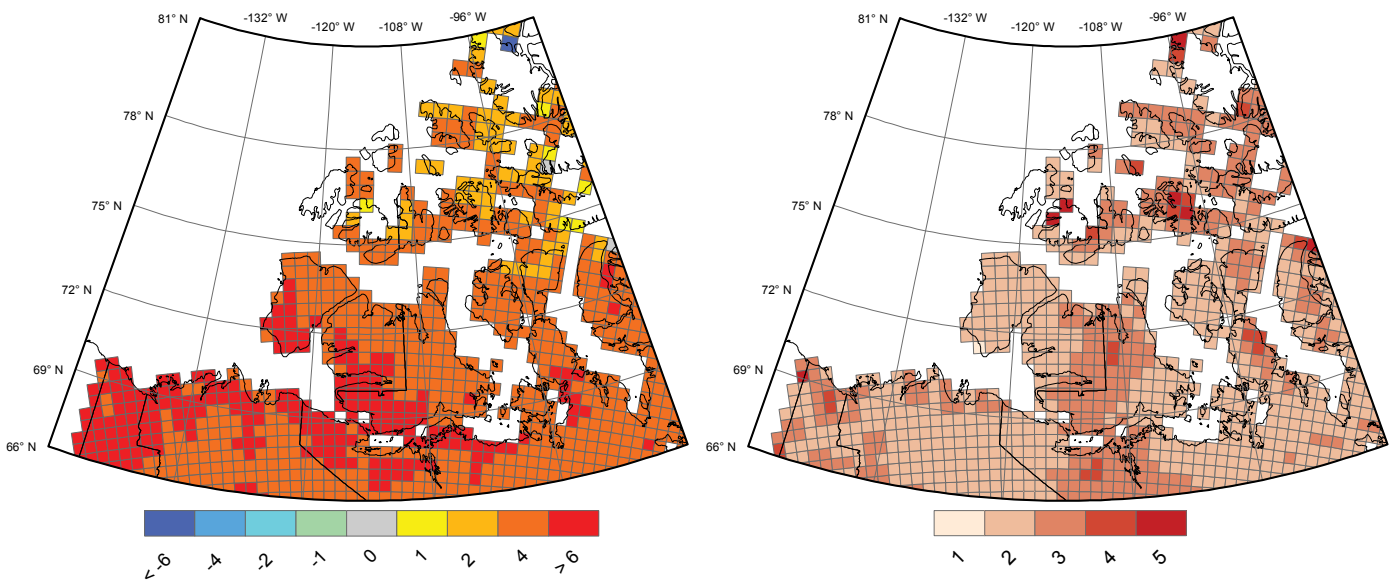


FIGURE A18. Projected change in mean annual maximum snow depth (cm) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

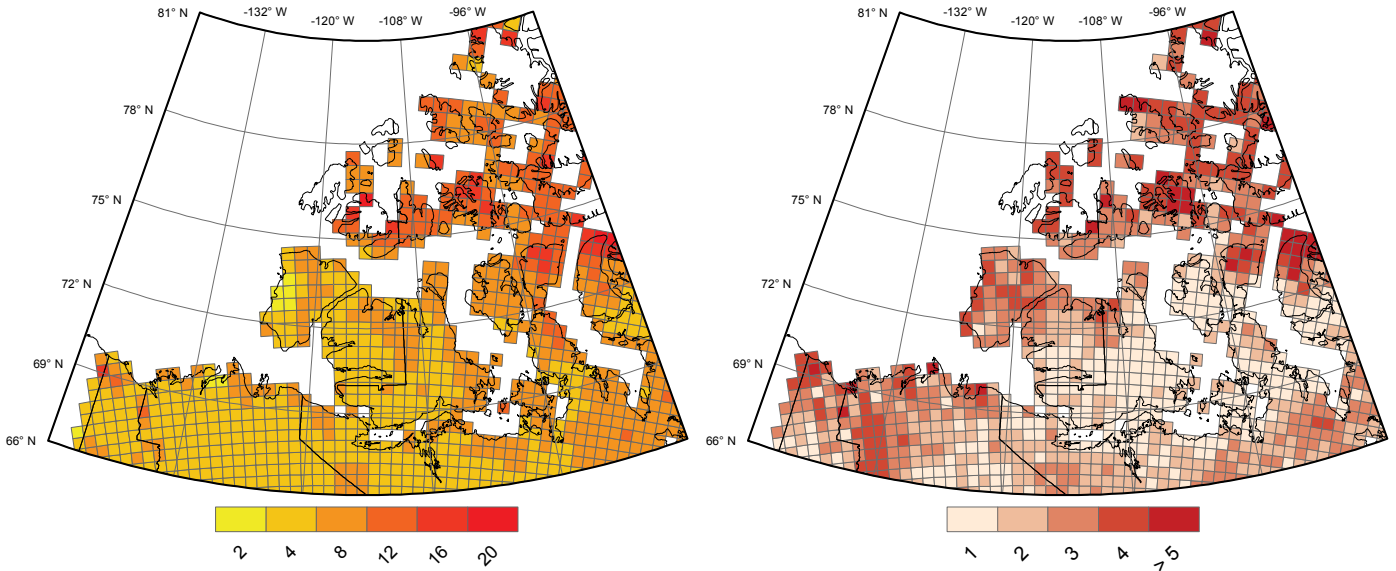


FIGURE A19. Projected change in snow cover-onset date (days) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel).

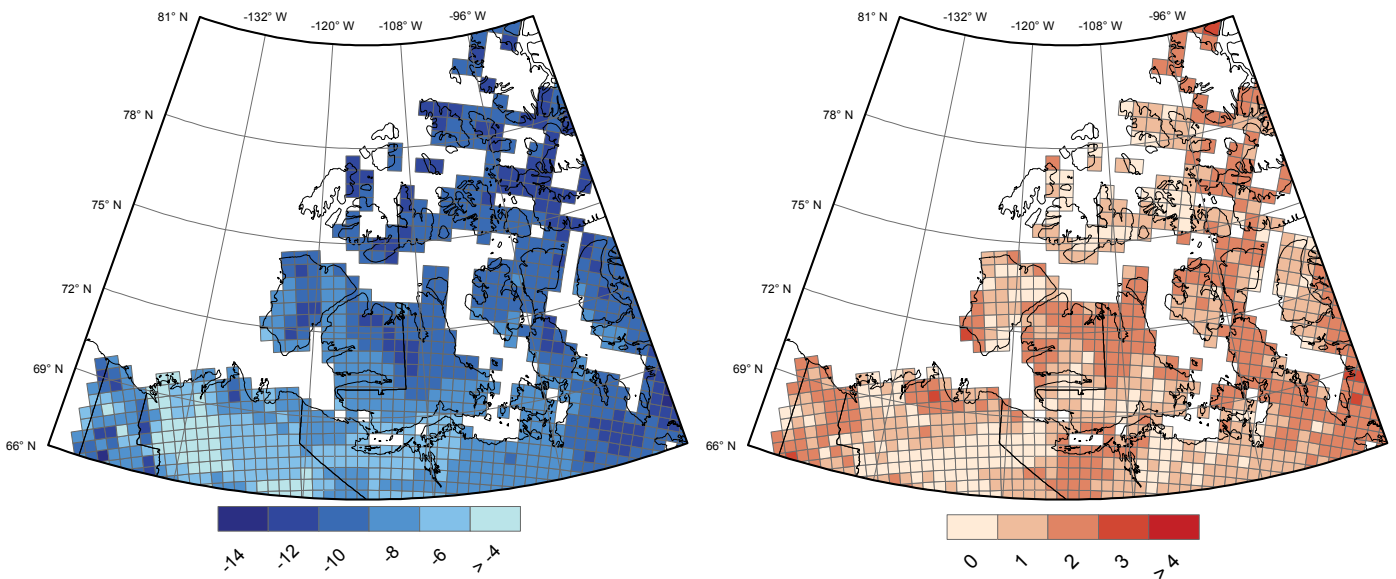


FIGURE A20. Projected change [- = earlier end] in snow cover end date (days) from eight CRCM runs for 2050 (left panel) and the corresponding STD (right panel). Negative numbers mean an earlier snow cover end date.

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Appendix B

Additional figures and analysis

Precipitation

Regionally-averaged seasonal total precipitation time series for the 1950-2010 period from CANGRD (Figure B1) show relatively low precipitation amounts in the cold period up to about 1970 followed by an increasing trend that is most pronounced in winter and fall. All four series have significant (0.05 level) linear increases over the 60+ years, with the strongest precipitation increases in winter (11.5% per decade) and fall (7.3% per decade) followed by spring (3.7% per decade) and summer (2.9% per decade). Both snowfall and rainfall exhibit significant increasing trends over the 1950-2010 period with total annual snowfall increasing at a faster rate than total annual rainfall (9.8% per decade versus 6.0% per decade).

Analysis of trends in annual snowfall and rainfall at individual stations over the recent 1981-2010 period showed increases in rainfall amounts at all stations but none were statistically significant. The sign of the snowfall trend varied considerably between stations and was only statistically significant (increasing snowfall) at Kugluktuk. The corresponding precipitation trends from CANGRD (Figure B2) show a highly variable pattern over the Canadian Arctic with few coherent regions of statistically significant trend. Two points that can be made are: (1) significant increases tend to be more frequent than significant decreases, and (2) the largest area of coherent significant trend is the increase over the western Arctic in the OND period. These conclusions are consistent with warming and moistening of the Arctic and delayed ice-onset in the fall period. The overall lack of coherent trends is a result of the noisiness of the data, the large interannual variability of precipitation (e.g. see winter panel in Figure B1), and the short 30-year period for trend analysis which is dominated by natural variability.

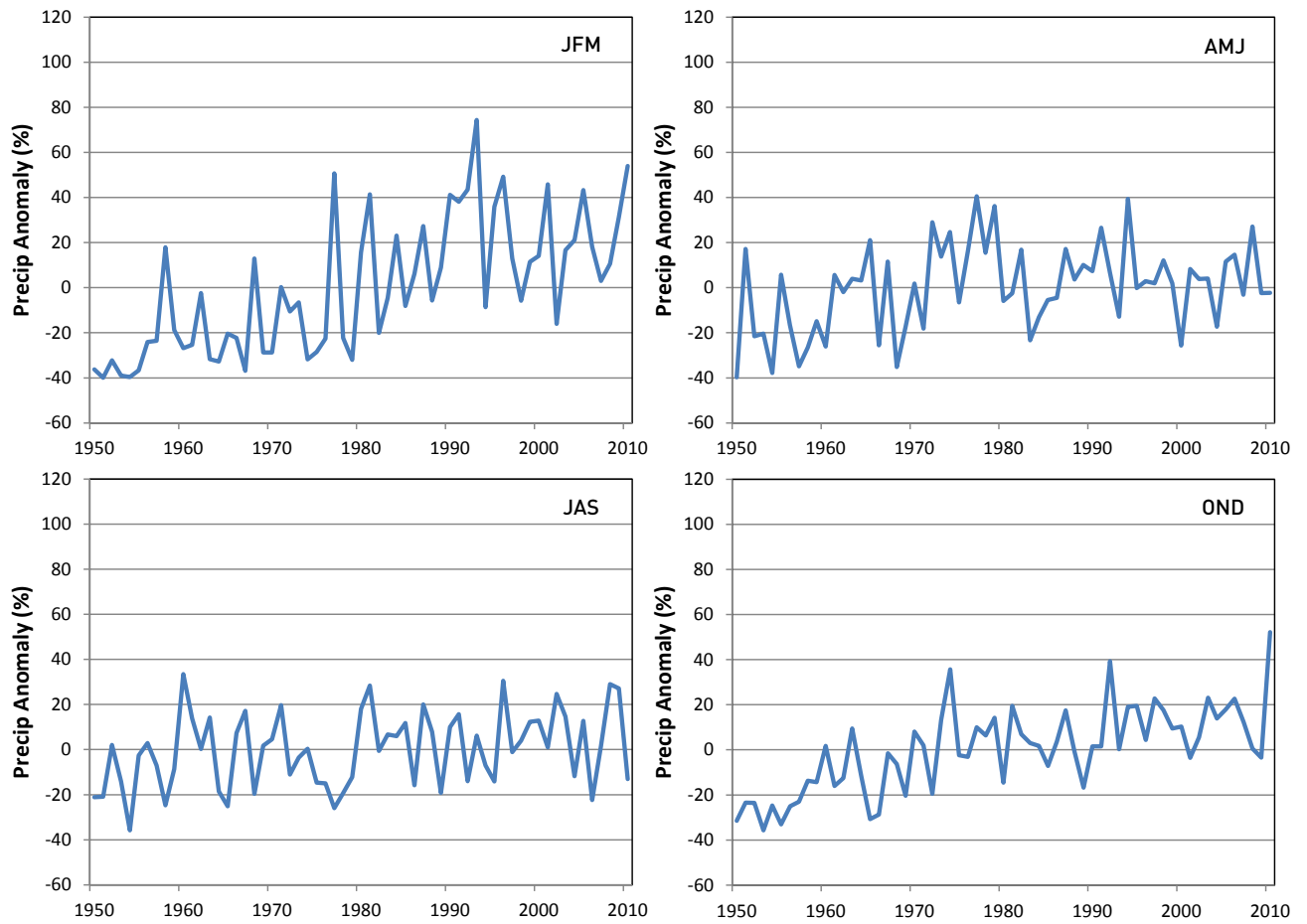


FIGURE B1. Regionally-averaged time series of seasonal total precipitation over the 1950-2010 period from CANGRD. Annual anomalies are expressed as percentages of the 1961-1990 mean.

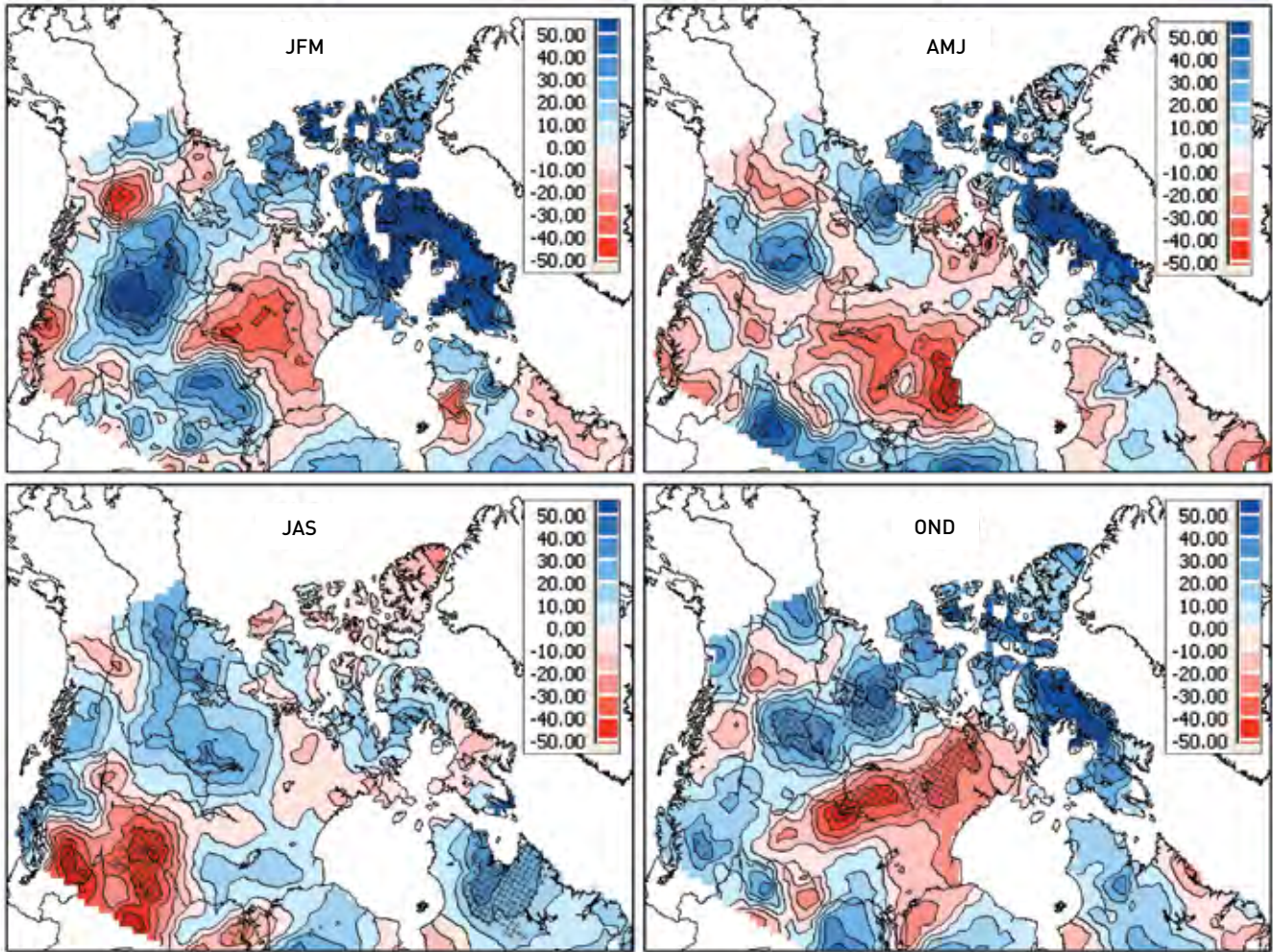


FIGURE B2. Precipitation trends from CANGRD over the 1981-2010 period expressed as a % of the 1981-2010 average. Grid points with locally significant trends are indicated with an “x”.

Sea ice

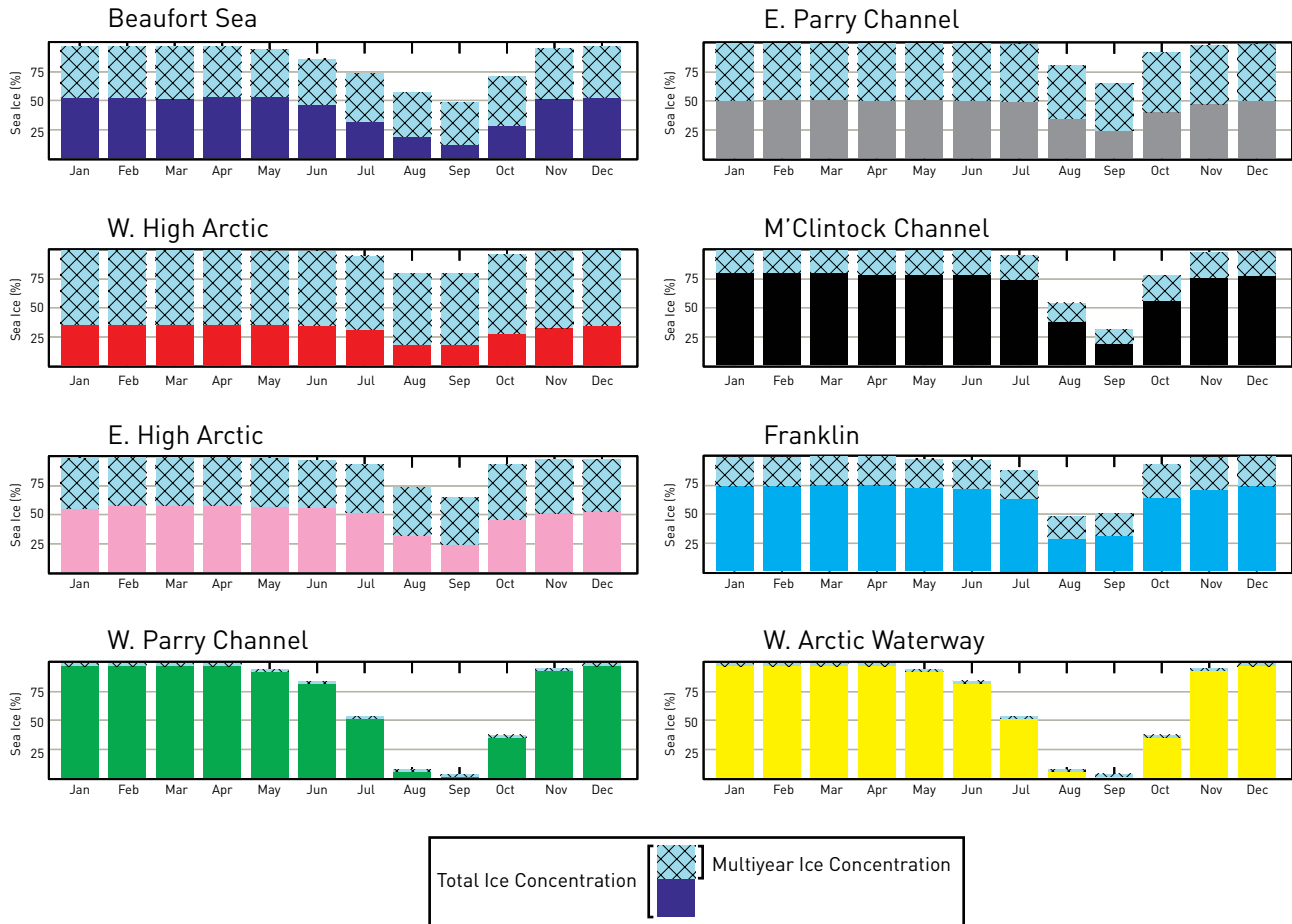


FIGURE B3. The monthly normal (1981-2010) for total sea-ice concentration and multiyear sea-ice concentration. The total ice concentration is represented by the height of the entire bar (both the coloured section and light blue), while the light blue section of the bar represents the multiyear ice concentration. From Candlish et al. (2014).

Winds

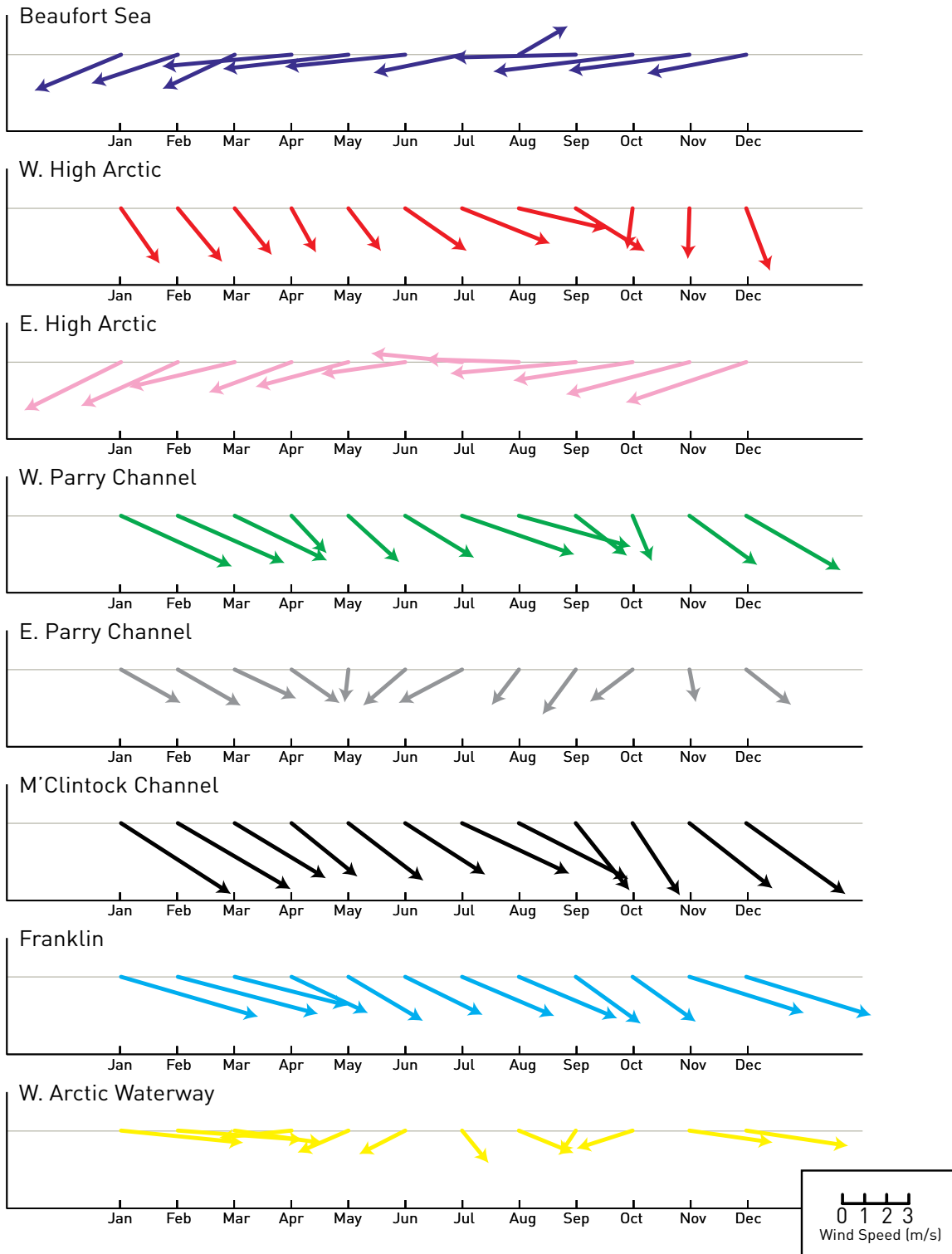


FIGURE B4. The 1981-2010 monthly normals for wind speed and direction. From Candlish et al. (2014).

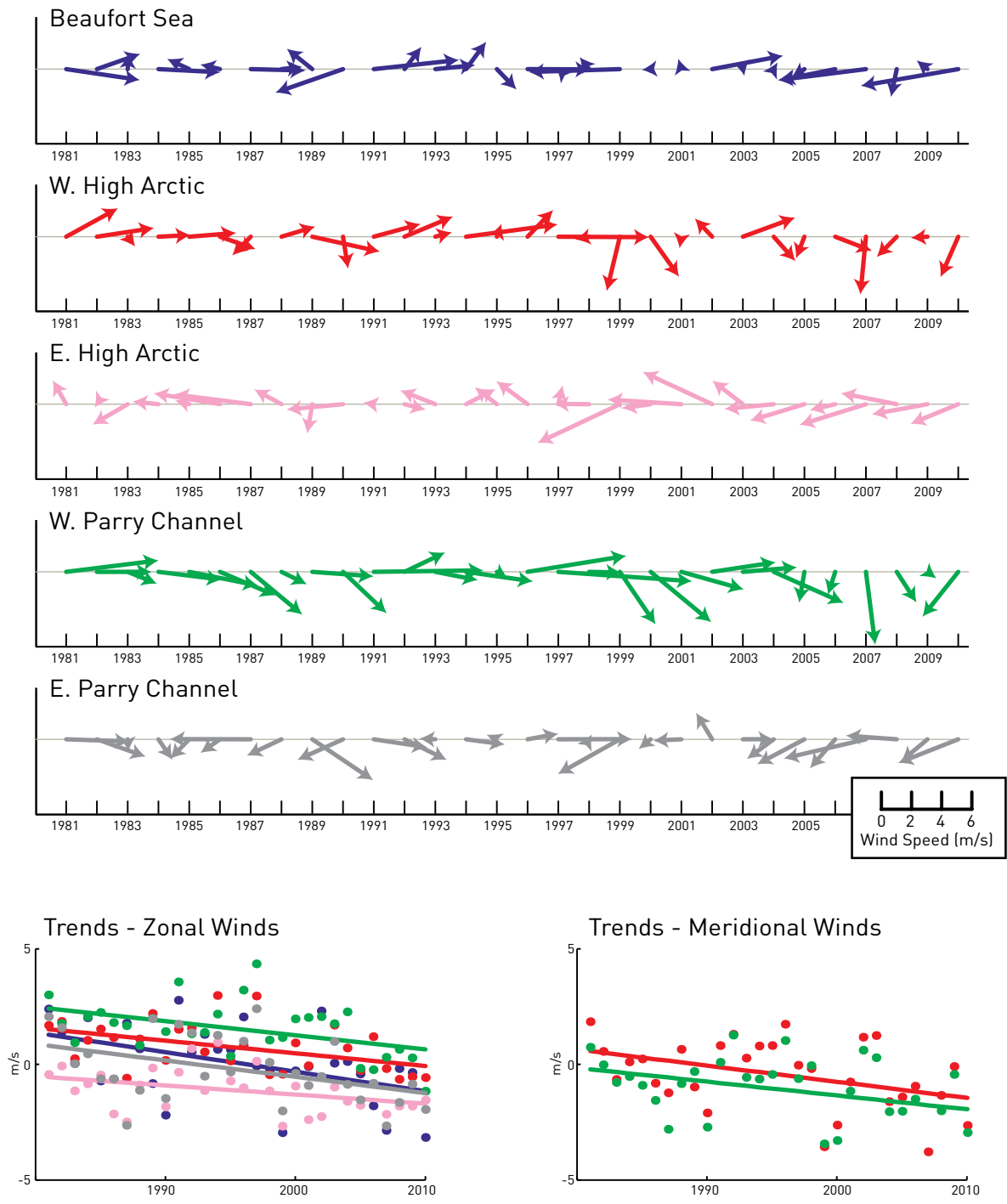


FIGURE B5. The top panels show the average wind speed and direction for the month of August during the years 1981-2010. The bottom left shows the statistically significant trends for zonal winds (blue – Beaufort Sea, red – W. High Arctic, pink – E. High Arctic, green – W. Parry Channel, grey – E. Parry Channel). Similarly, the bottom right shows statistically significant trends for the meridional winds. From Candlish et al. (2014).



Chapter 3. Terrestrial and Freshwater Systems

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ABSTRACT

Recent climate warming has already demonstrated impacts on diverse geophysical and biological elements of terrestrial and freshwater ecosystems in the western and central Canadian Arctic. Many impacts are likely to continue or become more severe with projected future warming trends. Permafrost temperatures have increased, and accelerated thermokarst activity has led to widespread landscape changes. Profound changes in tundra vegetation are attributed to climate and disturbance, but these changes are not uniform. The overall effect is clearly seen as the “Greening of the Arctic”, which indicates tundra plant life is more productive. The abundance and height of shrubs (alder, willow, birch) are increasing, a trend expected to continue in the future. Changes in forest trees have been more modest and to date there is no evidence of increased tree density in the forest-tundra in this area. Fishes such as Dolly Varden and Arctic char may be particularly vulnerable to climate-related disturbances because of limited populations and suitable habitats, and the pending invasion of competing temperate fish species. Across all groups of terrestrial wildlife (insects, birds and mammals), climate change will produce diverse and often divergent impacts characterised by large uncertainties. The most dramatic changes in animals will likely occur along the interface between taiga and low Arctic tundra, and in species which have specialized breeding or feeding requirements. Increases in insect abundance (numbers and biomass) in general, including some biting insects, is likely. The chemistry and bio-uptake of contaminants in Arctic ecosystems may be strongly influenced by climate-driven processes including thawing permafrost and increasing productivity of terrestrial and aquatic systems, in ways we cannot yet predict. Mercury concentrations in lake sediments and some freshwater biota have been increasing in recent decades despite stable atmospheric levels. This discrepancy may be the best clue to date that climate-driven changes in geochemical and ecosystem processes now more strongly influence mercury levels in the Arctic environment than do distant pollution sources.

3.1 Introduction

The Arctic (generally defined as the area north of the northern tree-line) is estimated to contain more than 21,000 species of mammals, birds, invertebrates, vascular plants, algae, mosses, fungi and lichens together with innumerable, mostly undescribed micro-organisms and parasites (CAFF 2013). Among the terrestrial and freshwater species are a number of iconic animals only or mainly found in the Arctic, including caribou/reindeer (*Rangifer tarandus*), muskox (*Ovibos moschatus*), snowy owl (*Bubo scandiaca*) and Arctic char (*Salvelinus alpinus*). Extreme seasonality of light, temperature and waterflows, together with permafrost, characterize the landscape which exhibits unique landforms such as pingos (i.e. ice-cored hills created by the aggradation of permafrost into the sediments of drained lakes), tundra polygons and thermokarst lakes. Arctic terrains also encompass many and varied freshwater habitats ranging from wetlands, shallow ponds and ephemeral streams to large, deep lakes and rivers that drain extensive catchment areas of the North American and Eurasian continents (Vincent and Laybourn-Parry 2008).

Although the biodiversity of Arctic terrestrial and freshwater ecosystems is not high by global standards, ranging from less than 1-2% of all terrestrial mammals, terrestrial and freshwater birds, and freshwater fishes, and up to about 10% of global lichen species (CAFF 2013), these ecosystems have supported Indigenous occupation of the land over thousands of years and continue to be culturally, nutritionally and economically vital for northern communities up to the present by providing food and material benefits as well as helping to sustain Indigenous cultures, languages and societies (Huntington et al. 2013). These ecosystems also play important roles globally as significant stores of soil carbon, and regulators of the climate through albedo and heat sinks of snow, ice and permafrost (AMAP 2012).

Anthropogenically induced climate warming over recent decades is widely regarded as the most serious threat to Arctic ecosystems and to the Indigenous cultures that rely on them (ACIA 2005; CAFF 2013). The objective of this

chapter is to synthesize and assess what is known about the impacts of recent warming and, to some extent, modernization (e.g. resource development) on the terrestrial landscapes and terrestrial and freshwater ecosystems in the Inuvialuit Settlement Region (ISR) and the Kitikmeot region of Nunavut. The chapter considers these impacts on the following ecosystem elements: permafrost processes, vegetation, fishes, terrestrial wildlife (mammals, arthropods and birds), and contaminants. Preliminary assessments are also provided of the likely future changes occurring as a result of the predicted continuation in warming trends and associated changing meteorological conditions (Chapter 2). Finally, key conclusions and recommendations are presented for the attention of policy-makers and research managers.

3.2 Permafrost and the impacts of thermokarst on the physical environment

Permafrost (i.e. earth materials that remain frozen for more than two years) exerts a fundamental influence on Arctic ecosystems by modifying micro- and macroscale topography, controlling soil temperatures and the depth of the rooting zone, influencing moisture regimes, and affecting biogeochemical and hydrological processes (French 2007; see also Chapter 7). By providing structural support to the terrain surface, permafrost is also integral to the physical stability of Arctic ecosystems. The surface zone of earth materials that thaw and refreeze on an annual basis is referred to as the active layer. Underlying permafrost can host a range of ground ice types. These can include: (1) near-surface segregated ice lenses immediately beneath the base of the active layer (Kokelj and Burn 2005); (2) wedge ice which consists of pure veins of ice which underlie polygonal terrain (Mackay 2000); and (3) bodies of massive tabular ice several meters thick (Mackay 1971), which are common in hummocky moraine deposits in the region (Rampton 1988; St-Onge and McMartin 1999). Since the 1970s, permafrost soil temperatures in the western Arctic have increased by about 2°C in response to accelerated climate warming (Smith et al. 2005; Burn and Kokelj

2009; Burn and Zhang 2009). Permafrost warming and an increase in active-layer thickness is of particular concern because thawing of ice-rich ground can cause terrain subsidence, slope instability, impacts to terrestrial and aquatic ecosystems, and thaw of ancient carbon preserved in the frozen ground (Mackay 1970; Lewkowicz 1987; Lantz et al. 2009; Kokelj et al. 2009b; Grosse et al. 2011; Thienpont et al. 2013).

Thermokarst refers to a suite of processes that involve the thawing of ice-rich permafrost resulting in terrain subsidence (Kokelj and Jorgenson 2013). For millennia, thermokarst has played an important role in shaping the landscapes of the western Arctic (Rampton 1988; Burn 1997), but climate warming and increasing ground temperatures are accelerating the frequency and magnitude of these processes (Lantz and Kokelj 2008; Kokelj et al. 2013). Coastal areas of the ISR are also susceptible to increased thermokarst activity (Lantuit et al. 2012). The coastline in the vicinity of the Mackenzie Delta has retreated more than 100 km through the Holocene and this has led to the preservation of subsea permafrost, extensive coastal erosion, thaw slump activity, and lake drainage. Sea level rise, reduced sea-ice extent and more severe storms will accelerate processes driving thermokarst activity in coastal regions of the Arctic. In this section we review some of the main types of thermokarst that impact permafrost regions and the environmental impacts of these disturbances.

3.2.1 Retrogressive thaw slumps

Retrogressive thaw slumps commonly develop in ice-rich moraine deposits throughout the ISR and the Kitikmeot region (Lewkowicz 1987; Lantz and Kokelj 2008; Lacelle et al. 2010; Lantuit et al. 2012). These disturbances represent one of the most dramatic manifestations of permafrost thaw (Figure 1). Slumps are initiated by a variety of mechanisms that expose ground ice including mechanical erosion by fluvial processes or wave action (Lantuit and Pollard 2008), thaw settlement along lake shores (Kokelj et al. 2009a) or mass wasting triggered by extreme thaw or

precipitation (Lacelle et al. 2010). Slump growth is driven by the thawing of ground ice exposed in the slump headwall (see Figure 1a). The thawed materials accumulate as a mud-slurry on the slump floor and can be transported downslope by mud flows and slope runoff (Figure 1b). Slumps may

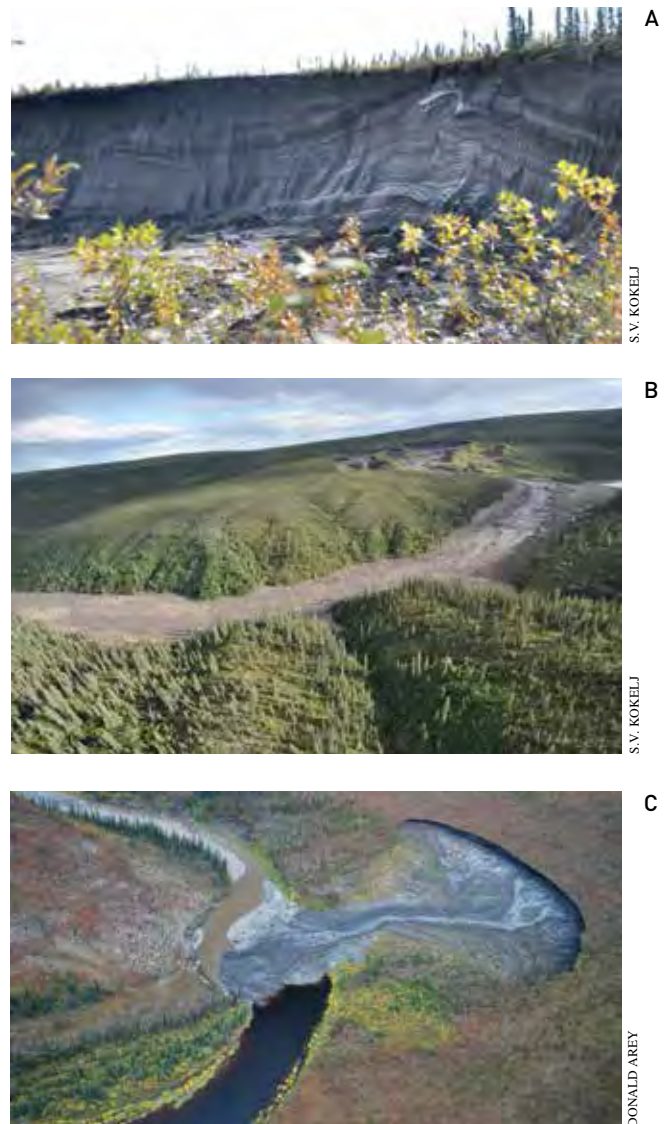


FIGURE 1. a) Large thaw slump on the Peel Plateau, NT, an area adjacent to the southwest boundary of the ISR. Headwall is approximately 30 m in height exposing massive ground ice; b) mud flow infilling several km of stream valley; c) slump mud flow and impacts to the Miner River, a small tundra stream east of Inuvik.

grow for decades until the ground ice is covered by the accumulation of thawed sediments. In the Mackenzie Delta region, the growth rate of slumps has increased in concert with rising air temperatures during the past 40 years (Lantz and Kokelj 2008).

The degradation of permafrost in slumps exposes materials to weathering and releases soluble materials previously trapped in the frozen ground. Slump soils are characterized by elevated soluble ion concentrations and higher pH than the undisturbed tundra (Kokelj et al. 2002; Lantz et al. 2009). Runoff over slump scar areas can elevate solute and suspended sediment concentrations in adjacent lakes and streams (Figure 1c) (Kokelj et al. 2005, 2009b; Malone et al. 2013). These disturbances can significantly alter snowpack, ground temperatures, vegetation structure and species composition, as well as aquatic food webs (Kokelj et al. 2009a; Lantz et al. 2009; Mesquita et al. 2010; Thienpont et al. 2013).

Slumps are characterized by freshly exposed, nutrient-rich soils, deep snow and warmer ground temperatures than the adjacent tundra (Lantz et al. 2009). These conditions favour the establishment of tall upright shrubs, and other disturbance tolerant species which distinguish these areas from the surrounding tundra. The water quality and habitat impacts of slumps on tundra lakes are manifested by shifts in diatom communities which have been documented with paleolimnological techniques (Thienpont et al. 2013).

As the magnitude and intensity of thaw slumping increases so do the geomorphic and ecological impacts (Kokelj et al. 2013). The largest slumps ever reported are developing in the fluvially-incised glaciogenic landscapes in the Peel Plateau (Figure 1b) (Brooker et al. 2014). The thawing of massive ground ice is now of sufficient magnitude to drive diurnal variations in stream sediment, solute and water fluxes in numerous small to medium sized watersheds (10^2 to 10^3 km²) that drain eastward from the Richardson Mountains (Figure 1c) (Kokelj et al. 2013).

3.2.2 Polygonal terrain

Ice wedges are bodies of pure ice that develop by thermal contraction cracking of the ground in winter and infilling of the cracks in spring with meltwater. Over time, repeated cracking can result in large ice-wedges several meters in width (Mackay 2000; Kokelj et al. 2014), which may comprise a significant volume of the near-surface permafrost (Pollard and French 1988). Ice-wedge networks form polygonal terrain, which is one of the most common forms of patterned ground in the ISR and the Kitikmeot region (Figure 2) (Mackay 1963; Kokelj et al. 2014). The proximity of wedge ice to the ground surface makes polygonal terrain extremely sensitive to climate warming or physical disturbance. Active layer deepening can cause differential subsidence and formation of water-filled troughs over the wedges (Mackay 2000), leading to landscape and ecological change. Abrupt increases in ice wedge degradation associated with a warming climate and increasing ground temperatures have been documented in the Alaskan Arctic (Jorgenson et al. 2006). Thermo-erosion of ice-wedge polygons on slopes can lead to gullying and the rapid modification of hydrological networks (Fortier et al. 2007).

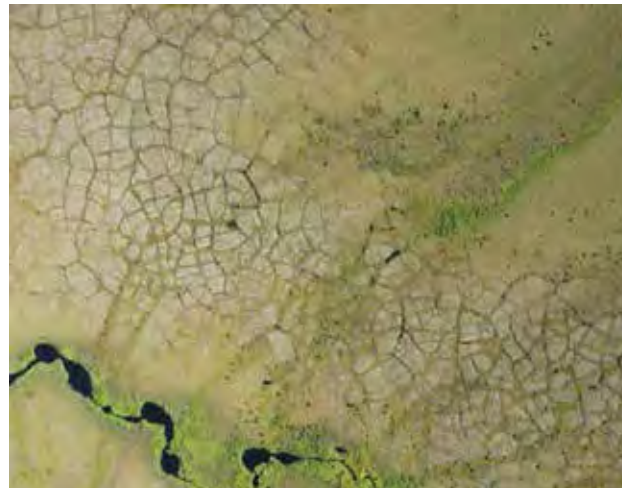


FIGURE 2. Tundra polygons, Mackenzie Delta region. Note beaded stream in bottom left where stream channel is controlled by patterns of underlying ice wedges, with beads (pools) occurring at junctions of ice wedges. Also note ponding in some ice-wedge troughs.

3.2.3 Thermokarst lakes

The ISR is generally a lake-rich environment (Mackay 1963). Many of these lakes are of thermokarst origin, occupying closed depressions formed by settlement of the ground following the thawing of ice-rich permafrost (Rampton 1988; see Box 1). In permafrost regions, water bodies that do not freeze to the bottom in winter are underlain by an unfrozen zone called a “talik” (Burn 2002). The presence of a talik beneath lakes has a significant thermal impact on the surrounding permafrost. A range of mechanical and thermal processes drive the expansion of thermokarst lakes. Increases in permafrost or lake-bottom temperatures can thaw permafrost adjacent to the lake shore, which can cause shoreline subsidence, lake expansion and lakeside slump initiation (West and Plug 2008; Kokelj et al. 2009a). A decrease in ice thickness and a change in the extent of bottom-fast ice can also impact lake-bottom thermal regimes (Burn 2002) and may result in thermokarst lake expansion. The rates of lateral lake expansion can range from 0.3 to 0.8 m yr⁻¹ (Jorgenson and Shur 2007; Plug et al. 2008), but a variety of processes including wave action, ice-push, and wind driven currents and water levels, augmented by sediment and ground ice conditions, causes these rates to vary among lakes and between regions.

Thermokarst lake expansion is anticipated to be a primary mode of landscape change in a warming Arctic (Grosse et al. 2012). Thermokarst processes including peatland degradation, bank collapse, and retrogressive thaw slumping (see section 3.2.1) can cause lake growth and deliver organic and inorganic materials into lakes (Sannel and Kuhry 2011; Dieson et al. 2012; Thienpont et al. 2013). The ecological consequences to lakes will vary with the nature and rates at which terrestrial materials are delivered to the lake and with the degree of progressive lake bottom changes that may occur as the lake enlarges (West and Plug 2008; Kokelj et al. 2009a). Anaerobic decomposition of fossil and fresh organic matter in lake bottoms derived from thawing permafrost will contribute to the emission of the greenhouse gas methane (CH₄), and potentially to the permafrost degradation-climate feedback (Walter et al. 2006).



FIGURE 3. Partially drained lake basin, Mackenzie Delta region.

Permafrost degradation can also lead to the disappearance of lakes (Figure 3). In the western Arctic, catastrophic drainage of lakes can result due to some combination of bank overflow, coastal erosion, shifting stream channels, or thermal erosion along ice-wedge networks (Mackay 1992; Marsh et al. 2009). In Alaska, climate warming causing talik enlargement has also been reported to cause lake drainage via subsurface drainage pathways (Yoshikawa and Hinzman 2003). In the ISR, the rates of catastrophic lake drainage have decreased from more than one lake per year between 1950-1970 to less than 0.3 lake per year from 1985 to 1990 (Marsh et al. 2009). The processes are believed to be linked to climate change, but the drivers are not well understood. Lake drainage initiates several related processes: (1) permafrost aggradation (i.e. permafrost growth), and active layer and ground ice development (Mackay 1997); (2) terrestrial ecological succession (Ovenden 1986); and (3) carbon sequestration (Jorgenson and Shur 2007). Drained lake basins are typically characterized by ice-wedge polygons, but in certain circumstances pingos may develop (Mackay 1992).

BOX 1. The Mackenzie River ecosystem

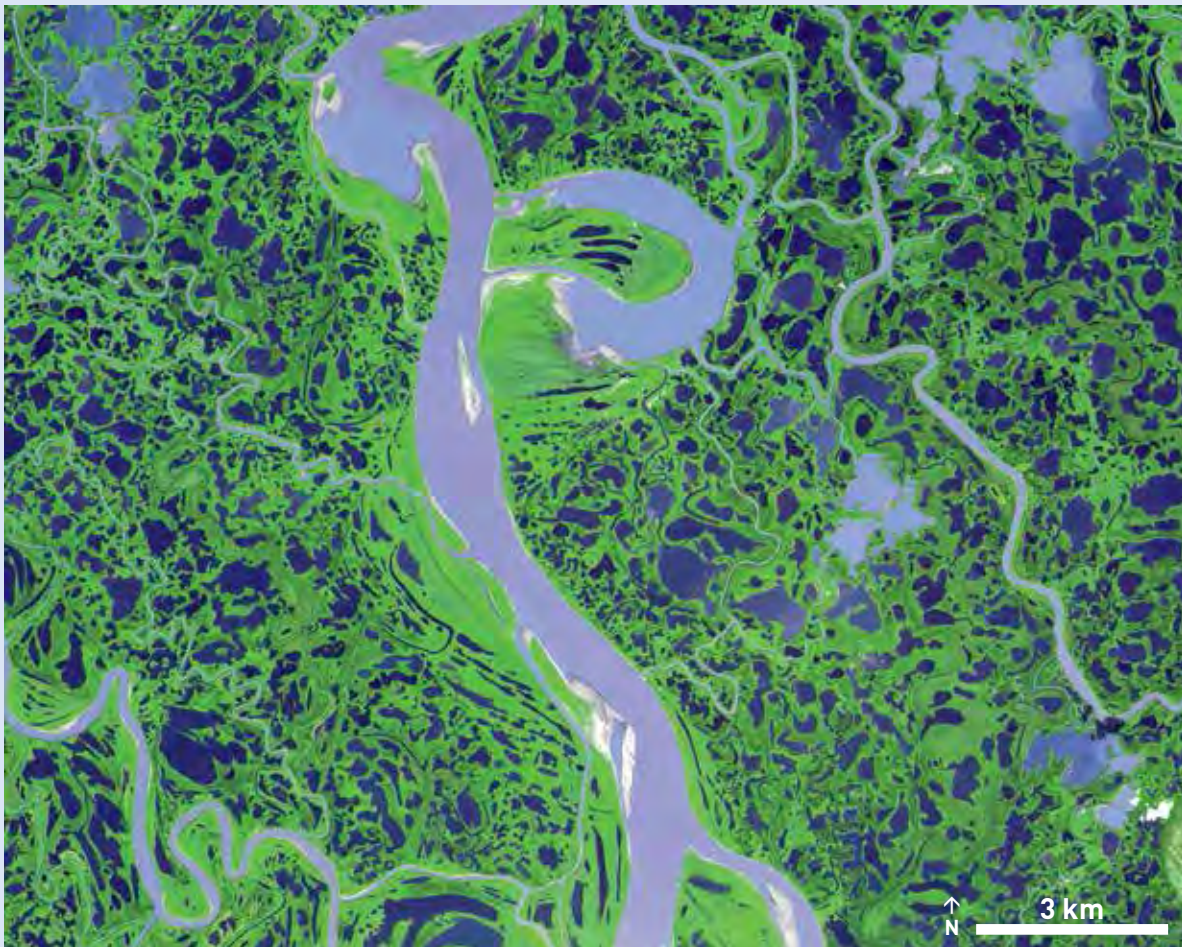
The Mackenzie River Basin is one of the world's great ecosystems. It is the longest river in Canada, with a total length from its headwaters to the sea of 4241 km; the main stem of the river extends 1738 km, from the outlet of Great Slave Lake. The river drains a catchment of 1.8 million km², 20% of the Canadian landmass, and its multiple channels discharge about 325 km³ of freshwater (Environment Canada 2013), as well as enormous quantities of sediments, organic carbon, nutrients, other chemicals, and plankton into the coastal Arctic Ocean each year. Its influence on the salinity and other properties of the Beaufort Sea can be detected more than 350 km offshore.

Lakes are a major feature of the Mackenzie River Basin system (Wrona et al. 2010). Three large lakes (Great Slave, Great Bear, and Athabasca) and a myriad of small lakes drain into the river. In the final 200 km before its discharge to the sea, the river opens out into an extensive delta, and GIS analysis of satellite images (see figure right) has shown that this floodplain contains around 49,000 lakes (Emmertson et al. 2007). These are mostly thermokarst lakes formed by thawing and subsidence of ice-rich permafrost, which underlies about 75% of the Mackenzie River catchment. Analyses of the river water have shown that limnological processes in the delta lakes during the annual flood period greatly modify the nutrient and particle content of the river water before its discharge to the sea (Emmertson et al. 2008).

The high sediment load and turbidity of the Mackenzie River mean that there is little light available for photosynthesis, and this flowing water part of the ecosystem is heterotrophic: that is, respiration in the water column exceeds photosynthesis and the river is a source of CO₂ to the atmosphere (Vallières et al. 2008). The flowing waters contain a complex microbial food web, with an unexpectedly high diversity of microscopic species whose ecological roles are still mostly unknown (Galand et al. 2006). In contrast, the floodplain lakes are autotrophic: primary production exceeds respiration because of their aquatic plant communities, and the lakes are a net sink of CO₂ during summer. The bottom-dwelling plants grow on the rich sediments delivered by the river floods each year. They attain surprisingly high biomass levels, as great as that of even tropical aquatic ecosystems, and research on these lake waters has underscored the importance of the Mackenzie River floodplain as a 'biological hotspot' in the circumpolar North (Squires et al. 2009).

The Mackenzie River also has a remarkable lake-like feature that forms seasonally at its entrance to the sea. When the Arctic Ocean pack ice collides against the landfast coastal ice it creates a thick ice-ridge (stamukhi) that can extend as much as 20 m below the ocean surface. This acts as a dam that retains the inflowing river water, and for up to six months of the year a vast lagoon is produced of freshwater floating on the sea, unofficially called 'Lake Mackenzie' (Carmack and Macdonald 2002). Microbiological analyses have shown that this ephemeral freshwater system may modify the chemistry and biology of the river water before its discharge to the sea in late June-July when the ice barrier thaws and ruptures (Galand et al. 2008).

The Mackenzie River ecosystem has always been vitally important to the people of the region for food, water and transport. Known in Inuvialuktun as Kuukpak ('Great River'), the river provides the habitat for some 55 species of fish, including several species that are traditionally harvested. The fish community structure appears to have been relatively stable over the last 40 years, but ongoing climate change, the arrival of new species and industrial development are likely to affect these populations in the future (Tallman et al. 2005). Given that the Mackenzie River and its associated floodplain lakes are strongly dependent on ice (permafrost thaw lakes, ice jam floods, the stamukhi barrier, coastal sea ice), climate warming will have a broad range of impacts on the structure and functioning of this remarkable ecosystem (Lesack et al. 2014), with downstream effects on the coastal Arctic Ocean.



Satellite image (in false colour) of a small section of the Mackenzie River Delta, showing one of the main channels and the myriad of permafrost thaw lakes across the floodplain. Photo credit: NASA GSFC/METI/ERSDAC/JAROS and the USA/Japan Aster Science Team.

3.3 Impacts to vegetation

Northern terrestrial ecosystems, including the northern boreal forests, the broad transition between forest and tundra, the low Arctic, and the high Arctic tundra cover nearly 40% of Canada (Henry et al. 2012). These ecosystems play important roles locally, regionally and globally as resources for communities, habitat for species, stores for soil carbon, and regulators of the climate through albedo and heat sinks of snow, ice and permafrost. The rapid warming in the Arctic is affecting the structure and function of terrestrial ecosystems which will impact wildlife habitat, the ability of people to use the resources, and will have feedbacks to the climate. For example, increasing height and cover of shrubs in low Arctic regions and greater density and growth of trees in the forest-tundra will affect travel routes, change soil carbon storage, and lower the surface albedo resulting in greater absorption of solar radiation leading to increased warming of the atmosphere (ACIA 2005; Myers-Smith et al. 2011a, b; Elmendorf et al. 2012a; Lantz et al. 2012). In addition, the warming climate is leading to drier conditions in some areas resulting in the disappearance of tundra ponds and lakes and increased frequency and magnitude of tundra fires (e.g. Mack et al. 2011). The impacts of the changing climate are taking place at the same time as increased industrial activity throughout the Arctic, including road building and resource extraction. These activities bring with them the increased potential for invasive species and localized contamination from waste products and industrial chemicals. Hence, predicting how these terrestrial systems will react and how the responses will affect other systems is very difficult and will require multi- and interdisciplinary approaches, beginning with assessments of the current state and potential for change of regional areas.

In this section, we focus on the terrestrial ecosystems in the western and central Canadian Arctic, where the climate has been changing over the past 50-100 years at some of the highest rates in all of the Arctic (ACIA 2005; Hinzman et al. 2005). This unique area of the Canadian Arctic has the most northerly extent of the forest-tundra boundary, a consequence of the influence of the Mackenzie Delta, and

is poised for greatly increased industrial activity through production of oil and gas reserves in the Beaufort Sea. We review the evidence for changes in these ecosystems and assess the potential for future changes and their consequences at local, regional and global scales.

3.3.1 Vegetation in the western and central Canadian Arctic

The western and central Canadian Arctic region extends from the northern extent of the boreal forest to the high Arctic tundra. Vegetation in this region spans forest, sparse woodland at tree-line, shrub tundra, wetlands, and high Arctic tundra (Figure 4). Tree species such as black spruce (*Picea mariana*), white spruce (*Picea glauca*), paper birch (*Betula papyrifera*), tamarack, (*Larix laricina*), trembling aspen (*Populus tremuloides*), and balsam poplar (*Populus balsamifera*) grow at the southern borders of the region. In the shrub tundra, tall shrub species such as willows (*Salix* spp.), alder (*Alnus* spp.) and dwarf birches (*Betula* spp.) dominate with canopy heights of 40-400 cm. At higher latitudes dwarf shrubs less than 40 cm (*Arctostaphylos* spp., *Ledum decumbens*, *Empetrum nigrum*, and *Vaccinium* spp.) and sedges (*Carex* spp. and *Eriophorum* spp.) predominate. Further north erect dwarf shrubs are replaced by prostrate dwarf shrubs and forbs less than 10 cm tall (*Cassiope tetragona*, *Dryas integrifolia*, *Draba* spp., and *Saxifraga* spp.).

3.3.2 Observed vegetation changes

There are several lines of evidence indicating that vegetation is changing in the western and central Canadian Arctic. These changes have been observed empirically using repeat photography, plot-scale vegetation monitoring, and satellite data analysis (Figure 5) as well as local knowledge. These approaches are allowing us to paint a picture of how this region might be changing, but there are still many unknowns making it difficult to predict future vegetation change.

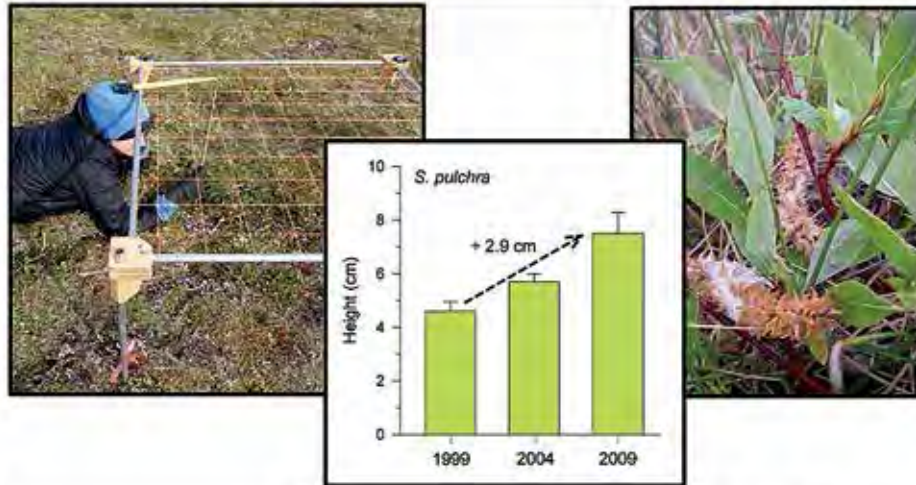


FIGURE 4. Vegetation zones in the ISR and the Kitikmeot region based on the Circumpolar Arctic Vegetation Map. Data accessed from the Circumpolar Arctic Vegetation Mapping Project (CAVM 2003).

1. Repeat photographs showing increased shrubs between 1987 and 2009



2. Long-term monitoring showing increases in shrubs over 10 years



3. Maps showing increasing "greenness" in 2006 compared to 1985



FIGURE 5. Observations of vegetation change: (1) repeat photographs from Herschel Island showing increases in willow shrubs; (2) long-term monitoring plots on Herschel Island where the shrub species diamond leaf willow (*Salix pulchra*) has been found to have almost doubled in height over 10 years (see inset graph; Myers-Smith et al. 2011b); and (3) satellite data between 1985 and 2006 on the Yukon coastal floodplain and Herschel Island (Fraser et al. 2011). The areas in bright green are where the satellite data indicate the greatest increase in greenness most likely indicating vegetation change.

Studies using repeat photography show that the abundances of alder, willow, and birch shrubs are increasing (Tape et al. 2006; Lantz et al. 2010, 2012; Mackay and Burn 2011; Myers-Smith et al. 2011a, b). Plot-based monitoring studies also show an increase in both the cover and height of shrubs (Elmendorf et al. 2012a). Shrub species are expected to continue to increase in this region, and this will likely be one of the most prominent vegetation changes in this region over the next 50 years. Satellites can be used to detect changes over large areas. Current trends reveal increased ‘greenness’ over large areas of tundra (Olthof et al. 2008; Bhatt et al. 2010; Fraser et al. 2011; Epstein et al. 2012). Though there is uncertainty associated with the interpretation of trends in satellite imagery over time, the increasing greenness likely indicates greater cover and abundance of tundra vegetation.

Changes in forest cover and tree recruitment have been more modest. An increase in recruitment of white spruce and subalpine fir (*Abies lasiocarpa*) during the past century has been observed at tree-line in the Mackenzie Mountains; however, to date there is no evidence for tree-line advance up mountain slopes in this region (Mamet and Kershaw 2011). Near Tuktoyaktuk, white spruce produced more cones in 2009 than in the early 1990s yet the seed germination rate remained low (Walker et al. 2012). Trees are likely responding to the changing climate conditions, but these responses are not uniform and do not suggest a rapid expansion of the tree-line northward in the next decades.

When asked about environmental changes occurring in their community, the majority of participants in a survey from the community of Kugluktuk described an increase in shrub growth (Gérin-Lajoie et al. unpublished data).

Shrubs are starting to grow in June now, when they used to grow in July. They grow more all around, over the crowberries (paongat) areas. There were not so many when we moved here in 1945. – Alice Ayalik, Kugluktuk

Participants in the Arctic Borderlands Ecological Knowledge Cooperative have also noticed changes in vegetation including increased shrub cover and more rapid growth (Gordon et al. 2008).

Berries such as blueberry (*Vaccinium uliginosum*), crowberry (also known as blackberries, *Empetrum nigrum*), cloudberry (*Rubus chamaemorus*) and cranberry (*Vaccinium vitis-idaea*) are an important source of wild food for many northerners. Berry development is dependent on climate conditions, the nutrient resources available to the plants (Krebs et al. 2009), and the presence of insect pollinators (Trudel et al. 2012). Extreme weather events can also influence berry production (Bokhorst et al. 2008, 2011). If weather conditions become more variable in the western and central Canadian Arctic, berry production is also likely to change. Kugluktukmiut have observed plants blooming at different times, more grasses growing, and Arctic cottongrass (*Eriophorum* spp.) decreasing in abundance. New plant species have also been noted. Survey respondents reported that lichens are growing less and that blueberries and crowberries are getting smaller and drying more easily (Gérin-Lajoie et al. unpublished data).

There is a picture of long time ago when the plants used to bloom all at the same time; it is different now, they don't bloom at the same time. I worry about it sometimes; they are a little too late in growing and in some years they grow too early. – Lena Niptanatiak, Kugluktuk

I noticed a difference where I go to pick cloudberry (akpit): it is getting dryer, and there is hardly any water in that area now. Cloudberry are growing less nowadays. – Lena Allukpik, Kugluktuk

We used to get really big blueberries, but now we don't get very much. They are not like long ago, they hardly grow small little blueberries. Their taste is different and they are not as sweet. Blackberries are the same, they don't get big or sweet like they used to. – Laura Kohoktak, Kugluktuk

3.3.3 Factors influencing vegetation change

A variety of factors and processes influence the vegetation growth across this region, including climate, natural physical disturbances, herbivory and human activities (Figure 6). Changes in the type or intensity of these processes could influence plants in different ways.

Climate

Climate factors such as temperature, snow and rain fall, wind patterns, and growing season length all influence tundra plants. Warmer spring and summer temperatures, longer growing seasons (trends to earlier snow melt and later snow onset), and increased evaporation from drier habitats are evident in the regional climate projections for the ISR and the Kitikmeot region (Chapter 2). Warmer summer temperatures and longer growing seasons will promote increased primary production in many regions, especially those with more continental climates (Walker et al. 2012), and the western and central Canadian Arctic is likely to experience substantial increases in growing degree-days in the interior mainland and southwestern Victoria Island (Chapter 2).

An association between summer warming and local changes in plant abundance has been observed at sites around the tundra biome, though the strength of these relationships were dependent on the climate zone, moisture conditions and the presence of permafrost (Elmendorf et al. 2012a). Experiments have demonstrated that warmer temperatures increase the abundance of certain plant species such as deciduous shrubs, though this response varies among sites with different climates and soil moisture (Elmendorf et al. 2012b). Experimental warming can also influence plant phenology (i.e. the timing of growth, flowering and fruiting) in tundra ecosystems (Klady et al. 2011). Snow fence experiments have demonstrated the importance of snow cover for determining plant growth and species composition (Wipf and Rixen 2010). Warmer summer temperatures and longer growing seasons seem to have favoured more rapid growth in white spruce in taiga forest near the tree line during the

20th Century (Andreu-Hayles et al. 2011). Willow shrubs are expanding and growing taller in the taiga-tundra transition zone as well as the low Arctic tundra throughout the circumpolar North (Myers-Smith 2011b), and this pattern is evident in the western and central Canadian Arctic (Myers-Smith et al. 2011a; Lantz et al. 2012). Kennedy et al. (2001) report increases in grass cover in upland heath tundra that might reflect a drying trend in these habitats. Extreme climate events have been shown to damage tundra plants including shrub species (Bokhorst et al. 2008). Because plant responses to changes in climate are varied, it is difficult to predict the net results of warming on northern ecosystems.

Permafrost

Changes in permafrost conditions create disturbances that influence the distribution of plants. These disturbances involve degradation of permafrost features such as pingos, frost boils and ice wedges, and include thaw slumps and active layer detachment slides (see section 3.2 for more details). These soil disturbances can cause changes in plant species composition over time including an increase in shrub cover (Lantz et al. 2009), grass and forbs (Kennedy et al. 2001). Permafrost thaw can also lead to ponding of water or increased drainage creating wetlands or draining lakes and ponds (Hinzman et al. 2005; Marsh et al. 2009).

Fire

Another major disturbance that could potentially increase with climate warming in the western Arctic is tundra fire. A large tundra fire (>100,000 ha) was observed on the North Slope of Alaska in 2007 and has been viewed by many as an indication that tundra fires will become more common (Mack et al. 2011). Fires can influence the establishment of plant species and alter plant communities in northern ecosystems (Lantz et al. 2010, 2012; Brown and Johnstone 2012). If tundra fires increase in frequency and extent in the western and central Canadian Arctic, this could alter the composition of plant communities and potentially increase the recruitment of shrub and tree species in the resulting burned areas.

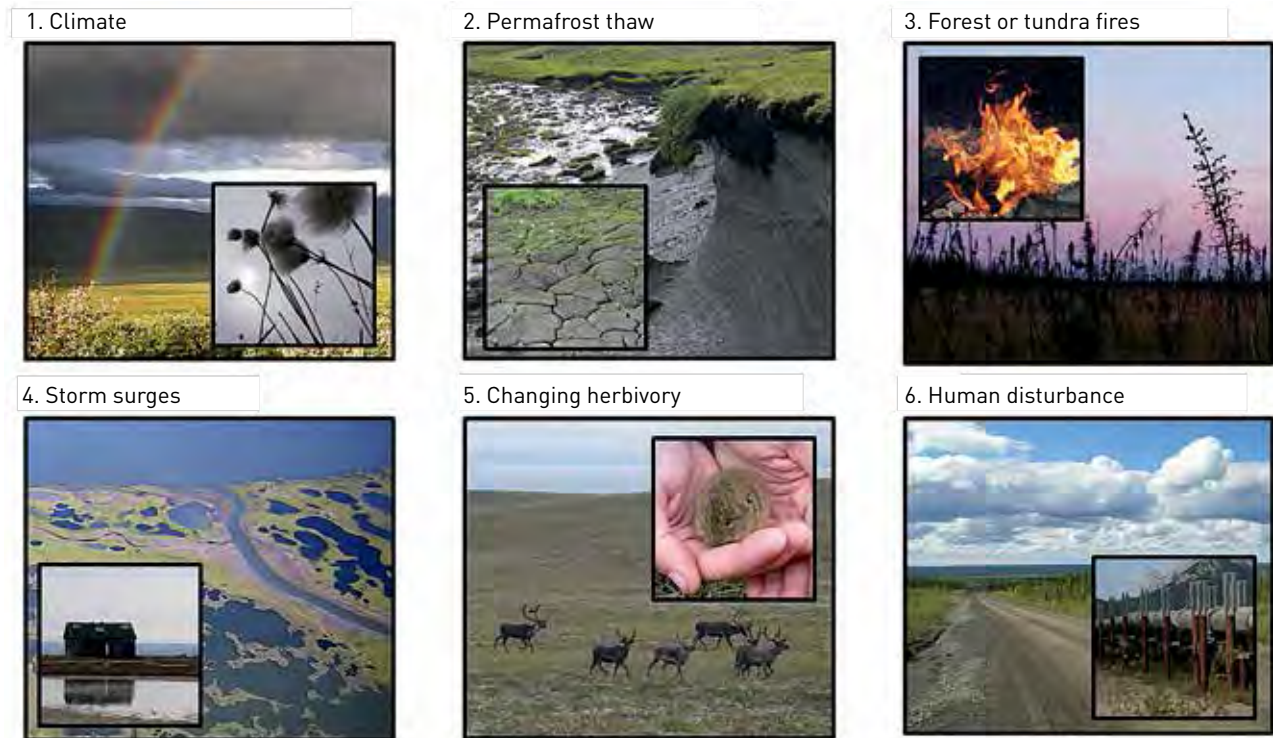


FIGURE 6. Examples of different types of disturbance influencing plants in the western Arctic: (1) Climate – e.g. warming temperatures, changes in the growing season or winter conditions; (2) Permafrost thaw – disturbances such as thaw slumps and patterned ground; (3) Fire – including forest and tundra fires; (4) Storm surges – for example those observed in the Mackenzie Delta; (5) Herbivory – feeding by large and small animals such as caribou to lemmings or insects; and (6) Human disturbances – including roads, pipelines, and other infrastructure.

Storm surges

More frequent storm surges (i.e. high waves that cause coastal flooding), combined with increased sea level and reduced sea-ice cover, are also likely to influence the vegetation along the coast in the western and central Canadian Arctic. Recent flooding of low lying Arctic ecosystems suggests that these impacts have already begun (Pisaric et al. 2011; Kokelj et al. 2012). A 1999 storm surge in the Mackenzie Delta significantly increased soil salinity, killing more than 13,000 ha of vegetation in a 129,000 ha portion of the outer Mackenzie Delta. Future storm surges of this magnitude will dramatically alter vegetation growing along low-lying areas of the Arctic coastline.

Herbivory

Herbivores can influence the abundance and biodiversity of plants on the landscape. Where herbivore populations are high, the biomass (i.e. the amount of leaves, stems and roots) of the plants that they feed on can decrease (Olofsson et al. 2009). In the ISR and the Kitikmeot region some of the dominant animal herbivores are caribou, muskox, lemmings, and insects (see section 3.5). In this region, there is some evidence that caribou can change the abundance of lichen species (Joly et al. 2007, 2009). In northern Alaska, lemming populations influence the amount of plant litter in Arctic tundra (Johnson et al. 2011). However, since these animals go through large cyclic fluctuations in population, their influence on plants will probably change cyclically

over time. Thus, a climate-related trend in plant populations may be difficult to detect amidst the cyclic pattern. In other regions of the Arctic, herbivores have been shown to significantly influence the abundance of shrub and tree species (Olofsson et al. 2009; Speed et al. 2010). There is a great deal of uncertainty about interactions between herbivores and plant abundance, hence it is difficult to project with certainty how animal species might influence tundra and northern forests in the future.

Human disturbance

The construction of human infrastructure such as houses, roads, drilling sumps, and seismic lines create soil disturbances that change local vegetation composition (Johnstone and Kokelj 2009; Kemper and Macdonald 2009). Road traffic also generates dust that can alter the plant community (Myers-Smith et al. 2006), and invasive species have been found along roads and other disturbances in the western and central Canadian Arctic probably by being transported into the area on vehicles (Carlson and Shephard 2007; Line et al. 2007). These invasive species are not yet abundant in the ISR and the Kitikmeot region, but their range expansion into tundra ecosystems is a potential concern for the future.

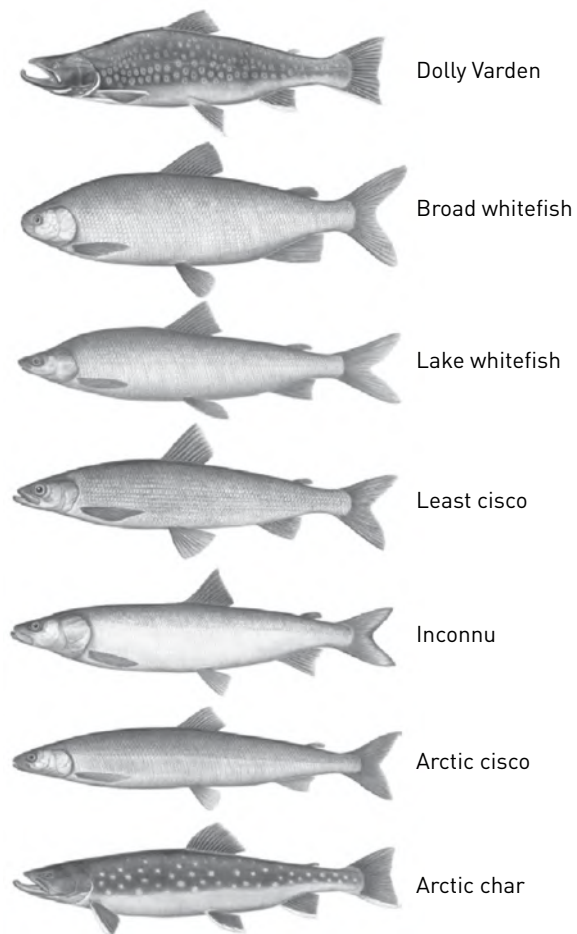
3.4 Impacts to freshwater and anadromous fishes

3.4.1 Freshwater and anadromous species

Fifty-six named species of freshwater and anadromous (i.e. sea-run) fishes are found in the western Arctic many of which are also distributed in the central Canadian Arctic (Sawatzky et al. 2007). Diversity in the NWT and Nunavut declines significantly with latitude on the mainland. Diversity also declines from west to east, thus the Mackenzie Basin is very species-rich in comparison to river systems further east in Nunavut. No wholly freshwater species are reported to be present on either the southern or northern islands within the western and central Canadian

Arctic; rather there are derivatives of anadromous species found in freshwater systems in this area.

Freshwater species may be associated primarily with lakes (e.g. cisco, *Coregonus artedii*) or rivers (e.g. Arctic grayling, *Thymallus arcticus*), although they may migrate between or within these two habitats either seasonally or over the life time of the individual fish (but they generally do not enter marine waters). Many freshwater fishes are small bodied (i.e. minnows, sculpins) and will not be considered further. About seven species of freshwater fishes are typically



GERRY KUEHL

FIGURE 7. The principal species of anadromous fishes of the ISR and the Kitikmeot region arranged roughly from west (top) to east (bottom) with respect to major geographic distribution (see text). Illustrations are not to scale.

large-bodied adults and are important to humans, including longnose sucker (*Catostomus catostomus*), white sucker (*Catostomus commersoni*), northern pike (*Esox lucius*), cisco, round whitefish (*Prosopium cylindraceum*), Arctic grayling and burbot (*Lota lota*). These species may be fished (e.g. burbot), are generally present only in mainland fresh waters (e.g. northern pike), and may also be particularly important ecologically (e.g. suckers).

Anadromous species of fishes are by definition migratory (or at least significant components of the population exhibit this behaviour) with spawning occurring in inland areas of rivers and lakes and feeding occurring during the summer in marine areas. Species of high relevance to humans and ecological processes include Arctic char (*Salvelinus alpinus*), broad whitefish (*Coregonus nasus*), Dolly Varden (*Salvelinus malma malma*), lake whitefish (*Coregonus clupeaformis*), Arctic cisco (*Coregonus autumnalis*), least cisco (*Coregonus sardinella*), and inconnu (*Stenodus leucichthys*) (Figure 7). Additionally, lake trout have recently been shown to demonstrate semi-anadromy (Swanson et al. 2010; Kissinger et al. 2014)

3.4.2 Cultural relevance of fishes

Fish are an important part of the culture, diet and subsistence economy of residents of the ISR and the Kitikmeot region (Condon et al. 1996; Usher 2002; Joint Secretariat 2003; Papik et al. 2003; Priest and Usher 2004; Communities et al. 2005; Nuttall 2005; Community Corporations et al. 2006; WKSSS 2008). Even though the wage-earning economy has become prominent in these communities, for many families subsistence hunting and fishing remain the primary source of food, and fishing can provide food year round (Condon et al. 1996; Nuttall 2005; Community Corporations et al. 2006; WKSSS 2008). As done in the past, families continue to travel to lakes, rivers and coastal sites to collect fish to make dried, smoked, quak (frozen raw) and cooked fish for eating immediately or storing for future consumption. Harvesters bring fish meat back to community Elders and people who can no longer go out on the land (pers. comm.

with local fishers in the ISR). This practice of country food sharing and food distribution among community members still plays an important societal role in these communities (Morrison and Germain 1995; Condon et al. 1996; Papik et al. 2003; Nuttall 2005; WKSSS 2008). Freshwater and anadromous fish are still collected in large quantities for storage in household freezers for times when there is little meat in the local grocery stores, the cost of meat has increased to unaffordable prices due to fly-in cargo costs, or country food is desired for meals (Morrison and Germain 1995; Nuttall 2005; WKSSS 2008; Knopp et al. 2011).

Landlocked and anadromous Arctic char is the species harvested in highest numbers for subsistence fisheries in the northern ISR and all Kitikmeot communities (Joint Secretariat 2003; Priest and Usher 2004; Furgal and Prowse 2008), whereas broad whitefish is the species caught in highest number in subsistence fishing efforts in the Mackenzie River Delta communities (Akavik, Inuvik and Tuktoyaktuk), which are outside of the normal range for Arctic char. In Nunavut, a survey of 1,569 people reported that 88.9% of people surveyed ate Arctic char, and it was the second highest consumed country food after caribou (Centre for Indigenous Peoples' Nutrition and Environment 2008a). In the ISR, a survey of 266 people reported that 66.9% of people surveyed ate Arctic char, and it was the third most consumed country food after caribou and berries (Centre for Indigenous Peoples' Nutrition and Environment 2008b).

3.4.3 Changes, threats and stressors to fishes

The primary risks posed to freshwater and anadromous fishes include fishing, climate change, and industrial development. Provided below are discussions on the latter two stressors illustrating, as four examples, impacts to regional species, ecosystems and subsistence activities. Traditional knowledge from the ISR and the Kitikmeot region describing recent changes to local conditions over recent decades that have the potential to affect Arctic freshwater and anadromous fish and fishing are also covered.

Example 1. Climate change effects upon northern Dolly Varden

The riverine anadromous char, Dolly Varden, exhibit migratory and non-migratory life histories, grow slowly, mature late, and do not always spawn in consecutive years (i.e. are iteroparous) (Reist et al. 1997; Stewart et al. 2010). Anadromous populations spawn and overwinter in small sections of headwater habitats (<10 km long) that are associated with perennial groundwater sources fixed in location (Mochnacz et al. 2010). These biological characteristics and specific habitat requirements increase the vulnerability of this species to anthropogenic impacts and environmental perturbations (Reist et al. 1997; Mochnacz et al. 2013), and as such, Dolly Varden were recently assigned “Special Concern” status by the Committee on the Status of Endangered Wildlife in Canada (Sandstrom and Harwood 2002; COSEWIC 2011; Stewart et al. 2010). Given the vulnerability of this species to impacts, it is important to assess the risk of potential effects of climate change on its populations. Many of these effects are assumed to impact the populations, however, explicit causal linkages are uncertain and undocumented in many cases. Some of the potential effects are described below.

Habitat degradation: Infilling of spawning habitat due to bank instability can be caused by permafrost degradation (see photo opposite page). Evidence of permafrost thawing and large-scale slumping into some rivers as observed by community members in the ISR (e.g. Jolly et al. 2002; Nickels et al. 2002; Nichols et al. 2004; Communities et al. 2005; Huntington and Fox 2005; Barber et al. 2008; see also section 3.2) suggests this may be a significant threat that potentially will increase in the near future. It is unclear, however, whether annual spring freshets (i.e. spring flooding) will ensure removal of in-filled sediments or whether these will accumulate in critical habitats. Locations of spawning and overwintering habitats are both restricted in area and fixed in space, thus bank failures (i.e. slumps) at critical locations or times of the year may heavily impact entire populations within some rivers. Thaw slump inventories (Brooker et al. 2014) may provide useful insight into

determining which streams are most susceptible to habitat degradation as a result of permafrost thaw.

Juvenile survival: Emergence in salmonids is usually timed to coincide with conditions favourable for survival and growth for these highly vulnerable young fish. Climate-related shifts in water temperature and discharge could result in different dates of emergence of young-of-the-year from the gravel areas where they hatch. This could be beneficial or detrimental to northern populations. Earlier emergence, if in advance of the spring freshet, should be beneficial due to longer growing seasons in the first year. Conversely, if juveniles emerge earlier, but if spring freshet is also earlier (i.e. before emergence), then survival could be compromised.

Competition: Dolly Varden may face limited spawning and overwintering habitat due to potential competition by bull trout (*Salvelinus confluentus*) and Pacific salmon (*Oncorhynchus* spp.; see Example 2). Critical habitat is limited for Dolly Varden, particularly spawning habitat located in specific thermal regimes on or downstream of perennial groundwater springs. Moreover, because these rivers freeze to the bottom over much of their lengths during the winter, over-wintering habitat volumes available to the entire population (and other co-occurring species such as Arctic grayling) appear to be limited. The probability of climate change-aided colonization of these rivers by bull trout moving northwards, and Pacific salmon moving eastwards, is uncertain. However, the consequence of invasion could conceivably be local extirpation, especially for small populations where spawning habitat carrying capacity has been reached (e.g. Babbage River system, population estimate ~ 6000 individuals). Bull trout, which is ecologically very similar to Dolly Varden, is presently distributed in mountain streams from the northern Sahtu region southwards. It is possible that, as a result of a warmer climate, bull trout may begin moving northwards along the Mackenzie River basin where they may compete with Dolly Varden.

Parasites and disease: The potential for increased mortality due to altered dynamics of local parasites or diseases, or to the introduction of new parasites and viruses (e.g.



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Permafrost thaw slumps impacting potential freshwater fish habitat, Richardson Mountains, west of Aklavik, NT

through newly colonizing species as vectors) is uncertain. Existing baseline information and ongoing monitoring are limited. However, this possibility remains particularly as a result of invading species that have similar general habitat preferences (e.g. bull trout or pink salmon (*Oncorhynchus gorbuscha*)).

Ecological productivity: Earlier ice-off in the spring and warmer summer water temperatures, as observed by community members in the ISR and the Kitikmeot region (Jolly et al. 2002; Nickels et al. 2002; Thorpe et al. 2002; Nichols et al. 2004; Communities et al. 2005; Government of Nunavut 2005; Huntington and Fox 2005; Knopp et al. 2011, 2012), and earlier freshets leading to longer access to marine systems (which are more productive than fresh waters), could improve the condition of anadromous adults due to longer growing seasons and/or additional food resources in coastal feeding locations.

Life histories: Anadromy is thought to have evolved in fish in response to significant differences in the general

productivity of fresh waters (low) and marine waters (high). This difference is particularly acute in the Arctic and thus likely underpins the propensity for northern fishes generally and Arctic fishes particularly to exhibit anadromy. Increased terrestrial productivity, generally visible as a “Greening of the Arctic” (see section 3.3), will decrease this differential, particularly if adjacent marine systems do not keep pace with terrestrial productivity increases. Higher relative production in freshwater systems is predicted to reduce the propensity for anadromy in populations where this trait is facultative and dependent upon growth. Thus, the relative abundances among life history types (migratory vs non-migratory) within populations may change. At least one example of the expected change to a greater frequency of non-migratory form is already apparent (e.g. Arctic char, Finstad and Hein 2012). Decreased frequency of migratory anadromous individuals, the preferred form in fisheries, will affect fishery production and thus impact the people relying upon this resource.

Mobility: Some environmental factors (e.g. increased evaporation) may cause reduced stream flow during summer months, thus creating physical barriers to upstream fish passage or decreased quality and quantity of spawning habitat. Many community members across the ISR and the Kitikmeot region have already witnessed low water levels in freshwater lakes and rivers (Thorpe et al. 2002; Nichols et al. 2004; Government of Nunavut 2005; Barber et al. 2008; Knopp et al. 2011). Warmer environments along with higher freshwater flows increase energy demands for basic metabolic processes and migrations. Although less likely for most rivers occupied presently, high water temperatures in stream reaches may also lead some fishes to avoid some habitats. If realized, these scenarios will decrease adult survival, reproduction, and juvenile survival and recruitment. The individual riverine populations of Dolly Varden are small in number, exist as independent stocks and, due to restricted distributions in fresh water for much of the year, are highly vulnerable to localized extinction events.

Adaptation: A key consideration for Dolly Varden is whether or not populations can adapt to a changing environment and what the limits are to this change. If they can adapt, will they be able to keep pace with environmental change (i.e. rates of climate change) and what is the maximum extent of biological adaptation of this species? Improving understanding of potential impacts of climate change and how Dolly Varden will respond will aid in prioritizing management options and promote species persistence in a changing environment.

Example 2. Pacific salmon – potential colonizers?

Chum (*Oncorhynchus keta*) and pink salmon are the most common Pacific salmon species occurring in the Canadian Arctic. Chum salmon are the only salmon species to maintain spawning populations in the Canadian Arctic, with suspected locations in the Slave River (McPhail and Lindsey 1970) and the upper Liard River (McLeod and O’Neil 1983), which are all tributaries of the Mackenzie River. Evidence of spawning also exists for chum salmon



Chum salmon (*Oncorhynchus keta*)

in several drainages between Point Hope and Prudhoe Bay, Alaska (Craig and Haldorson 1986; Johnson and Blanche 2011) and it is possible that strays from these potential northern Alaskan populations contribute to the Mackenzie River harvest (Stephenson 2006). Chum salmon have been infrequently reported east of the Mackenzie River. Pink salmon are found in Arctic Alaskan waters, but these observations do not yet indicate robust, self-sustaining populations (Nielsen et al. 2013). Chinook (*Oncorhynchus tshawytscha*), sockeye (*Oncorhynchus nerka*) and coho (*Oncorhynchus kisutch*) salmon have also been captured, although rarely.

Recently, the frequency of reported capture of salmon in the western Canadian Arctic has increased (Dunmall et al. 2013), perhaps due to increased survival of salmon spawned in the Mackenzie River, increased frequency of vagrants, or both (Irvine et al. 2009b). Captures of vagrant pink salmon (i.e. occasional individuals well outside their normal geographic range) have been increasing in even-numbered years, with most reported in or near the Mackenzie Delta (Dunmall et al. 2013) and one recorded on Banks Island, NT (Babaluk et al. 2000; Stephenson 2006). In odd-numbered years, pink salmon harvest in the Canadian Arctic remains exceedingly rare. Chum salmon are incidentally harvested yearly in subsistence fisheries throughout the Mackenzie River and many of its tributaries; however, the frequency of years with exceptionally high harvest of chum salmon has recently increased (Dunmall et al. 2013). Chum and pink salmon are best suited for colonization because of their better tolerance of the lower freshwater temperatures found in Arctic habitats compared to other

salmonids, and because they spend less time post-emergence in freshwater (Salonius 1973; McLeod and O'Neil 1983; Craig and Haldorson 1986). However, conditions in the winter Arctic marine environment may limit current salmon distributions and therefore future colonization (Irvine et al. 2009b). Regardless, climate warming will lessen the temperature barrier for range expansion, resulting in the increased possibility of vagrants becoming colonizers, perhaps with follow-on consequences to native fishes that share similar ecological requirements.

Spawning habitat in the Arctic is likely limited due to the extreme cold temperatures associated with Arctic winters. Substrate-spawning salmonids, such as Pacific salmon and native riverine charrs, require perennial groundwater flow in spawning habitat to avoid freezing temperatures in winter (Craig and McCart 1975) and competition from colonizers may displace native fish species in these key spawning areas. In addition, climate change may adversely affect the local fish species due to loss of optimal habitat or the fluctuation of environmental variables outside the tolerance levels of these populations. Thus, the range expansion of chum salmon and colonization by pink salmon in the western Arctic may pose serious risks to native salmonids, and may threaten the local fisheries on which people depend.

Example 3. Impacts to Husky Lakes, NT

The Husky Lakes (HL) are one of Canada's and the Arctic's most unique lacustrine ecosystems. These lakes are located along the southeastern shoreline of the Tuktoyaktuk Peninsula, 45 km northeast of Inuvik and due east of the Mackenzie Delta (Figure 8). Unlike most large river deltas in the Arctic which have massive drainage basins resulting in increased nutrient and warm water inputs from southern regions, HL are characterized by small drainage basins with low freshwater inputs (typically of cold water) and a significant marine influence. Salinity tolerance is therefore a determinant for where particular species occur (Roux et al. 2014). Species diversity shifts drastically in higher saline waters characterizing the outer basins, resulting in the loss of species preferring low salinities (e.g. lake trout

(*Salvelinus namaycush*) and Arctic grayling) and in the gain of species tolerant of higher salinities (e.g. Arctic flounder (*Liopsetta glacialis*), Pacific herring (*Clupea pallasii*), and saffron cod (*Eleginus gracilis*)).

The projected increase in mean annual air temperature for the Husky Lakes by 2050 is 2.8-3.0°C (Chapter 2). This increase could result in changes similar to those observed and projected for Toolik Lake, Alaska (Prowse et al. 2006), where average air temperatures have increased 2°C over the past 30 years. At Toolik Lake, increased thawing of the permafrost has not only resulted in increased sediment runoff but also weathering and release of trapped soil ions, nutrients, and contaminants. Nutrient runoff into nutrient-limited systems (as are most lakes in low-tundra areas) will likely result in an increase in productivity similar to that observed in Toolik Lake. This can have positive effects in lakes resulting in a greater forage base. However, it could potentially also result in low oxygen conditions during fall/winter due to increased organic matter decomposition in lake bottom waters, termed "eutrophication". An increase in summer air and water temperatures, combined with prolonged ice-free conditions, may promote seasonal density-driven structuring of the water column ("stratification"), which will prevent the mixing of oxygen throughout the lake and create a particular problem for bottom-dwelling fish.

In addition to the effects of climate change, the Husky Lakes are also subject to anthropogenic impacts. In particular, the Inuvik to Tuktoyaktuk Highway under development (Chapter 7, Box 3) will likely have some ecological consequences to the HL ecosystem. The 2009 proposed Upland Route will connect Inuvik via the 134 km highway. This route will cross over 40 temporary and/or permanent streams and come near many lakes requiring gravel that has been sourced near important lakes, including Jimmy Lake which supports a productive and culturally important Lake Trout fishery. All streams are linked to the HL and will likely increase sediment loading and possibly contaminants within these streams, resulting in potential negative impacts to flora and fauna. The proposed highway

alignment is located in the vicinity of the popular fishing locations on the HL, the Fish Lakes, and Rivers management area, an area which provides important fish habitat and is the site of historic and current subsistence harvest areas for the people of Inuvik and Tuktoyaktuk (Kiggiak EBA Consulting Ltd. 2010).

The highway will border for about 60 km the southern three basins of HL, allowing easier access to certain fishing locations. Ease of access may increase fishing pressure in areas nearest the highway and potentially result in over-harvest. Fishing in these three basins is focused primarily on lake trout (Roux et al. 2014) which have been shown to grow slowly and attain ages of 50 years (Roux et al. 2014). Slow-growing fish populations are extremely susceptible to over-fishing, disease and parasitism, as demonstrated by declines

in southern populations heavily impacted by anthropogenic stressors (e.g. the Lake Michigan lake trout extirpation due to intense overharvest, sea lamprey parasitism and likely habitat change; Clark and Huang 1985).

Example 4. A changing climate: impacts to fishing

Climatic and environmental changes occurring since the 1980s have the potential to cause direct and indirect effects not only on fishes and their habitats but also fishing activities. Local Inuit traditional knowledge holders in all communities in the ISR and most in the Kitikmeot region have observed and reported various changes and impacts to their fishing regimes (Jolly et al. 2002; Nickels et al. 2002; Thorpe et al. 2002; Nichols et al. 2004; Communities et al.

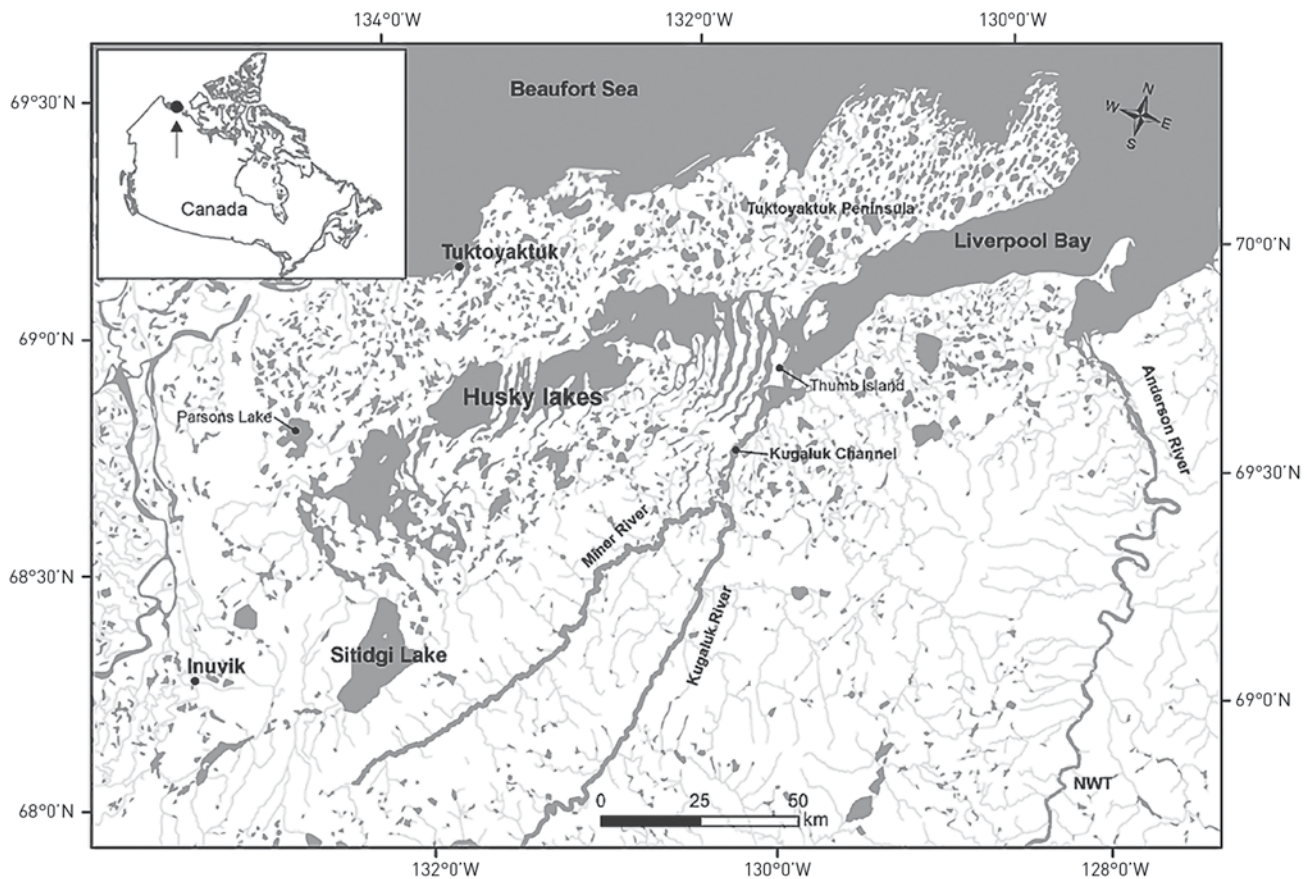


FIGURE 8. Husky Lakes, from Roux et al. (2014), Fisheries and Oceans Canada. Accessible online at http://publications.gc.ca/collections/collection_2015/mpo-dfo/Fs97-6-3071-eng.pdf

2005; Government of Nunavut 2005; Huntington and Fox 2005; Nuttall 2005; Barber et al. 2008; Knopp et al. 2010, 2011, 2012). Rapidly changing weather patterns, increased variability in weather events, storms, and thin lake ice have impacted the safety of travelling to and accessing fishing locations (see Chapter 6). Furthermore, earlier ice break-up and longer ice-free seasons have forced harvesters to not only modify the routes to their fishing locations (e.g. away from ice crossings) but also the timing of their fishing efforts. With respect to increased water temperatures, the quality of netted fish has been observed as “soft” and has become a concern for harvesters. The warmer weather is also making it hard to prepare dry and smoked fish as higher temperatures result in the flesh turning soft or “cooking” in the air (Huntington and Fox 2005).

3.4.4 Community-based monitoring

Increased knowledge to redress information gaps, particularly those associated with climate change effects, is now required within an ecosystem-based management approach (e.g. Howland et al. 2012). The effects of external stressors such as climate change and internal stressors such as increased tourism, mining, oil and gas resource exploration and extraction, infrastructure and development, and pollution will need to be monitored, and the effects on freshwater fisheries that lead to direct negative impacts on human health and subsistence activities will need to be mitigated (Furgal and Prowse 2008; WKSSS 2008). Local residents and organizations, and territorial and federal government organizations, will need to continue to work together to ensure the on-going conservation of the freshwater fish resource for Inuit in the ISR and the Kitikmeot region. Coping responses may be needed to mitigate these changes including choosing new fishing routes and locations, changing the timing of fishing efforts, altering fishing methods and the types of species harvested as well as ensuring safety and minimizing risk while conducting subsistence fishing activities (Jolly et al. 2002; Nuttall 2004; Reist et al. 2006).

Community monitors and community-based monitoring plans (CBMPs) will play a crucial role in the management and conservation of this resource. Existing CBMPs need to be ramped up to address the needs of local communities and new CBMPs need to be put in place where they do not already exist (Parlee and Lutsel K'e Dene First Nations 1998; Government of Nunavut 2005; Kristofferson and Berkes 2005; Harwood 2009; Prowse et al. 2009; see Chapter 1, section 1.4.5). The importance of the inclusion of traditional knowledge as well as community-based monitoring in understanding, monitoring and managing the potential effects of climate change on Arctic char is outlined in Box 2.

3.5 Impacts on terrestrial wildlife

Climate change is affecting the distribution and abundance of many wildlife species using sub-Arctic and Arctic tundra habitats in the circumpolar North (Callaghan et al. 2005; Meltofte et al. 2013). Some impacts, especially on migratory birds, are also responses to changes driven by human activities outside the Arctic (Ganter et al. 2013). Some changes in distribution and abundance, especially for mammals with highly cyclic populations, are driven by natural dynamics, with species responding to changes in local limiting factors over numbers of years (Reid et al. 2013). The inherent mobility of many Arctic species, and the instability of their population dynamics, means that we need to be cautious in concluding that climate shifts are causing the observed changes. Nevertheless, climate change poses a huge challenge for many wildlife species relying on tundra habitats.

BOX 2. Collaborative mixed methods research to determine environmental effects on Arctic char growth for use in designing community-based monitoring plans in the Inuvialuit Settlement Region

Since 2008 Jennie Knopp has been conducting her PhD research on community-based monitoring (CBM) of Arctic char (*Salvelinus alpinus*) using a research approach that integrated contemporary scientific knowledge and Inuvialuit contemporary and traditional Knowledge (IK). Jennie's research was conducted in collaboration with the communities of Sachs Harbour and Ulukhagak in the ISR and with her supervisors Drs. Chris Furgal and James Reist through the ArcticNet funded project "Understanding Impacts of Environmental Change on Char in the ISR: Science and Inuit Knowledge for Community Monitoring". This research extends previous work (Riedlinger and Berkes 2001; Nichols et al. 2004), which documented observations by the residents in Sachs Harbour of unprecedented and rapidly changing conditions in the local land, water, and weather surrounding their communities. The importance of Arctic char and other fishes to the northernmost ISR communities and the impending effects of a changing environment outside of local norms necessitate effective long-term community-based monitoring to gather systematic information needed to detect changes in and make decisions about the resource. CBM using both local expert and scientific knowledge can produce a more robust suite of monitoring indicators that incorporate local expertise and understanding of the resource (Huntington et al. 2004; Berkes et al. 2007; Knopp et al. 2012).



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Trevor Lucas of Sachs Harbour, NT has worked with Jennie Knopp for six years on the mixed methods research project. They teach each other about scientific and local expert knowledge of Arctic char and their environment. Here Trevor is removing otoliths (fish ear bones) from young Arctic char.

The goal of this collaborative mixed methods research project has been to identify and understand the effects of key environmental indicators of changes in Arctic char growth by linking CBM, Inuvialuit knowledge and contemporary scientific knowledge. This approach structures the collection, analysis and constant comparison of both biological and ecological data IK gathered through social research methods (Creswell 2009). The continuous parallel analyses between the two bodies of knowledge supports the development of a more robust understanding of the changing Arctic environments and the primary and secondary effects on Arctic char growth. Furthermore, this parallel analysis identifies areas where the two knowledge systems agree or disagree with one another, helping to find common ground for scientists and local experts to work together (Huntington et al. 2004; Furgal et al. 2006; Creswell 2009).



Jennie Knopp presenting the preliminary results of her mixed methods PhD research at the ArcticNet conference in Vancouver in 2012. Trevor Lucas came to the conference to assist Jennie in presenting the poster, to share his local expert knowledge and to learn from other researchers presenting at the conference.

BREANNE REINFORT

Arctic char age and annual growth analyses conducted using an age-specific otolith (fish earbone) back-calculation method (Kristofferson et al. 1991; Li et al. 2008) are compared to the environmental study parameters (e.g. fish habitat characteristics; Power et al. 2000, 2012; Kristensen et al. 2006; Chavarie 2008) as identified by IK and scientific knowledge. The analysis supports either a lake-specific or a local climate-driven driver of changes in growth in Arctic char across a range of ages within a given year. Parallel differences in a given year of growth across the study lakes would indicate a regional rather than a lake-specific phenomenon. Preliminary results show differences in lake water chemistry, lake volume and depth, Arctic char diet and parasite load among the study lakes. Arctic char in the study lakes fit expected growth patterns but attained different maximum sizes and reached their maximum size at different ages among the lakes. This demonstrates that local lake environment does have an effect on Arctic char growth. However, the results of the otolith back-calculation showed a large increase in growth in a single calendar year across a range of char age classes in two study lakes.

The environmental study parameters determined through both the ecological study methods and local expert IK show that increased growth in char correlates to a year with anomalously low sea-ice conditions and higher than average annual temperatures. Open sea water has a lower albedo than sea ice, resulting in the absorption of more solar radiation which has the potential to lead to warmer water (Barber et al. 2008). Reduced sea ice and warmer ocean waters could lead to warmer ambient air temperatures in the local environment, which in turn could result in warmer conditions in the local lake environments. A study on long-term data collected in the Nain anadromous Arctic char fishery in eastern Canada showed that ambient temperatures were linked with increases in char growth and weight (Chavarie 2008; Power et al. 2012). All of this points towards the need to monitor local ambient temperatures and local sea-ice conditions as parameters in CBM of Arctic char.

Few ArcticNet projects within the western and central Canadian Arctic have assessed climate change impacts on tundra animals, so 'IRIS 1'-specific expertise is limited. However, projects in this region, supported by the International Polar Year and other agencies, have addressed ongoing changes in wildlife distribution and abundance, often with climate change in mind (e.g. Parks Canada monitoring - Parks Canada Agency 2008; IPY ArcticWOLVES project – Gauthier and Berteaux 2011). In addition, other reports have assessed climate change impacts on Arctic wildlife across the circumpolar North (Meltofte et al. 2013), and in other ArcticNet regions (Côté 2012). We also draw on studies from neighbouring regions, such as Arctic Alaska, because of its pertinence to the ISR. We have arranged this review by taxonomic group: Invertebrates, Birds and Mammals.

3.5.1 Invertebrates

Invertebrate species comprise the majority of animal diversity, at the species level, in Arctic tundra ecosystems (Hodkinson 2013). This diversity is primarily evident during the summer, in mobile and above-ground life stages of insects, spiders and springtails. Invertebrates are ecologically influential in many ways. They collectively comprise the primary food for shorebirds and songbirds (Ganter et al. 2013). Many are detritivores (i.e. feed upon dead plants and animals) and speed up the inherently slow process of decomposition in cold climates. Some are pollinators of tundra plants, and others consume a substantial portion of annual plant growth (Hodkinson 2013). Some are primary pests or parasites of vertebrate species, including humans (Davidson et al. 2011).

The direction and strength of climate induced changes to invertebrate distribution and abundance are likely to be diverse (varying by taxonomic group or species) and variable among years (varying with region-specific trends or extremes in weather phenomena) (Hodkinson 2013). Dominant climate or weather factors influencing invertebrate life histories include mean winter and summer

temperatures, availability of soil moisture (driven by solar radiation, cloud cover and evaporation regimes), timing of onset of snow cover and its accumulated depth, timing of snow melt, and summer precipitation (Danks 2004; Hodkinson 2013).

Distribution

Changes in terrestrial invertebrate distributions in the western and central Canadian Arctic are poorly documented because of a scarcity of repeated historical surveys. Leung and Reid (2013) document northerly range extensions in six species of butterflies onto Herschel Island, north Yukon, with records collected in 2007-2009 compared to historical records dating back to 1916. These species may have moved north in response to warmer summer temperature regimes and longer growing seasons (Leung and Reid 2013). Results suggest that northerly range extensions of species from more productive and bio-diverse sub-Arctic ecosystems feature prominently in changes in distribution in the low Arctic. Sufficient time to complete the necessary stages of the life cycle in a growing season may define the northern range limits for many invertebrates. This time period is growing longer throughout the terrestrial portions of the ISR and the Kitikmeot region, with increases in thawing degree-days and growing degree-days, and therefore summer season length, especially on tundra near coastlines (Chapter 2). It therefore seems likely that more mobile invertebrate species in taiga/tundra transition habitats, and in low Arctic tundra habitats, will respond rapidly by expanding distributions farther north, especially on the mainland. However, even mobile species may not be able to extend their ranges into regions with newly suitable living conditions as fast as those conditions improve with a warming climate (Bedford et al. 2012). This lag may also result from the strong limiting effect of extreme weather events, such as early spring thaws followed by re-freezing, which are more likely with the increasing projected variability in climate conditions (Chapter 2). We can expect that species with generalist food habits and habitat affinities will be more successful in initial colonizations.

Large stretches of open water (e.g. Amundsen, Coronation and Queen Maud gulfs) may act as absolute barriers to movement of some species, such as biting insects. A few mosquito species (Culicidae) are found throughout the latitudinal range of the Canadian Arctic Archipelago, but black flies (Simuliidae) have not been found north of McClure Strait and Lancaster Sound. Horse and deer flies (Tabanidae) have very limited historical distributions on islands in the Archipelago, with ranges probably limited by climate (Danks 1981; Schaefer 2011). Evidence from the Northern Biodiversity Project indicates that some tabanid flies are extending their ranges farther north from sub-Arctic to low Arctic regions, and at least one black fly may have extended its range from the mainland to the low Arctic islands (Schaefer 2011). These data are not from the western and central Canadian Arctic, but suggest the need to look for such changes along the Boreal-Arctic transition and through the islands in the western Arctic. Biting insects may be responding directly to improved temperatures for successful completion of their life cycles, but this conclusion requires that suitable host species for a blood meal are present. For generalist biting insects such as mosquitoes and many black flies these conditions may well be satisfied, meaning that northern birds and mammals may experience increasing harassment and metabolic costs from insects. Alternatively, some biting flies may be moving north as their host species, such as moose (*Alces alces*) or some birds, colonize new areas.

Some biting insects (mosquitoes, deer flies) are vectors for human pathogens spread from other animals. These include brucellosis, tularemia and various viruses. Although some of these have yet to reach the western and central Canadian Arctic, others are endemic and increased surveillance and monitoring is recommended as a public health precaution (Parkinson and Butler 2005).

Some invertebrates are particularly influential in Arctic ecosystems as intermediate hosts of parasites whose adult forms infest other species, such as mammals. Climate change may be influencing the infestation rate and distributions of some parasites because increasing air temperatures



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(affecting ground temperature and growing season length) and increasing precipitation (affecting soil moisture) tend to increase the development rates of parasites in intermediate hosts. One example, documented in the western and central Canadian Arctic, is the nematode lungworm (*Umingmakstrongylus pallikuukensis*) of muskoxen whose intermediate host is a mollusc (*Deroceras laeve*). Warming has resulted in considerably higher probability that the parasite life cycle can be completed in the mollusc in one growing season instead of two, leading to increased rates of transmission to muskoxen in each growing season (Kutz et al. 2005). Recent evidence indicates an expansion of the range of this parasite, and another lungworm (*Varestrongylus* spp.) of caribou, from the mainland to Victoria Island probably through movements of infected muskoxen and caribou but supported by new opportunities for successful completion of the life cycles on Victoria Island following recent warming (Kutz et al. 2013). Movements of infected ungulates can spread the parasites to previously uninfected populations, and heavily infested muskoxen are more likely to succumb to extreme weather events (Kutz et al. 2005), such as projected increases in tundra icing events (Chapter 2, Figure A10).

Abundance

Recent changes in abundance (e.g. biomass) of Arctic terrestrial invertebrates are generally unknown because we often lack historical estimates, and abundance estimates are often imprecise for most species (Hodkinson 2013). However, we are beginning to understand the patterns of abundance by latitude and season. McKinnon et al. (2011) and Bolduc et al. (2013) analysed patterns in arthropod (primarily insects and spiders) abundance across four Canadian Arctic sites, one of which was Herschel Island, YT. Species diversity and biomass decreased dramatically from low to high Arctic sites, with Herschel Island (low Arctic) supporting the highest diversity of arthropod families (89) with a community dominated by various flies (Diptera) and wasps (Hymenoptera) (McKinnon et al. 2011; Bolduc et al. 2013). The duration of the pulse of mobile life stages, as well as the absolute biomass of that pulse, were also highest at Herschel Island (Bolduc et al. 2013). Wet habitats supported greater diversity and biomass than dry (mesic) habitats for most insect families (Bolduc et al. 2013). Current mean daily temperature and thawing degree-days collectively explained most of the variation in biomass, while average daily wind speed, relative humidity and incidental radiation were less influential (Bolduc et al. 2013). Straka (2009) also analysed patterns in arthropod abundance (direct counts of mobile life stages converted to biomass) at Sheep Creek, Ivvavik National Park. Species diversity at this lower latitude in the ISR yielded approximately 22 families, with peak biomass generally occurring towards mid-July (Straka 2009). These results emphasize the dominant role of temperature, especially accumulated degree-days of warming in the current growing season. Although mean daily temperatures in the ISR and the Kitikmeot region are projected to increase less in spring and summer than in other seasons, the summer warming will be sufficient to drive substantial increases in thawing degree-days and an earlier onset of summer, especially on the mainland and Victoria Island (Chapter 2). These changes will almost certainly advance the timing of emergence of mobile life stages of most arthropods, and they may allow some species to reach greater peaks in abundance during each growing season.

Although warming temperatures may induce positive changes in the abundance, phenology (i.e. timing of life cycle events) and distribution of many invertebrates, projected reduction in the duration of winter snow cover, especially with later onset of snow (Chapter 2), may limit the survival and abundance of some species that rely on snow cover as insulation against freezing temperatures while they develop their freeze-tolerance in autumn (Hodkinson 2013). Also, high temperatures lead to increased evaporation from the soil surface and a drying of upper soil layers which in some habitats will decrease abundance and perhaps distribution of some worm, ciliate and tardigrade species (Hodkinson 2013). The future composition and dynamics of invertebrate communities will be in long-term disequilibrium as climate changes interact with differing dispersal abilities and changing trophic interactions, often in seemingly random ways, to influence the distribution and abundance of tundra species (Hodkinson 2013). In summary, our knowledge is limited, but substantial changes are certainly underway especially in the low Arctic, and continued monitoring is essential.

3.5.2 Birds

In the western and central Canadian Arctic, as with most of the Arctic, birds having a strong affinity to water - shorebirds, seabirds and waterfowl - make up the large majority of species (Ganter et al. 2013). They also rely on terrestrial habitats at least for reproduction, as do a smaller contingent of passerine (i.e. perching) and non-passerine land birds including raptors (Ganter et al. 2013). Although Arctic food webs are relatively simple in terms of vertebrate species, they are hugely enriched in the growing season with the influx of migratory birds (e.g. snow goose (*Chen caerulescens*), lapland longspur (*Calcarius lapponicus*), upland sandpiper (*Bartramia longicauda*), rough-legged hawk (*Buteo lagopus*)) that take advantage of the long daylight, sufficient food, and possibly a general scarcity of parasites, pathogens, and predators (Ganter et al. 2013). A few species such as hoary redpoll (*Acanthis hornemanni*), ptarmigan (*Lagopus* spp.) and snowy owl can reside throughout the

year. Birds are valuable natural indicators of Arctic ecosystems because they occupy a diverse range of trophic levels, provide substantial food and cultural value to northern communities (Berkes and Jolly 2001; Wildlife Management Advisory Council (North Slope) and the Aklavik Hunters and Trappers Committee 2003; Kay et al. 2006), and perform essential ecosystem functions such as insect predation and nutrient cycling. With the Arctic facing disproportionately rapid yet regionally diverse climate change (ACIA 2005; Chapter 2), coupled with increasing human activity (Meltofte et al. 2013), bird populations are likely to respond in diverse ways. However, the most critical effects will be on the reproductive cycle, in terms of how both the trends and variability (especially extremes) in climate/weather and habitat affect food availability, timing of nesting, nest success and fledgling survival (Ganter et al. 2013).

Distribution

The breeding distributions of most Arctic-nesting birds have been stable over historical time. Some, including nesting colonies of the white-fronted goose (*Anser albifrons*) at the mouth of the Anderson River, NT and the lesser snow goose (*Chen caerulescens caerulescens*) on Kendall Island and Banks Island, NT within the western and central Canadian Arctic, and nest sites of many raptors, are remarkably fixed, leading to clear needs for site-specific conservation measures. However, future latitudinal or regional shifts in the distribution of Arctic-breeding birds are expected due to alterations of the forest-tundra transition zone (Turner 2013; Miller et al. in press), and changes to the structure and plant community composition of tundra habitats (ACIA 2005; Meltofte et al. 2007; Barber et al. 2008; see also section 3.3).

The recent increases in the abundance of shrub-nesting common redpolls (*A. flammea*) and white-crowned sparrows (*Zonotrichia leucophrys*) on Herschel Island (Cooley et al. 2013; Grabowski et al. 2013) and Ivvavik National Park (Turner 2013) may be a response to increased height and density of willows in some habitats (see section 3.3). Turner (2013) also suggested that greater bird abundance,



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specifically American robin (*Turdus migratorius*), yellow-rumped warbler (*Setophaga coronata*), and dark-eyed junco (*Junco hyemalis*) in Ivvavik National Park was associated with greater tree density and height, likely attributed to the rapid growth in white spruce. However, expansion of willow cover may negatively affect habitat suitability for upland tundra species such as Baird's sandpiper (*Calidris bairdii*), upland sandpiper (Miller et al. in press), rock ptarmigan (*Lagopus lagopus*) and snowy owl. Another example of a possible response to these changes is the seed-eating, white-winged crossbill (*Loxia leucoptera*), first observed in the forest tundra of Ivvavik National Park, YT in 2011 (eBird 2013). These birds were likely responding to a high abundance of white spruce cones that year (D.M. Turner, Trent University, pers. comm.), but it is unclear whether high cone production near the tree-line is driven by changing regional weather patterns that may become more common.

Inuvialuit (particularly residents of Sachs Harbour, NT) are seeing mainland waterfowl (e.g. northern pintail (*Anas acuta*) and mallard (*A. platyrhynchos*)) and passerines (e.g. American robin) shift their ranges northward (Berkes and Jolly 2001; Barber et al. 2008). This latitudinal shift may provide new harvest opportunities, but some hunters have noted difficulties harvesting traditional wildlife, such as lesser snow geese, because geese are flying higher and



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migrating on routes that do not take them over traditional hunting camps (Wildlife Management Advisory Council (North Slope) and the Aklavik Hunters and Trappers Committee 2003; Kay et al. 2006).

Numerous species nest in coastal habitats that are affected by the sea. The longer ice-free periods in the western and central Canadian Arctic (especially the Beaufort Sea), coupled with more intense cyclonic storm activity, are resulting in increasing rates of coastal erosion and larger storm surges (Comiso et al. 2008; Lantuit and Pollard 2008; see Chapters 6 and 7). Some birds are being or will be negatively affected (Kittel et al. 2011). Declines in beach and coastal pond habitat used by ruddy turnstone (*Arenaria interpres*) and red phalarope (*Phalaropus fulicarius*) seem to explain the near-disappearance of these species from Herschel Island in the last few decades (Cooley et al. 2013). A storm flooded out nearly all the red phalarope nests on Niglintgak Island, located in the mouth of the Mackenzie Delta (Walpole et al. 2008). Flooding, as in the outer islands of the Mackenzie Delta, causes a die-off of much of the salt-intolerant shrub community which is nesting habitat for species such as the American tree sparrow (*Spizella arborea*) and savannah sparrow (*Passerculus sandwichensis*). At the Kendall Island snow goose colony, low nesting numbers have been attributed to occasional flooding by storm surges from the Beaufort Sea to the northwest, particularly in 1993 when no geese nested (Wiebe Robertson and Hines 2006). Storm surges during the nesting period also result in

nest failure for other shorebirds (e.g. semi-palmated plover (*Charadrius semipalmatus*)) and waterfowl (e.g. common eider (*Somateria mollissima*)).

As described in section 3.2, increasing summer temperatures result in deeper permafrost melt and more evaporation, thus thermokarst tundra ponds and lakes could more rapidly drain underground or evaporate. Loss of tundra ponds and lakes would remove foraging, moulting and staging habitats for shorebirds and waterfowl. Such loss of standing water has been observed in taiga regions of northern Alaska, but this was less prominent on the Arctic coastal plain (Riordan et al. 2006). Evaporation rates from many Mackenzie Delta lakes exceed precipitation, so lakes rely on periodic flooding to maintain levels (Marsh and Bigras 1988). Given the generally low precipitation levels in the ISR and the western Kitikmeot region compared to other Arctic regions, the trends of increasing summer warmth and longer summer periods (Chapter 2), and the small catchment basins of many tundra lakes, the risks of lakes drying up seem even higher but may be somewhat offset by the trends to higher annual precipitation through the region (Chapter 2).

Phenology (timing of life cycles)

Earlier springs, resulting from earlier snowmelt, as observed and projected in the ISR and the Kitikmeot region (Derksen and Brown 2012; Chapter 2), change the timing of key tundra processes such as green-up of grasses and sedges, flowering, and emergence of mobile life stages of arthropods. There is concern that the earlier emergence of arthropods will be a problem for migratory birds that rely on them for food both when the birds arrive at the tundra nesting grounds and particularly when they feed their young. The birds may not be able to match their egg-laying to the changing spring temperatures which drive arthropod production later in the summer, so they may hatch their chicks with a poor match in time to the peak availability of their arthropod prey (Melfo et al. 2007; Tulp and Schekkerman 2008). The longer duration and higher amplitude of the pulse of arthropod biomass at the low Arctic site

of Herschel Island compared to mid to high Arctic sites (Bolduc et al. 2013) suggests that birds at low Arctic sites have more flexibility in matching the timing of hatching to the period in which food for hatchlings is most abundant. Birds at high Arctic sites with a shorter pulse of food may not have such flexibility. However, much depends on how flexible individual bird species are in their choice of prey types, which are less synchronous in their emergence in the low Arctic (McKinnon et al. 2012; Bolduc et al. 2013).

The birds' adaptability depends primarily on their ability to shift their migration schedule to start nesting earlier in warmer springs with earlier snow melt. The most common shorebirds and songbirds on Herschel Island show considerable flexibility, tending to nest earlier in years with earlier snow melt, but they do not exactly track the snow melt (Grabowski et al. 2013). East of the Kitikmeot region, on Southampton Island, Smith et al. (2010) also found that shorebirds could not fully adjust their arrival on the nesting grounds to track snow melt, but the birds showed some ability to shorten the time between arrival and egg laying in early springs probably because prey was more abundant in those warmer years. Birds of other taxonomic groups studied by Grabowski et al. (2013) did not show such flexibility. For common eiders, this is apparently because spring melt of sea ice has not advanced as fast as tundra snow melt, so this species has not had earlier access to marine foods close to its nesting grounds. The migration rate of rough-legged hawks may be primarily affected by the timing of snow melt in the boreal forest which has not advanced as rapidly as melt on Arctic tundra (Grabowski et al. 2013). A lack of direct response to snow melt probably does not pose such a direct problem for these species as they do not appear to rely on such a time-limited pulse of summer food as do the shorebirds and passerines.

Although a trend to earlier snow melt has occurred and is projected to continue, the western and central Canadian Arctic has experienced and will continue to see large inter-annual variation in timing of snow melt (e.g. range of 36 days in the past 33 years on Herschel Island) (Grabowski et al. 2013; Chapter 2). Consequently, the birds' behavioural

flexibility will be strongly tested in the future, and extreme years will likely reduce nesting success. For example, the timing of snowmelt appeared to be the main factor affecting nesting performance and productivity of lesser snow geese on Banks Island (Samelius et al. 2008). In late springs, these geese have been known to dump their eggs on the late melting snow, with some eggs being washed downstream in the runoff during break-up (Kay et al. 2006). This impacts the Inuvialuit residents of Sachs Harbour because fewer eggs are harvested as part of their traditional activity (Berkes and Jolly 2001). Spring weather that fluctuates widely between progressive warmth followed by a recurrence of winter-like conditions will significantly reduce reproductive success (Martin and Wiebe 2004) and may be more decisive in its negative effects than the average warming trend across years.

Abundance

Bird abundance and distribution are closely linked. There is evidence of substantive changes to abundance resulting from human activities on the tundra and elsewhere in annual ranges and from other trophic interactions. Many of these relationships are independent of climate change, but some are influenced by it.

Human activities can affect abundance by direct disturbance and by changing the structure of tundra habitats which are inherently simple. During spring nest initiation and early incubation (late May through mid-June), for example, many tundra nesters may abandon nest sites if disturbed, so keeping human activity to a minimum on the tundra is recommended during this period (Reid et al. 2011b).

Populations of peregrine falcon (*Falco peregrinus tundrius*) have increased strongly at least in the ISR since the banning of harmful insecticides such as DDT which had caused their numbers to decline in the 1970s (Holroyd and Kirk 2010; Mossop 2012; GNWT 2013a). These raptors (and also rough-legged hawks) generally nest on cliffs, but their population expansion has been aided by the availability of man-made structures such as military radar towers

at Distant Early Warning (DEW) line stations and marine navigation beacons, especially along the Yukon North Slope (Holroyd and Kirk 2010; Mossop 2012). Because the falcons can kill and displace some other smaller raptors such as the short-eared owl (*Asio flammeus*), the human-made nesting structures may indirectly be changing the composition of the tundra food web in certain localities (Reid et al. 2011b).

Networks of roads, pipelines and towers supporting communications and oil and gas infrastructure are not yet extensive in the ISR and the Kitikmeot region, but experience in the oil fields of the Alaska North Slope indicates that they bring changes to bird abundance (Liebezeit et al. 2009). These changes include reduced reproductive success in passerines and some shorebirds nesting close to the infrastructure because the infrastructure supports higher local densities of predators such as Arctic fox (*Vulpes lagopus*), red fox (*Vulpes vulpes*) and raptors, either by creating new denning and nesting habitats or by extending their effective foraging ranges. Similar effects may occur in the ISR and the Kitikmeot region with development of terrestrial oil and gas extraction infrastructure, and new all season roads to mine sites and communities (e.g. the new Tuktoyaktuk highway). High grade roads on mainland areas will also increase the denning habitat for Arctic ground squirrels (*Spermophilus parryii*) because the roads mimic the sand and gravel ridges they prefer for denning sites (Batzli and Sobaski 1980). The ground squirrels are also nest predators, along with one of their key predators, red fox, so they could have a strong effect on local bird nesting. As part of a larger study in Ivvavik National Park, D.M. Turner (Trent University, pers. comm.) discovered two radio-transmitters recently attached to bird nestlings underground in Arctic ground squirrel dens. Routing communication cables underground rather than with poles, and planning that reduces the actual footprint of the development layout, may mitigate some of the potential impacts of new infrastructure (Wilson et al. 2013).

Lesser snow geese nest in small colonies along the mainland at Kendall Island and Anderson River. This population

appears vulnerable to climate change primarily by indirect effects on breeding habitat and predator availability (Kerbes et al. 1999; Hines 2006). Hunters have noticed that predators such as barren-ground grizzly bears (*Ursus arctos*) expand their range and feed on geese eggs as an alternative food source (Hines 2006). In contrast, the goose population on Banks Island, where grizzly bears are rare, has dramatically increased in size (Kerbes et al. 1999), raising the risk of overgrazing and habitat destruction (Samelius et al. 2008; Hines et al. 2010). The severe and long-term impacts of overgrazing by nesting and migrating snow geese have been well-documented in Canadian sub-Arctic coastal salt marshes at La Perouse Bay, MB. These impacts include carry-over effects on other sympatric (i.e. coinciding) breeding birds and result from goose population growth driven by improving winter habitat conditions outside the Arctic (Gratto-Trevor 1994; Abraham and Jefferies 1997; Rockwell et al. 2003; Sammler et al. 2008). The impact of heavy goose grazing on sympatric bird species at the Banks Island colony was quite variable: fewer shorebirds nested within 10 km of this colony compared to elsewhere, while passerine numbers remained similar (Latour et al. 2010).

Tundra nesting birds may face a growing threat from biting insects if longer growing seasons and warmer temperatures allow higher production and reproductive success in these pests. Black flies have recently induced nest abandonment by snowy owls in Scandinavia, which appears to be a relatively rare and novel event (Solheim et al. 2013). This has not been reported in Arctic Canada, but it needs to be kept in mind, especially for birds whose incubation and nesting periods are long and overlap the period of maximum abundance of adult biting insects.

On Herschel Island, peregrine falcons and rough-legged hawks nest on cliffs of unconsolidated glacial till held together by permafrost. Recently, a high proportion of their nests (up to 50% per year) have collapsed during the nesting season, resulting in complete reproductive failure for those pairs (Gauthier et al. 2011). This increasing rate of nest collapse compared to the 1980s (Talarico and Mossop 1986) probably results from increasing summer

temperatures, possibly amplified by reduced cloud and fog cover, which have been increasing the rate of permafrost thaw and slumping on the island (Lantuit and Pollard 2008). This may be a relatively localized pattern, as these species more often nest on bedrock cliffs, but this phenomenon warrants more study.

3.5.3 Mammals

The mammal portion of the terrestrial tundra food web has two main branches defined by the body size of the herbivores. Small herbivores (notably the brown lemming (*Lemmus sibiricus*), collared lemming (*Dicrostonyx groenlandicus*) and tundra vole (*Microtus economistus*)) are limited most strongly by predation by a large suite of competing mammalian and avian predators that are food-limited. The predators keep the herbivores at densities at which they consume a relatively small proportion of the annual plant growth in most years (Krebs et al. 2003; Legagneux et al. 2012). In the simpler food webs, predators can drive the small herbivores to such low densities in some seasons that many predators drop out of the system, giving the small herbivores time to recover and again reach high population densities. At these densities, herbivores may become limited by a variety of social interactions and food availability for a short period, before the predators' populations respond through increased immigration and reproduction. This pattern describes the three- to five-year cyclic dynamic of lemming and vole populations found in many North American Arctic regions (Krebs 2011). In the western and central Canadian Arctic this pattern has been documented on Banks Island (Maher 1967; Parks Canada Agency 2009), Herschel Island, north Yukon (Krebs et al. 2011), and at sites east of the Mackenzie Delta to Horton River and the Bathurst Inlet - Kent Peninsula region (Krebs et al. 2002). However, in contrast to this pattern, cycles are of very low amplitude or non-existent in some low Arctic mainland regions such as Pearce Point, east of Paulatuk (Krebs et al. 1995) and the Yukon coastal plain (Krebs et al. 2002). In these areas a more diverse food web, in particular the presence of Arctic ground squirrels, supports more generalist



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Top: brown lemming (*Lemmus sibiricus*); Bottom: collared lemming (*Dicrostonyx groenlandicus*)

predators, notably the red fox, that can maintain predation pressure on the small herbivores most years (Reid et al. 1997). In addition, relatively low snow accumulations in these regions may limit the lemmings' winter reproduction which drives a cyclic population increase (Reid and Krebs 1996; Reid et al. 2012b).

On the second branch of the tundra food web, large herbivores, principally caribou and muskoxen, appear to be primarily food-limited, consuming a relatively large proportion of the annual production of their key foods and suffering relatively little predation mortality from a few large carnivores that are themselves apparently food-limited (Krebs et al. 2003; Legagneux et al. 2012). The dynamic of such food-limited herbivore populations is also frequently one of boom and bust but often with a long cycle period

such as the 40-60 year cycles of abundance in barren-ground caribou (Gunn 2003; Miller 2003). Herbivores at high densities can severely deplete the abundance of key food plants such as lichens, and unusual snow conditions (very deep or hard snow) can limit access to existing foods (Miller 2003). The important point overall is that the search for a signal of climate change in the ecology of any tundra mammal needs to account for these inherent geographical and temporal patterns of change which are driven by differing trophic interactions, and it also needs to assess the role of snow in forming habitat structure.

Distribution

Herbivores and insectivores

There have been very few well documented changes in historical distributions of mammals in the western and central Canadian Arctic. The broad patterns of distribution result from species survival through the last Ice Age in either the Beringian or the northwest Canadian glacial refugium, followed by Holocene range expansions from those refugia (Reid et al. 2013). Ocean barriers, including inhospitable ice crossings for small mammals, continue to limit the ranges of mainland species, specifically tundra shrew (*Sorex tundrensis*), barren-ground shrew (*Sorex ugunak*), tundra vole and Arctic ground squirrel. A warming climate will not provide new opportunities for small mammal range expansion across ocean passages such as Dease Strait, because those opportunities have already been present for the past millennia. Distributions of resident Arctic tundra small mammals will remain relatively static in contrast to the more mobile bird and invertebrate groups. Consequently, tundra species with ranges restricted to the mainland will gradually lose portions of their range as the sub-Arctic taiga biome expands onto the southern tundra (Gilg et al. 2012). However, these species should not be deliberately moved north on to the Arctic Archipelago islands because doing so could significantly alter the cyclic dynamics of lemmings on the islands by introducing a different predator community and by changing competitive interactions between small herbivores and between their predators.

Large mammals such as caribou can cross frozen channels, and some do so regularly (e.g. annual migration of the Dolphin and Union herd on and off Victoria Island; Poole et al. 2010; Figure 9). However, less predictable and weaker ice, resulting from changes in timing of freeze-up and loss of multi-year ice, will likely increase the risk of animals drowning (Poole et al. 2010). Marine vessels that break ice through the channels south of Victoria Island would make the situation far worse, perhaps stopping the annual migration by the Dolphin and Union herd.

Recent changes in mammal distribution are of two main categories: (1) shifts in use within a historical range, occasionally following a re-introduction; and (2) expansion of boreal species into the low Arctic in association with the ongoing biome shift from tundra to taiga shrub land. Shifts in use among various portions of a historical range have been noted in the Arctic island ecotype of caribou (*Rangifer tarandus pearyi*) in the Canadian Archipelago, often following a pattern of expansion and contraction correlated with herd size (Miller et al. 1977; Gunn and Dragon 2002). About 6,000 Peary caribou migrated between Prince of Wales and Somerset Islands in the 1970s and early 1980s, but nearly disappeared from these islands between 1985 and 1990 (Gunn et al. 2006). These multi-decadal patterns appear permanent in the relatively short human memory, but may have an underlying long-term dynamic driven by food abundance (Ferguson et al. 1998; Messier et al. 1988).

Since the late 20th Century, some of the Porcupine caribou herd (Figure 9) has stayed on portions of the summer tundra range in north Yukon through the subsequent winter (Kofinas et al. 2002; Reid et al. 2012a). The prominent trends of autumn warming and later onset of snow (Chapter 2) may be encouraging these animals to be more sedentary, saving the energetic costs of a long migration at the risk of suffering from reduced food availability later in winter as lichens on this range are scarce and winter icing events becoming more common (Reid et al. 2012a; Chapter 2, Figure A10).

Highly mobile barren-ground and Arctic island caribou are known to shift their summer and winter ranges fairly

frequently, but changes are also becoming evident in what were considered to be very constant calving grounds. During 42 years of monitoring the Bathurst herd, the average annual overlap in calving grounds was 43%, forming two geographically consistent clusters (1966-1984 and 1996-2011), broken by a brief period at peak caribou densities when the calving ground shifted (Gunn et al. 2012). In early springs plants tend to grow and flower earlier, and calving grounds tend to have high concentrations of plants that provide a burst of nutrient-rich early growth that is crucial to caribou milk production (Griffith et al. 2002). So, there has been concern that migrating caribou may not reach calving grounds in time to give birth and take advantage of the short-lived pulse of nutrients for peak lactation (Post and Forchhammer 2008). Summer season onset date is projected to advance by six to twelve days by 2050 (driven by earlier springs and earlier snowmelts, Chapter 2) at calving grounds of many barren-ground herds (Porcupine, Cape Bathurst, Bluenose West, Bluenose East, Ahiak/Beverly) (Figure 9) in the western and central Canadian Arctic. This raises key research questions around whether caribou can advance their migration movements and timing of birth, whether food abundance and quality is as high on new calving grounds as old ones, and how the changes are affecting growth and survival of calves. If the timing mismatch is real for these herds, their rates of growth and recovery from low densities will be reduced.

The muskoxen, reintroduced to the Arctic National Wildlife Range in northeast Alaska in 1969, have spread well into north Yukon and the Richardson Mountains along the Yukon-Northwest Territories border in the last 40 years (Reynolds 1998; Reid et al. 2012a). These are the exploratory movements of an expanding population and have not, in their broad pattern, been driven by climate change, although particular areas may have become inhospitable in some winters because of ice crusts on snow (Reid et al. 2012a).

The gradual conversion of low Arctic tundra to erect shrub communities more typically found in the northern taiga forests is well underway, although the coniferous tree-line is not advancing as fast as the deciduous shrubs, notably willows (Callaghan et al. 2002) (see section 3.3). Willows provide excellent food for a number of boreal herbivores which may be expanding northwards in the ISR and the Kitikmeot region. Moose range extends north of the tree line in the mainland Northwest Territories (Cape Bathurst region) and Nunavut (Thelon Game Sanctuary to Bathurst Inlet) (GNWT 2013b). Moose have used some of the willow-rich valley habitats on the Yukon North Slope at least since the 1970s (Ruttan 1974) and are probably finding increased habitat opportunities at least in some seasons with the proliferation of shrub willows on more upland sites. In western Alaska, Yup'ik hunters and trappers report expansion of moose and



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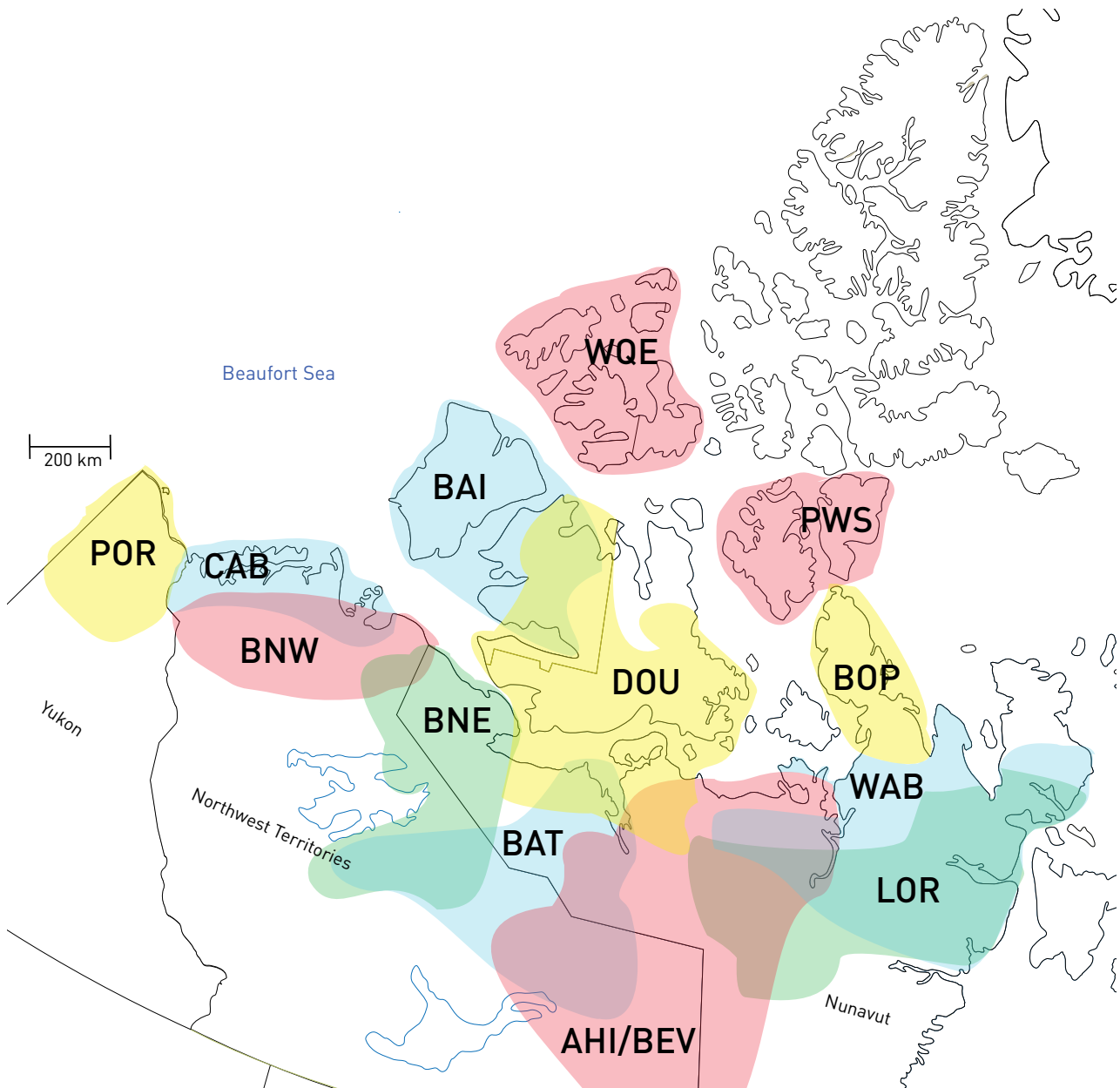


FIGURE 9. Caribou herd ranges in the ISR and the Kitikmeot Region of Nunavut. Adapted from the CircumArctic Rangifer Monitoring & Assessment Network (www.carmanetwork.com) accessed 20 January, 2015 and pers. comm. with D. Russell (CARMA Network). POR-Porcupine; CAB-Cape Bathurst; BNW-Bluenose West; BNE-Bluenose East; BAT-Bathurst; AHI/BEV-Ahiak/Beverly; WAG-Wager Bay; LOR-Lorillard; BAI-Banks Island; WQE-Western Queen Elizabeth Islands; DOU-Dolphin-Union; PWS-Prince of Wales-Somerset; BOP-Boothia Peninsula.

beaver (*Castor canadensis*) distribution to the West in the shrub-rich habitats of the Yukon River Delta in the past decade (Herman-Mercer et al. 2011). Northern red-backed voles (*Myodes rutilus*) are occasionally found on the tundra of the Yukon North Slope, where there is also evidence of singing voles (*Microtus miurus*) (Reid et al. 2011a). The former may profit from the expansion of the erect willow shrub communities, and the latter from drying of upland tundra and proliferation of grasses, such as has been documented by Kennedy et al. (2001). The actual process of range expansion by these various boreal herbivores, including snowshoe hare (*Lepus americanus*), remains poorly documented in the western and central Canadian Arctic.

Carnivores

The red fox has expanded its distribution from the boreal forests into a number of Arctic tundra regions (e.g. northern Norway, Alaska and Russia), where it outcompetes Arctic fox (Tannerfeldt et al. 2002). This range expansion has often been attributed to a warming climate under the assumption that winter temperatures limit the northern distribution of red fox (e.g. Post et al. 2009). Various lines of evidence, some from the western and central Canadian Arctic, indicate that climate warming is not driving this process. First, the range expansion of red fox onto the Arctic tundra was first reported in the 1930s (Marsh 1938) and clearly documented in the 1960s (Macpherson 1964), well prior to the current warming trend and correlated with the movement of humans off the land and into permanent settlements. Second, the red fox expansion in northern Norway seems to be driven primarily by an increase in scavenging opportunities with more semi-domesticated reindeer dying on the tundra in winter (Killengreen et al. 2011). Third, both fox species have co-existed on the Yukon coastal tundra since the 1970s and perhaps well prior to last century (Gallant et al. 2012). During the period of warming winters in north Yukon since the 1970s, repeated fox den surveys indicate that both species have remained at approximately stable densities, often switching dens back and forth across years, with neither species gaining a competitive advantage at the expense of the other (Gallant et al. 2012). However,

the warming climate is not necessarily responsible for the red fox expansion. A more compelling argument is that its expansion results from this opportunistic mammal finding new food resources left by humans (e.g. hunter-killed carcasses, garbage, dead domesticated animals) which allow it to overcome the strong food limitation it would normally experience on the tundra in winter (Killengreen et al. 2011).

Regarding other mammalian carnivores, there is little documentation of significant changes in distribution in the western and central Canadian Arctic. One exception may be the grizzly bear. Climate trends, notably an increasing growing season length (Chapter 2) resulting in higher plant production and warmer winter temperatures reducing the energy costs during winter torpor (i.e. hibernation), may be advantageous to this species. Grizzly bears occupy most of mainland Arctic Yukon, Northwest Territories and Nunavut (Ross 2002), but traditional ecological knowledge suggests that its range in Nunavut has expanded eastwards (McLoughlin and Messier 2001). Hunters and residents of Gjoa Haven, NU confirm the northern range expansion of bears onto King William Island (Keith and Arqviq 2006). There have been sightings of the species on Banks and Melville Islands and associated coastal areas over a period of many decades (Doupé et al. 2007; Struzik 2012), and increasing reports of hybridization with polar bears (*Ursus maritimus*) (Struzik 2012). Some of these events precede the current period of warming, and their relationship to a changing climate is unclear. They may just be exploratory movements of a few dispersing individuals more often documented with increasing human presence on the land. Or they may represent a more frequent overflow of dispersers from an expanding mainland population, and ultimately a secure range expansion (Doupé et al. 2007).

Abundance

Herbivores

Arctic herbivore populations have shown dramatic population fluctuations since well before the current period of climate warming, and these fluctuations have often

appeared cyclic with a period of three to five years in small rodents (principally lemmings) and 40-60 years in caribou (Stenseth and Ims 1993; Ferguson et al. 1998; Gunn 2003; Miller 2003). Consequently we cannot necessarily blame a warming climate for declining populations which may be responding primarily to other long-term ecological dynamics. We have to ask, based on our understanding of the factors driving the cyclic dynamics, how a warming climate might influence the dynamics.

Considering small rodents around the Arctic, some fairly dramatic changes have occurred, especially during the period of recent Arctic climate warming since the early 1970s (Reid et al. 2013). Field monitoring, coupled with modelling, indicate that aspects of winter snow quality and quantity strongly influence the lemming dynamics and are likely causing some of the changes (Gilg et al. 2009; Bilodeau et al. 2013). A cyclic population increase of lemmings depends, at least in part, on winter and spring reproduction under the snow (Stenseth and Ims 1993), so winter food availability and thermal conditions are crucial. In regions with relatively low total snow fall but consistently cold temperatures (e.g. semi-desert of much of western Arctic North America and Siberia), lemmings and voles select habitats with deeper snow (ideally >60 cm deep), and their winter populations are more likely to grow when snow comes early and deep in the autumn (Reid and Krebs 1996; Duchesne et al. 2011; Reid et al. 2012b). With a warming climate, the first snow is tending to accumulate later in the fall and melt earlier in spring (Dye 2002; Brown and Robinson 2011), and winter rain and thaw events are becoming more frequent with a consequent reduction in the insulative capacity of the snow.

The western and central Canadian Arctic receives little snowfall overall. Data from 1979-1997 indicate average maximum snow depth of <30 cm over the Archipelago islands and 30-50 cm on the mainland, with only the Mackenzie Delta reaching >50 cm in maximum snow depth, and these maximum depths are only reached late in winter (Atlas of Canada 2013). The entire region is projected by 2050 to experience later onset of winter snow

by up to 24 days, and earlier melt by 1-13 days (Chapter 2). The climate projections also indicate that the northern, Archipelago portion of the region, along with the Yukon north coast, will experience up to an additional thaw event per winter (Chapter 2). These patterns suggest a reduced capacity for winter population growth in the future leading to reduced amplitude of cycles (reduced densities during peak populations) and perhaps a longer period between years with relatively high densities (Bilodeau et al. 2013).

Such outcomes may be partly offset by the projected increases in solid precipitation (October to May: 14-30%) that the entire region is expected to experience by 2050 (Chapter 2). Currently, because of the overall scarcity of snow fall in this region, good quality lemming winter habitat is limited to topographic features where wind-blown snow accumulates in drifts (Reid et al. 2012b). Taller willow growth in some areas will provide additional snow-trapping structures which could increase the area of reasonable winter habitat. However, it seems unlikely that the amount of good quality winter habitat (i.e. snow depths reaching 60 cm early in winter (Duchesne et al. 2011)), is going to increase substantially overall because the topography will not change and projected increases in vegetation height will have limited impact on snow depths regionally.

There is only one long-term data set on lemming abundance in the western and central Canadian Arctic maintained by Parks Canada on northern Banks Island. Lemming outbreaks occurred every three to four years on south and central Banks Island in the 1960s and 1990s (Maher 1967; Larter 1998). Parks Canada data suggest that the cycle period has increased to five years since the late 1990s, with less variability between years overall (Parks Canada 2009, unpublished data; Reid et al. 2013). Lemming monitoring at various sites (Pearce Point, Kugluktuk, Walker Bay, Hope Bay, southern Victoria Island) until 2000 showed that 3-5 year cycles were common but not ubiquitous (Krebs et al. 1995, 2002; Eamer et al. in prep). This monitoring has been discontinued. Renewed monitoring, coupled with research focussed on winter reproduction, is required to demonstrate

pattern and understand the role of snow quantity and quality in this dynamic.

The Arctic ground squirrel is widespread through the mainland portions of the western and central Canadian Arctic, but patchily distributed where particular substrates (notably eskers, gravel banks and sand deposits) provide good denning conditions. Its presence in the food web can have dramatic influences on the makeup of the predator community and the dynamics of alternative prey (Reid et al. 1997). This is the only true hibernator in this region and experiences winter temperatures in its hibernation burrows far below those experienced by most temperate hibernators. It has evolved a particular mechanism of hormone-driven muscle accumulation in summer to fuel winter energy needs (Boonstra et al. 2011). Trends towards a later onset of insulative winter snow cover will increase the intensity of cold stress experienced by hibernating squirrels. Strong winter thaw events may occasionally flood hibernation sites and subsequently freeze, perhaps resulting in local mortality. These issues have not been studied on the Arctic tundra.

In the ISR and the Kitikmeot region, barren-ground caribou herds have shown long-term fluctuations. Many of the herd sizes were low from the 1950s to the 1970s, growing to peak sizes in the mid-1980s to late 1990s. Some herds (Cape Bathurst, Bluenose West, Bathurst) (Figure 9) have since declined often to historical minimums, though they now appear to be stable or increasing at low densities (Gunn et al. in prep; Russell and Gunn 2012). The Porcupine herd experienced a moderate decline in the 1990s but has since increased to high density, and the Bluenose East herd is also increasing (Russell and Gunn 2012; Reid et al. 2013). Although there has been concern that a changing climate, with extreme weather events such as deeper or harder snow cover, driving the synchronous declines in so many herds (Vors and Boyce 2009), recent reversals in some of the declines, and the inability to relate all declines to weather patterns suggest that fluctuations may be part of longer term cycles and their underlying causes (Russell and Gunn 2012). However, the influence



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of a changing climate cannot be ignored because its signal will be much reduced at current low densities below carrying capacity. These herds spend much of the year outside the western and central Canadian Arctic in boreal forest winter ranges. Climate change may have considerable influence on herd dynamics by influencing the availability of winter foods through two main mechanisms: (1) more frequent and intense forest fires reducing the total extent of mature forest winter range with lichen food base (Zinck et al. 2012); and (2) deeper and harder snow reducing the ability to find food. The effects may not be strongly noticed at the current low densities but would reduce the carrying capacity of the winter range and result in density-dependent food limitation coming into effect at lower population densities compared to the situation without these climate change effects. As a result we might expect lower amplitude population fluctuation through the next cycle. Meanwhile, the potential timing mismatch on the calving grounds between peak food availability and caribou calving (Post and Forchhammer 2008) would reduce the rate of population recovery, probably prolonging the cycle period. This is because the demographic parameters most strongly correlated with abundance trends, and likely driving those trends, are adult female and calf survival (Boulanger et al. 2011).

Across the Canadian Arctic islands, including those in the western and central Canadian Arctic, Peary caribou have declined dramatically in the last 50 years, with winter starvation being a primary cause (Miller and Gunn 2003). These starvation-induced die-offs are strongly correlated with severe winters, in particular icing of the ground or

the snowpack following winter rain or melting (Miller and Barry 2009). However, the adverse effects of reduced access to food in winter are more pronounced when caribou are at relatively high densities; herds at low densities may be able to cope with difficult winters when per capita food abundance is still high (Ferguson 1996; Tyler 2010). The future for these herds may continue to be tenuous given projected increases in the frequency of winter thawing events across the Arctic islands (Chapter 2). However, some of these winter risks may be partially offset by projected increases in food growth with warmer summers and hence higher food abundance in winter (Tews et al. 2007).

Insect harassment can have dramatic effects on caribou calf weight gain and survival (Helle and Tarvainen 1984; Weladji et al. 2003). Longer growing seasons and warmer spring and summer temperatures are likely to increase the breeding production of many biting insects leading to increased levels of harassment by warble (*Hypoderma tarandi*) and nose-bot (*Cephenemyia trompe*) flies, leaving caribou with less time to feed. If warmer conditions reduce the number of water bodies for mosquito larvae, harassment from mosquitoes might decline in some regions (Vors and Boyce 2009).

Muskox populations in the ISR and the Kitikmeot region generally increased in abundance in the 20th Century, especially on the southern tier of islands, such as Banks and Victoria (Fournier and Gunn 1998; Gunn and Forchhammer 2008). However, some of these populations have suffered substantial recent die-offs during hard winters probably because they had reached such high densities that the effects of winter thaws and icing events severely reduced per capita food availability (Gunn and Adamczewski 2003; Gunn and Forchhammer 2008; Nagy and Gunn 2009). As with Peary caribou, muskoxen will experience conflicting trends in the effects of a warming climate on food availability and insect harassment, with increasing length of the growing season and increasing duration of the snow-free period enhancing food availability, while increases in total solid precipitation and frequency of winter thaw events may reduce food availability in some winters. At present no clear net effect is obvious.

Carnivores

If lemming populations become less variable over time, predators such as snowy owl, ermine (*Mustela erminea*), least weasel (*Mustela nivalis*) and Arctic fox will likely experience reduced population fluctuations and probably reduced reproductive success, perhaps leading to lower breeding densities and more widespread absences from some tundra regions. Whether or not there is a conservation concern depends on the survival rates of these specialist predators and the number of consecutive years in which lemming densities in spring are insufficient to support breeding. The short-lived and less mobile weasels are probably at greatest risk.

Lemmings are the preferred prey of many predators and so predation pressure on other species is reduced when lemming densities are high (Summers et al. 1998). If lemming populations in the western and central Canadian Arctic become less variable and generally lower over time, there may be negative effects on alternative prey species, notably shorebirds and geese. It has long been known that nesting success for these birds is strongly influenced by predation. For example, there is recent evidence indicating that lower amplitude lemming cycles in Siberia may result in more persistent inter-annual predation on geese by Arctic foxes with a consequent decline in the goose population (Nolet et al. 2013).

Generally, the historical abundance of large and medium-sized mammalian tundra carnivores has been primarily influenced by factors other than climate change, especially direct human harvest and industrial development (Reid et al. 2013). Commercial fur trapping has been at relatively low levels in the past few decades, but wolverines (*Gulo gulo*) are still quite heavily targeted and are susceptible to harvest pressure and to the attraction of food supplementation at human settlements (COSEWIC 2003). Disturbance from diamond mining and road construction near wolf dens has a negative effect on their reproductive success directly or, indirectly, by altering the distribution or timing of movements of caribou, their main prey (Walton et al. 2001). In

wilderness settings without strong human influence, these carnivores are often food limited, and large scale changes in abundance of their prey are likely to show up in the predator dynamics, often reflecting the cyclic dynamics of the prey. This is especially true of the smaller carnivores such as foxes, ermine and least weasel, but also on a much longer time scale with wolves and wolverine. Particular winter die-offs of ungulates, such as caribou and muskoxen, will produce short-lived food bonanzas for all these predators because they can readily survive as scavengers.

A warming climate is likely to have differing impacts on each of the carnivore species. Many Arctic foxes turn to scavenging from polar bear kills on sea ice to survive the winter (Roth 2002). Delayed onset of ocean freeze-up significantly increases the period of time during which foxes have to rely on terrestrial foods which are particularly scarce in autumn when birds have migrated south and small rodents may be at their lowest numbers annually. Ocean freeze-up is now four to five weeks later on Herschel Island than it was a century ago (Burn 2012). Well frozen sea-ice crossings are necessary for re-colonization of some islands by carnivores such as wolves (Carmichael et al. 2008), although the risk of the complete loss of these winter crossings in the western and central Canadian Arctic is very low.

It has been suggested that reduced snow cover will be detrimental to wolverines which rely on deep snow drifts for digging dens, especially natal dens (Brodie and Post 2010). This risk is very low to non-existent in the ISR and the Kitikmeot region because the annual period of maximum snow depth (March through May) will continue to overlap well with the wolverine natal denning period (March through May) (Copeland and Whitman 2003). Also, the entire region is projected to experience increases in solid precipitation (October through May) between 14 and 30%, with the largest increases being on mainland regions where wolverines predominantly live (Copeland and Whitman 2003; Chapter 2).

The ongoing biome shift on portions of the low Arctic where tundra is turning to erect shrub land may indirectly affect carnivore abundance by way of changes in distribution and abundance of their prey. Expanding shrub lands will likely allow at least seasonal expansions in moose distribution, and possibly year-round new snowshoe hare and beaver populations. These prey species could provide opportunities for incursions of lynx (*Lynx canadensis*) and more robust populations of wolves. Such possible effects have yet to be documented in the western and central Canadian Arctic.

3.6 Contaminants

Contaminants (specifically, in this case, metals and persistent organic pollutants (POPs)) in the Arctic environment and wildlife are an on-going issue of concern to communities which derive considerable nutritional, social and cultural benefits from the consumption of traditional wild foods. A significant amount of knowledge about contaminants in Arctic ecosystems has been gathered by ArcticNet researchers as well as by scientists working for the Northern Contaminants Program (Canada) and the multinational Arctic Monitoring and Assessment Program (AMAP). Several review articles and formal science assessments have been published on various groups of Arctic contaminants since 2002 (including metals: AMAP 2005, 2011; Evans et al. 2005; Gamberg et al. 2005; Lockhart et al. 2005; Poissant et al. 2008; Riget et al. 2011; and various groups of POPs: AMAP 2004, 2009; Evans et al. 2005; Gamberg et al. 2005; Butt et al. 2010; de Wit et al. 2010; Hoferkamp et al. 2010; Riget et al. 2010; Weber et al. 2010). The findings from these sources plus more recently published reports are summarized below for the western and central Canadian Arctic. Where no information was available from within the ISR or the Kitikmeot region, general inferences are drawn from studies in adjacent areas of the Canadian Arctic. Table 1 summarizes the major industrial uses and general biological effects of the contaminants discussed here.

3.6.1 Freshwater and sediments

No studies of legacy (i.e. banned or mainly used historically) or current-use (i.e. still in use) persistent organic pollutants (POPs, such as PCBs, DDT, chlordane, etc.) in lake and river sediments and waters in the western and central Canadian Arctic have been reported. Data on these compounds are generally sparse across the Canadian Arctic (see also Butt et al. 2010; de Wit et al. 2010; Hoferkamp et al. 2010; Weber et al. 2010). Findings from adjacent regions such as Alaska and the Canadian Arctic Archipelago indicate that even though there are no major urban/industrial sources of these compounds in the North American Arctic, these chemicals are today ubiquitous here owing to their

long-range transport via oceanic and atmospheric pathways from polluted southern regions.

Mercury (Hg), particularly the methylated form (methyl-Hg) which is the toxic form of Hg, is of considerable importance and has been studied in freshwater (FW) sediments and waters at a number of sites in the western and central Canadian Arctic. Mercury in the Mackenzie River has received particular attention. About 78% of the total Hg flux in the Mackenzie River where it enters the Delta (ranging from 1.2-4.3 t yr⁻¹ in different years) originates from weathering of sulphide minerals in the mountainous western sub-catchment, a further 10% from erosion of in-stream coal deposits, 6% from atmospheric deposition

TABLE 1. Summary of uses, and ecological and biological effects of the contaminants discussed in this report. Information from: AMAP (2004, 2005, 2009) and AMAP/UNEP (2013)

CONTAMINANT	MAJOR ANTHROPOGENIC SOURCE TO AIR	BIOMAGNIFYING SUBSTANCE*?	BIOLOGICAL EFFECTS
Metals			
Mercury (Hg)	Small-scale gold mining, coal combustion, cement production	Yes	Neurotoxic, organ damage
Lead (Pb)	Gasoline combustion, metal smelting	No	Neurotoxic
Cadmium (Cd)	Metal smelting	No	Organ damage
Persistent Organic Pollutants (POPs)			
DDT	Insecticide application	Yes	Suppresses reproductive, immune systems
PCBs	Industrial application	Yes	Neurotoxic; suppresses immune, reproductive systems
HCH	Insecticide application	Yes	Reproductive effects; suppresses immune system
Endosulfan	Insecticide application	Yes	Suppresses immune, reproductive systems
PBDEs	Leaching/break-down of products made with PBDEs (e.g. flame retardants)	Yes	Neurotoxic; impacts reproductive hormones; suppresses immune system
Perfluorinated compounds	Leaching/break-down of products made with perfluorinated compounds (e.g. surfactants and suppressants)	Yes	Suppresses reproduction

Note: *Biomagnifying substances increase in concentration in biological tissues with increasing trophic level of the species concerned.

throughout the catchment, and 5% from the eastern peatland/lake region bound mainly to algal-derived organic matter (Leitch et al. 2007; Carrie et al. 2010). Leitch et al. (2007) measured an average riverine flux of 2.2 ± 0.9 t yr⁻¹ total Hg over 3 years, and 15 kg yr⁻¹ of methyl-Hg (range 7–22 kg yr⁻¹ over two years), suggesting that the river is a major source of methyl-Hg to the Mackenzie Delta and immediately adjacent areas of the Beaufort Sea. Similar values were reported by Emmerton et al. (2013) in a later study. The Delta, however, was a sink for a substantial fraction of the total Hg flux, probably because of sedimentation at the freshwater-saltwater transition zone (Emmerton et al. 2013). Highest Hg concentrations in Mackenzie riverwater, and most of the total Hg flux, occurred during spring freshet (i.e. flood) (Figure 10; see also Emmerton et al. 2013). Similar seasonal findings were reported from the Yukon River although, because of its much higher sediment load, the total Hg flux from this river was 3 to 32 times higher on a unit catchment area basis than from six other Arctic rivers including the Mackenzie (Schuster et al. 2011). Lakes periodically connected to the Mackenzie River are particularly high in methyl-Hg compared to riverwater (Graydon et al. 2009). Methyl-Hg peaks in mid-summer in these lakes probably due to maximal microbial activity in sediments and wetlands coupled with relatively high amounts of labile (i.e. easily degraded) organic matter from algal productivity.

The role of anthropogenic Hg pollution deposited from the atmosphere, versus the role of climate change, in determining Hg fluxes into northern lake sediments has been a much-debated issue of relevance to the Canadian Arctic. Muir et al. (2009) showed that significant increases in Hg fluxes have occurred since the 19th Century in several dozen lakes across northern Canada, including several within the ISR and the Kitikmeot region. Lakes here exhibited similar Hg flux increases to others in the eastern Arctic at the same latitudinal range. The recent increases have been ascribed solely to long-range Hg pollution (Muir et al. 2009), and the calculated anthropogenic Hg fluxes averaged 2.8 ± 2.0 µg/m²/yr across the Arctic (i.e. North of 65°N). However, it has been proposed that climate warming is also increasing Hg fluxes to lake sediments in addition to anthropogenic inputs

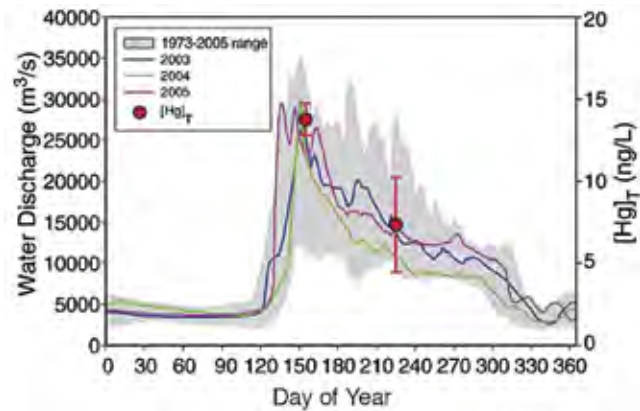


FIGURE 10. Water discharge of the Mackenzie River at the Arctic Red River in 2003–2005 relative to the range between 1972 and 2005 (the grey area). The red circles and error bars show the mean total Hg concentration and standard deviation during the spring freshet and later in the summer of 2003. From Leitch et al. (2007).

from air. Several ways in which this can occur include Hg exports from recently thawing permafrost and peatlands entering adjacent waterbodies (Schuster et al. 2011), and elevated algal productivity in recent decades scavenging more dissolved Hg from waters (Outridge et al. 2007; Carrie et al. 2010). Permafrost peat sampled near Inuvik, NT was found to contain Hg concentrations ($0.025 - 0.10$ µg g⁻¹ dry weight) similar to typical northern lake sediments (see Muir et al. 2009), and thus thawing and erosion of the peat profile could add substantively to Hg inputs to nearby lakes (Outridge and Sanei 2010). Evidence supporting the algal scavenging hypothesis was reported from the pre-industrial period in two thermokarst lakes in the Mackenzie Delta (Sanei et al. 2012), as well as in a tributary lake of the Mackenzie River (Carrie et al. 2010).

Anthropogenic lead (Pb) was found to be negligible in the sediments of Ya-Ya Lake in the Mackenzie Delta, similarly to other High Arctic lakes, despite its demonstrated presence in the atmosphere (Outridge et al. 2002). Low air-to-surface fluxes of Pb, caused by low precipitation rates at these high latitudes, was suggested as the explanation for this surprising finding.

3.6.2 Freshwater biota

Mercury concentrations and short-term trends in FW fish of various species were summarized by Lockhart et al. (2005) for over 200 lakes across northern Canada including more than a dozen within the western and central Canadian Arctic. Walleye, northern pike and lake trout generally had the highest Hg levels in fish flesh (mean muscle concentrations of 0.47 ± 0.35 , 0.38 ± 0.30 and $0.38 \pm 0.35 \mu\text{g g}^{-1}$ fresh weight, respectively) which often exceeded the subsistence guideline value of $0.2 \mu\text{g g}^{-1}$; burbot had lower levels and whitefish the lowest on average. Mercury levels in Arctic char sampled from the ISR and the Kitikmeot region, for which there were few available time series, fell within the range of 0.02 – $0.12 \mu\text{g g}^{-1}$ fresh weight with the exception of samples analyzed from Ellice River in 1977 ($0.42 \mu\text{g g}^{-1}$). A total of 167 fish Hg time-series from 45 lakes were analysed statistically, spanning varying periods between the early 1970s and 2001. No significant trends over time were reported in most cases, and the proportion of significantly increasing trends (20% of total) overall was only slightly higher than the decreasing trends (13% of total). A recent update (Riget et al. 2011), completed as part of the AMAP (2011) Arctic Mercury Science Assessment, reported no FW biological time-series of “adequate” length and statistical power from within the western and central Canadian Arctic. From sites just outside this region, they reported a mixture of findings, with no significant Hg fluctuations in several lake trout populations (e.g. in Great Slave Lake, NT and two Yukon Lakes) but significantly increasing patterns in burbot at several sites (Great Slave Lake West Basin, and Fort Good Hope, NT; see also Carrie et al. 2010)) and in land-locked Arctic char in lakes on islands within the Canadian Arctic Archipelago.

The explanation for the increasing Hg trends in some species, but not in others living in the same or nearby lakes, is still under debate, but possible reasons include varying natural factors over time such as feeding behaviour, effects of climate warming on Hg chemistry and bio-uptake rates, and greater availability or exposure to airborne Hg pollution by some species. Carrie et al. (2010) reported similarities

between Hg trends in Mackenzie River burbot at Fort Good Hope (see Figure 11), and simultaneous increases in Hg and algal-derived organic matter in lake sediments nearby. Furthermore, these changes may alter the chemical form of Hg in freshwaters, leading to a higher proportion of the more toxic and bioavailable methyl-Hg (see also Graydon et al. 2009). Carrie et al. (2010) also pointed out that Hg increases in the burbot were occurring despite stable or declining atmospheric Hg levels and deposition across the Arctic.

Much of the geographical variation in Hg levels of freshwater fish across the region may be explained by geological or ecological factors. Lockhart et al. (2005) compared Hg levels in FW fish across northern Canada, including lakes within the western and central Arctic, to underlying geology. A general correspondence was found with high average fish Hg levels generally occurring in areas containing high-Hg rocks (e.g. metamorphic, intrusive or volcanic types). Muir et al. (2005) analysed Hg in land-locked Arctic char from a number of lakes across the Canadian Arctic, including Boomerang Lake on Somerset Island, NU (north of the Kitikmeot region), and found that differences in char feeding behaviour explained differences between the average Hg levels in fish from each lake. From 2006–2008, fish migration and ecology, food web structure, and fish Hg concentrations were investigated in six lakes in the West Kitikmeot region of Nunavut (Swanson and Kidd 2010). All of the lakes contained lake trout, but only three contained partially anadromous populations of Arctic char. Both species are important components of domestic fisheries in this area; Arctic char from the many river systems in the area also underpin a significant fishery focused at Cambridge Bay. Fish Hg concentrations in the study lakes depended on species, life history type (i.e. anadromous vs resident), and whether anadromous Arctic char were present or not. Arctic char had significantly lower Hg levels than either form of lake trout, whereas anadromous trout had significantly lower Hg than resident trout. A surprising finding was that the presence of anadromous Arctic char resulted in resident lake trout with significantly lower Hg concentrations. These differences in Hg were best explained by the age-at-size relationships of the different forms and species,

body condition and carbon:nitrogen ratios, and the process of Hg biomagnifications (i.e. increase in biological contaminant concentration at each step or trophic level in the food chain). Overall, these results illustrate the ecological importance of anadromous Arctic char in Arctic freshwater lakes and highlight the importance of understanding fish ecology, biodiversity and life history when assessing the effects of anthropogenic contaminants on fish populations and fish-derived Hg intake in humans (see also Reist et al. 2013).

No reports on legacy or current-use POPs were found for FW fish in the western and central Canadian Arctic (Hoferkamp et al. 2010; Riget et al. 2010). In adjacent regions, POPs monitoring studies were focused on Arctic char (Cornwallis Island), burbot (Great Slave Lake, Yukon lakes, Slave River at Fort Smith, Mackenzie River at Fort Good Hope) and lake trout (Yukon lakes, Great Slave Lake). There was strong evidence of declining POPs concentrations, particularly of total HCH and total chlordane, in char populations across the region which likely reflected declining atmospheric inputs (Evans et al. 2005). In contrast, endosulfan concentrations increased in char, as in the atmosphere. There also was evidence of declining POP concentrations in burbot in the Slave and Mackenzie Rivers but not in Great Slave Lake and in Yukon lakes. POPs concentrations decreased in lake trout in Yukon lakes in the 2000s, most probably because of changes in the fish themselves (i.e. reduced lipid content, body condition) and possibly climatic variability. Similarly, POPs declined in Great Slave lake trout. New research on polybrominated and perfluorinated compounds determined that these contaminants are widespread in FW fish and concentrations may be increasing. A recent update (Riget et al. 2010) conducted as part of the AMAP (2010) Arctic POPs Assessment confirmed the general declining trends reported above, as well as the continuing absence of data from the ISR and the Kitikmeot region.

An exception to the declining patterns of POPs occurred in burbot monitored at Fort Good Hope, NT. Like Hg, PCBs in burbot muscle show a sharply increasing recent trend in contrast to declining airborne PCB levels (Figure 11).

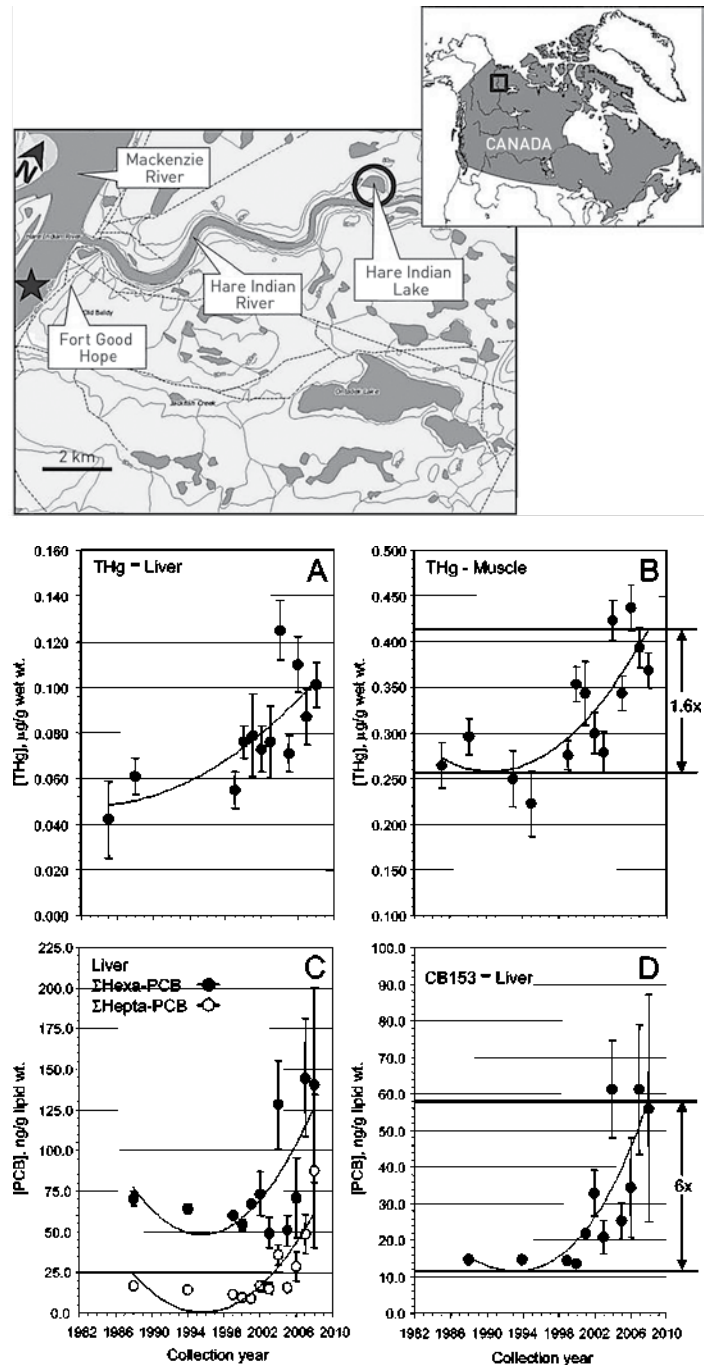


FIGURE 11. TOP: Map of Fort Good Hope, NT where burbot were collected (location marked with a star). **BOTTOM:** Trends of total mercury in liver and muscle and PCBs in liver of burbot in the Mackenzie River at Fort Good Hope, NT from the early 1980s to 2008. The increasing trends stand in contrast to the atmospheric trends of these contaminants during the same period. From Carrie et al. (2010).

Carrie et al. (2010) proposed that climate warming may have altered the environmental dynamics of PCBs in ways that are not yet understood, but which could include: higher amounts of algal organic matter increasing the retention time of the chemicals within lakes and rivers, thereby making them more available to local aquatic life; and the release of historically-deposited PCBs that were previously trapped in surface permafrost layers.

3.6.3 Terrestrial soils and biota

There are no data published for contaminants in soils and terrestrial biota in most areas of the western and central Canadian Arctic. However, heavily contaminated localized sites were reported within the region and across the circum-Arctic around current and former military bases, especially those associated with the DEW radar network (Dietz et al. 1998; Gamberg et al. 2005). DEW line sites have been shown to be significant sources of lead, PCBs and hydrocarbons from oil and fuel to surrounding ecosystems (Gamberg et al. 2005). As of March 2014 the Department of National Defense completed the cleanup of 21 DEW line sites in the Canadian Arctic, including the Stokes Point site in Ivvavik National Park and remaining 13 sites in the western and central Canadian Arctic, removing contaminated equipment and soils (<http://www.cbc.ca/news/canada/north/dnd-announces-dew-line-clean-up-completed-1.2564735>). A monitoring program for these sites has been established by the Canadian government for the next 25 years.

Some former military sites also received significant DDT applications. The bioavailability of this DDT to the local terrestrial environment was examined in a study at an abandoned Long Range Aid to Navigation station at Kittigazuit, NT (Nirwal 2001, as cited in Gamberg et al. 2005). The study site received applications of DDT between 1948 and 1950. Despite the passage of time, soil DDT concentrations in the 1990s remained high, and the composition of DDT still resembled the original pesticide formulation meaning that little degradation of the DDT had occurred over the last six decades. Samples of soil, sediment, willow,

grass (*Elymus* sp.), and Arctic ground squirrel collected at the station had higher concentrations of DDT than those collected from a nearby reindeer herding camp and background sites. Liver concentrations of total DDT in the squirrels declined to background levels with increasing distance from the contaminated area. Although a significant relationship between liver size and DDT concentration was found, the levels were below the no-observed effect threshold. The contribution of long-range atmospheric transport of DDT at Kittigazuit was believed to be negligible because an abrupt transition existed between soil contaminant levels on-site and immediately off-site, suggesting that the concentrations of DDT in the squirrels were mainly the result of the local, historical DDT applications.

In areas away from local sources, relatively low contaminant levels were reported in terrestrial ecosystems. Cadmium (Cd) levels in beaver and muskrat (*Ondatra zibethicus*) livers and kidneys in the Mackenzie Delta and Slave River Delta areas were low and considered to be normal for herbivorous small mammals (Gamberg et al. 2005). There were no significant patterns in trends of Hg (from 1994 to 2007) and Cd (from 1994 to 2003) in caribou kidneys from the Porcupine herd, Yukon (Riget et al. 2011, and Gamberg et al. 2005, respectively). Measured chlordane, PCB and DDT concentrations in Mackenzie and Slave River Delta beaver livers and muscle were below guideline levels, and other legacy POPs could not be detected. As expected, higher POPs concentrations, including various fluorinated compounds, were found in the liver and/or muscle tissue of terrestrial carnivores such as mink (*Mustela vison*) in the Yukon, Arctic fox at Ulukhaktok, NT and wolverine at Kugluktuk, NU (Hoekstra et al. 2003a, b; Gamberg et al. 2005 and references therein). Scavenging of marine mammal carcasses, rather than terrestrial mammal prey, was thought to be the main source of POPs in wolverine (Hoekstra et al. 2003b). In general, though, levels of these contaminants were below those associated with reproductive impairment in mammals.

3.7 Summary and recommendations

This synthesis and assessment show that climate warming over recent decades has already had demonstrated impacts on diverse geophysical and biological elements of terrestrial and freshwater ecosystems in the western and central Canadian Arctic. Many of these impacts are likely to continue or become more severe with the projected future warming trends.

Permafrost temperatures have increased significantly in this region over the last ~40 years, leading to significant increases in thermokarst activity and profound changes to some ice-rich landscapes. Thermokarst activity in this region includes thaw slump activity, degradation of ice wedges, lake expansion and lake drainage. It can be anticipated that rates of lakeshore expansion will increase with predicted future warming trends; rates of coastal erosion will also increase, exacerbated by sea-level rise, reduced sea-ice cover and more severe storms. Warmer soil temperatures, an increase in active layer thaw, and intensification of precipitation can interact to destabilize permafrost slopes. Physical disturbance to permafrost terrain can affect soil and surface runoff chemistry and increase erosion rates to adjacent water bodies, impacting terrestrial and aquatic ecosystems. Ice-rich glaciogenic landscapes, which are widespread throughout the study area, are anticipated to be the most sensitive to climate warming. In these settings, individual thaw slumps may exceed 40 ha and deliver massive amounts of sediment and solutes to adjacent streams, lakes and coastal zones. There is increasing evidence for profound changes occurring in tundra vegetation in this region which have been attributed to changes in climate and disturbance regimes, but these changes are not uniform across plant species or in all areas within the ISR and the Kitikmeot region. The overall effect is most easily observed as the “Greening of the Arctic” seen in repeated satellite imagery over decades, which indicates more plant life is growing on the tundra. The abundance and height of shrubs (e.g. alder, willow, birch) are increasing and these species are expanding northwards, a trend expected to continue in coming decades. Invasive plants are being

found particularly along roads, seismic lines and other areas receiving more human traffic. Changes in forest ecology have been more modest. Increased recruitment has been observed for some tree species at and below the tree-line, but to date there is no evidence of increased tree density in the forest-tundra in this area. Changes in the quality and quantity of berry-producing plants important to northern people have been reported from traditional knowledge studies. Increased disturbance regimes (e.g. fire, herbivores, storm surges in low-lying areas, wetter/drier soils) will likely characterise and control Arctic plant communities in the future, driven by climate warming.

Certain freshwater and anadromous fish such as Arctic char, broad whitefish and burbot play a vital role in the cultural, nutritional and social health of northern communities. As such the climate change-related threats to these fish, and the ecosystems which sustain them, threaten those communities. Recent changes in fish communities have been reported in some locations but baseline data and monitoring efforts are limited in the region in comparison to its scale, and so the explanation for those changes is not always clear. Some key species, including Dolly Varden and Arctic char, are believed to be vulnerable to climate-related disturbances because of limited populations and spawning/over-wintering habitats (for the former), and because of the pending invasion of competing, ecologically-similar southern species such as bull trout, and Pacific, chum and pink salmon. The latter salmon species have been recorded in increasing numbers across an ever-widening range of the western Arctic. There is evidence for a reduced tendency to undertake anadromy among Arctic char because of the increasing productivity of freshwater habitats. Anadromous Arctic char are one of the preferred harvest foods of northern communities and so if this trend became widespread it could impact the quality and quantity of char as a food. The Husky Lakes in the NWT has been identified as a sensitive and unique freshwater habitat at potential risk from future changes in lake chemistry caused by melting permafrost, as well as from increased road access via the planned Inuvik – Tuktoyaktuk highway. Better ease of access could open up hitherto isolated areas to increased fishing pressures which

could severely impact fish populations, especially for very slow-growing species such as lake trout.

Across all groups of terrestrial wildlife (arthropods, birds and mammals), climate change will produce diverse and often divergent impacts characterised by large uncertainties. Our ability to measure and fully understand the reasons for these impacts is partly compromised by the lack of an adequate baseline inventory of many important species populations and by our poor understanding of many ecological processes in the Arctic. A long period of ecological disequilibrium can be expected in coming decades, driven by changing climate, novel ecosystem processes (e.g. transformation of low Arctic tundra to taiga shrub land; tundra wildfire), differential mobility of species in response to climate trends, extreme weather events, and ongoing flux in the species composition of local ecosystems. Projections are difficult and risky but it is likely that, in general, species which specialize in restricted breeding habitats, migration or feeding behaviours (e.g. lesser and white-fronted snow geese) are likely to suffer, while generalist feeders (e.g. raptor birds) will fare better and perhaps prosper. The most dramatic changes in animal communities will likely occur along and across the interface of taiga and low Arctic tundra ecozones. Increases in insect abundance (numbers and biomass) in general, including some biting insects, is a likely consequence due to warmer spring and summer temperatures. Range expansion of grizzly bears eastwards and onto King William Island has been confirmed, while in Alaska, hunters have reported moose and beaver expanding their ranges westwards into the Yukon River basin.

Despite the pervasive nature of climate influences on tundra ecosystems, we must be cautious in attributing all observed change to climate or weather phenomena particularly in animals with widely fluctuating natural cycles such as some rodents and caribou. Human activities are expanding in many portions of the ISR and the Kitikmeot region, including natural resource exploration and development, new transportation infrastructure, as well as continued

traditional and commercial wildlife harvest practices. These activities can have more rapid effects on wildlife distribution and abundance than a changing climate and can exacerbate the effects of climate change.

Mercury and POPs such as pesticides and industrial chemicals are present everywhere in the western and central Canadian Arctic environment, mainly because of long-range transport from southern industrial areas. Mercury also has important local geological sources, such as in the Mackenzie River. The chemistry and bio-uptake of these chemicals in Arctic ecosystems may be strongly influenced by climate-driven processes including thawing permafrost, changing precipitation, increasing productivity, changing plant and animal physiologies, and the introduction or elimination of species into food webs. However, understanding of how these effects are mediated in the Arctic, and their impact on biological contaminant levels, is still developing. Outside the ISR and the Kitikmeot region, POPs levels have generally been declining in step with global emissions. Mercury, however, is an exception; its concentrations in lake sediments and some freshwater biota have been increasing despite stable atmospheric levels. This discrepancy may be the best clue to date that climate-driven changes in geochemical processes now more strongly influence mercury levels in the Arctic environment than do changes in distant emission sources.

The key recommendations coming from this synthesis and assessment of the state of knowledge are:

- Continued monitoring and research into thermokarst processes and vegetation dynamics will be an essential component of understanding and predicting future climate impacts on landscapes.
- Increased community leadership and involvement in fish monitoring programs is recommended as one strategy to help alleviate local pressures on fish communities resulting from increased tourist access, mining, and infrastructure developments.

- The Husky Lakes ecosystem is at particular risk in this region because of the proximity of industrial/tourist developments, and monitoring of impacts on water quality and aquatic life is strongly urged.
- It is especially important to prevent new settlements from becoming sources of food to foxes and other scavengers which would alter the local predator-prey balance in surrounding areas.
- It is strongly recommended that tundra species which may come under threat in the future because of restricted ranges on the mainland should not be deliberately translocated onto northern islands unless naturally present there. There is solid and widespread evidence of severe and irreparable effects on local ecosystems resulting from translocations onto many other islands around the world.
- Datasets should be developed on contaminant levels in some important groups of biota for some chemicals in this region, such as POPs in freshwater fish.
- Research into linkages between contaminants trends, distribution and bio-uptake and climate change should continue to be supported.

3.8 References

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Chapter 4. Arctic Change: Impacts on Marine Ecosystems and Contaminants

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ABSTRACT

The pelagic (open water) and benthic (seafloor) marine ecosystems of the western and central Canadian Arctic provide Inuvialuit and Nunavummiut with many services. With climate warming and a shift in sea-ice regime, these Arctic marine ecosystems are likely to become similar to the richer subarctic/boreal ecosystems over the present century. Presently, the pelagic and benthic ecosystems of the western Canadian Arctic are still essentially intact. However, studies in the Bering Sea indicate that a spectacular shift in the relative importance of the pelagic and benthic ecosystems can occur in less than 20 years. Recent scientific studies in the area point to the following potential transformations: (1) increased penetration of light in the surface layer of the ocean, and increased upwelling of nutrients by wind from the deep layer to the surface layer; (2) reduced production of ice algae and increased production of phytoplankton; (3) enrichment of the pelagic ecosystem to the detriment of the benthic ecosystem; (4) initial improvement of conditions for key Arctic specialists such as the large copepod *Calanus glacialis*, Arctic cod and several seabirds until mid-century; (5) a decline in the abundance and health of resident ice-dependant seals and polar bears after mid century; and (6) significant changes in the migration patterns of migratory species such as beluga, bowhead and killer whales. The lack of regional models and scenarios of the future ocean climate in the Canadian western and central Arctic weakens our capacity to forecast precise milestones in the ineluctable transition of the Arctic marine ecosystems towards boreal marine ecosystems. Oil exploration leases overlap with the distribution of Arctic cod and marine mammals. There is an acute need to inventory and increase knowledge about the marine ecosystems of the Kitikmeot region.

4.1 Introduction

From fisheries to ecotourism and the sequestration of greenhouse gases, marine ecosystems provide humans with multiple services. Communities in the Canadian Arctic are particularly dependent upon the sea and the sea ice (Hovelsrud et al. 2008; Zeller et al. 2011). Arctic marine ecosystems supply Inuit with necessary food and nutrition, consisting of a diet rich in omega-3 fatty acids and selenium, contributing to protection against cardiovascular diseases, diabetes, obesity and cancer (Bjerregaard et al. 2004). The unique fauna of the Arctic Ocean supplies many other ecosystem services such as hides and furs, heating oil, substrates for tools and sculpture (e.g. bone, ivory), ecotourism revenues, recreation, social and spiritual cohesion through the sharing of food and knowledge, and inter-generational bonding through the teaching of fishing and hunting. Overall, the open and ice-covered waters of the Arctic Ocean, as well as the plankton, benthos, fish, mammals and seabirds they harbour, support a large fraction of the economy, culture, tradition, and well-being of Northerners.

The extreme climate that has prevailed over the Arctic Ocean for about three million years has shaped unique marine ecosystems characterized by organisms that are adapted to low temperatures, continuous darkness of the polar night and continuous daylight of the midnight sun, a perennial or seasonal sea-ice cover limiting nutrients in the stratified surface layer of the water column, and an extremely pulsed annual cycle of primary production. Examples of hyper-specialized species unique to Arctic seas include the polar bear (*Ursus maritimus*), the beluga (*Delphinapterus leucas*), the narwhal (*Monodon monoceros*), and the bowhead whale (*Balaena mysticetus*), all of which depend on sea ice for hunting, reproduction or protection (Tynan and DeMaster 1997). These predators and several other carnivores, including fish and birds, in turn rely on the energy extracted from sunlight by the ice-algae and the phytoplankton and channelled by the zooplankton (Figure 1).

Our capacity to anticipate how the ongoing transformation of the Arctic Ocean will affect, either negatively or

positively, these hyper-specialized species and the services they provide to Northerners depends on our understanding of the response of marine ecosystems to the double pressure of climate change and industrialization. Exploration for oil spurred several research programs on the marine ecosystems of the Canadian Arctic and their vulnerability to human activities, such as the Eastern Arctic Marine Environmental Studies (EAMES) program (1976-1979), the Baffin Island Oil Spill (BIOS) project (1980-1983), and the Northern Oil and Gas Action Plan (NOGAP, 1983-1991) program (see <http://www.aadnc-aandc.gc.ca/eng/1310570943643/1310572541138> for details). In the Beaufort Sea region, the Beaufort Environmental Monitoring Program (BEMP, 1983, 1988) of NOGAP advanced the state of preparedness of federal and territorial governments to hydrocarbon development. More recently, the Beaufort Regional Environmental Assessment (BREA, 2011-2015) of the Department of Aboriginal Affairs and Northern Development Canada sponsored several environmental and socio-economic studies to help prepare stakeholders to respond to new investments in oil and gas exploration in the offshore Beaufort Sea. Based on these earlier efforts and more recent work conducted as part of the research programs of the Northern Contaminants Program (NCP, ongoing since 1991), the Network of Centres of Excellence ArcticNet (2004-2018) and BREA, we synthesize our present understanding of the potential impacts of climate change and industrialization on the main components of the marine ecosystems of the Inuvialuit Settlement Region (ISR) and the Kitikmeot region of Nunavut, and propose a number of recommendations for policy.

4.2 Plankton

In Arctic marine ecosystems, the abundance of large animals harvested by Northerners ultimately depends on the production of microalgae in the ice (ice algae) and in the surface layer of the sea (phytoplankton). The carbon and energy contained in these microalgae is transferred to fish, marine mammals, birds, and man via planktonic grazers such as herbivorous copepods (Figure 1). It is generally

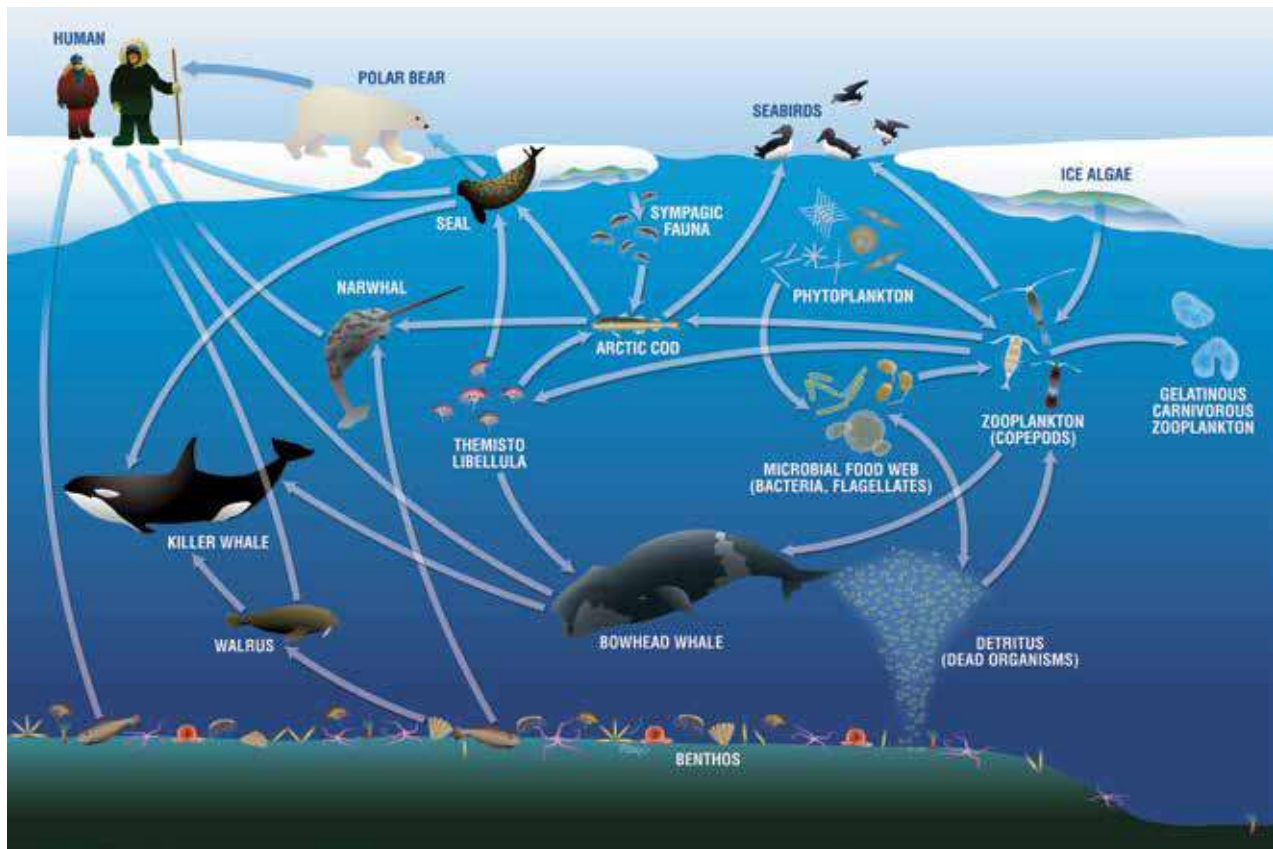


FIGURE 1. Schematic representation of the Arctic marine food web. From Darnis et al. (2012). Arrows represent the energy flux from a prey to its predator.

considered that Arctic marine ecosystems rely on a single burst of microalgal production during spring once solar radiation has reached a threshold and before the nutrients used by the microalgae (essentially nitrates) have been depleted in the surface layer of the ocean. However, this view is changing as the extent and duration of the summer sea-ice cover are declining. It is expected that, in the future, microalgal production will occur in a more continuous way throughout the summer (at least over the continental shelf) as wind mixing increasingly ice-free seas will bring nutrients from the deep layer to the surface layer (Tremblay et al. 2012).

In coastal waters of the southeastern Beaufort Sea, the recent increase of southeasterly winds and decrease in sea-ice cover have promoted the upwelling of nutrients to

the surface layer through the summer season, resulting in increased total production by microalgae (Tremblay et al. 2011). Small omnivorous copepod species characterized by a short vital cycle are expected to take advantage of the longer productive season. Beyond continental shelves, another observed and projected consequence of the rapidly melting sea-ice cover in the western Arctic is a decrease in the salinity and increase in the temperature of the surface waters in the offshore Canada Basin (McLaughlin and Carmack 2010). A warmer and fresher surface layer is less dense and hence more difficult to mix with the cold, saline, dense and nutrient-rich waters of the deep layer. The end result is a limitation of nutrient replenishment by wind mixing and a reduction of microalgal production that can cascade throughout the food web. Offshore, the warming and freshening of surface waters may favour the replacement

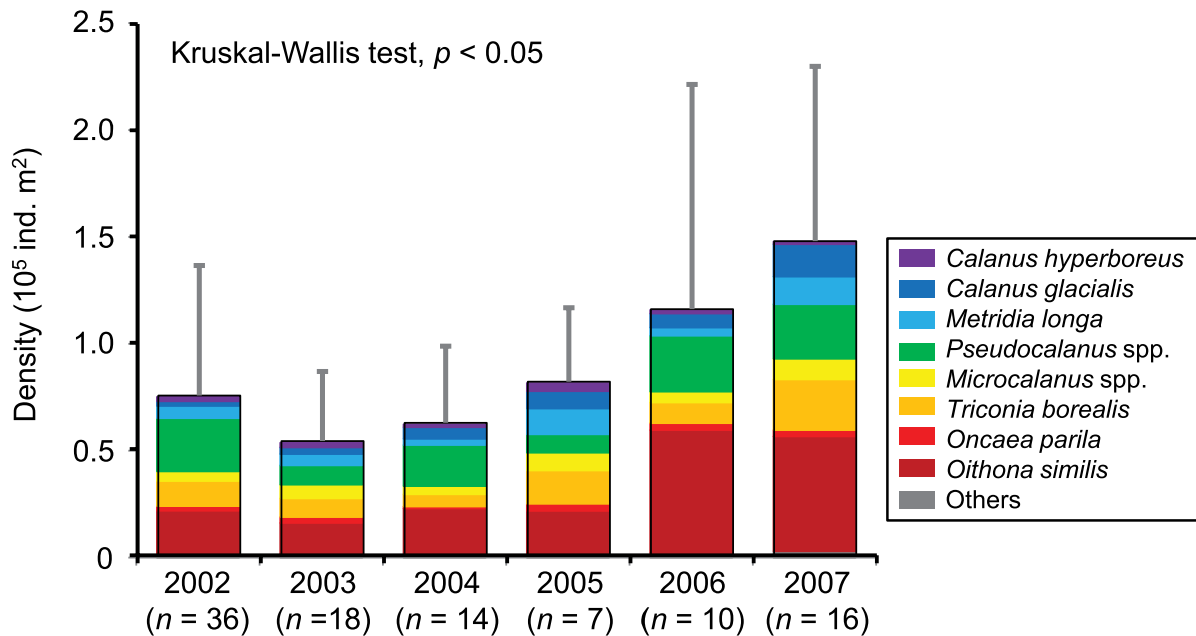


FIGURE 2. Copepod density (mean with standard deviation) observed on the continental shelf and slope of the southeastern Beaufort Sea in the autumns of 2002 to 2007. The different copepod taxa are represented by different colors. “n” represents the number of stations sampled in each year.

of relatively large microalgae such as diatoms by smaller species (Li et al. 2009). In the mid-term, the displacement of large phytoplankton cells offshore and the expansion of small copepods inshore are expected to negatively affect large herbivorous copepods of the genus *Calanus* that are the main energy conduit from microalgae to fish, seabirds and marine mammals (Darnis et al. 2012).

To test this hypothesis, Suzuki et al. (unpublished data) assessed the response of copepod populations to upwelling in coastal waters of the southeastern Beaufort Sea. They tracked the abundance of the main species by deploying zooplankton nets at several stations in the Beaufort Sea in the autumns of 2002 to 2007. Trends of decreasing sea-ice cover and increasing upwelling-favorable winds were observed through the time series. As expected, upwelling events were associated with increased total copepod density from ~70,000 individuals m⁻² in 2002-2004 to 170,000 individuals m⁻² in 2007 (Figure 2). The increase of copepod standing stock primarily reflects the increased abundance

of small omnivorous copepods such as *Oithona similis*, *Microcalanus* spp., *Oncaea parila*, and *Triconia borealis*. The abundance of the large herbivore *Calanus glacialis* also increased, benefiting from favourable upwelling conditions. Tremblay et al. (2011) and Forest et al. (2011) reported similar results, with a positive response of *C. glacialis* populations associated to upwelling-driven phytoplankton production in 2007 and 2008, respectively. However, the other large herbivore *Calanus hyperboreus* presented no obvious trend in abundance. At this time, no copepod species appears negatively impacted by the changing environmental conditions. Our observations may represent the first sign of the general increase in zooplankton abundance predicted to result from a reduction of ice cover, a warming of the surface layer, and an intensification of wind-induced upwelling on continental shelves of the western Canadian Arctic. However, any firm conclusion as to an actual long-term increase in zooplankton abundance is precluded by the shortness of the time-series. Continuous annual monitoring of zooplankton dynamics is crucial to anticipate



GERALD DARNIS/ARCTICNET

Paraeuchaeta glacialis (magnified)

the response of *Calanus* copepods to ongoing changes, as well as modifications in carbon pathways among the main components of marine ecosystems of the western Canadian Arctic.

4.3 Marine fishes of the western and central Canadian Arctic

4.3.1 Overall diversity and general distributions of marine fishes

Approximately 84 species of fish are presently confirmed to occupy marine waters in the western and central Canadian Arctic (Coad and Reist 2004; Mueter et al. 2013). Of these, 20 are anadromous species (i.e. migrate seasonally or over life between fresh and marine waters) that are discussed in Chapter 3. The remaining ~59-64 species (representing 14 families) are primarily marine and occupy several of the sub-regions in the area. Appendix A provides the common and scientific names of these species and their families. The five families with most species are eelpouts (13 species), sculpins (11), cods (6), eelblennies (6) and right-eyed

flounders (5). The remaining nine families have 1-4 species represented (Appendix A). Exact species numbers are uncertain due to a variety of causes: limited sampling in northern areas which remain ice bound and in deeper areas (see Figure 3), some groups such as eelpouts contain species new to science, and described fish are difficult to identify (Appendix A footnotes). Recent work in the southern Canadian Beaufort Sea suggests an additional 13-14 species may be present, however, these require confirmation of identities (Marine Fishes Project of BREA, Reist et al. unpublished data).

Consistent with previous reports for the Arctic Ocean (e.g. Christiansen et al. 2013), bottom-dwelling (benthic) species are more abundant than water column (pelagic) species in the western and central Canadian Arctic. For the shelf areas of the Beaufort Sea in particular 46 benthic species from 11 families are documented compared to six pelagic species from three families (Majewski et al. 2009a, b, 2011; Logerwell et al. 2011; Lowdon et al. 2011; Rand and Logerwell 2011). Arctic cod appears ubiquitous occurring in wholly marine waters (i.e. generally outside the 20 m isobath), offshore in ice (epipelagic), and in pelagic and benthic habitats to depths of at least 1000 m. Largest concentrations are found in zones of mixed or intersecting water masses between about 250-450 m depths (Geoffroy et al. 2011; Reist et al. unpublished data).

Figure 3 presents six oceanographic/geographic sub-regions of the Canadian Arctic for which fish species occurrences have been researched (Appendix A). Fifty-two species are present in the Canadian Beaufort Sea proper, four of which have only recently been documented through the Northern Coastal Marine Studies Program (NCMS 2003-2009) – i.e. halfbarred pout, pale eelpout, and Arctic eelpout (Majewski et al. 2009a, b, 2011, 2013b; Lowdon et al. 2011) and walleye pollock (identified genetically, J. Nelson, SeaStar Biotech, Victoria, BC, pers. comm.). More recent work conducted through the Marine Fishes Project of the BREA program delivered by Fisheries and Oceans Canada from 2010-2013 has added an additional 13-14 species that are as yet unconfirmed occurrences (Reist et al. unpublished

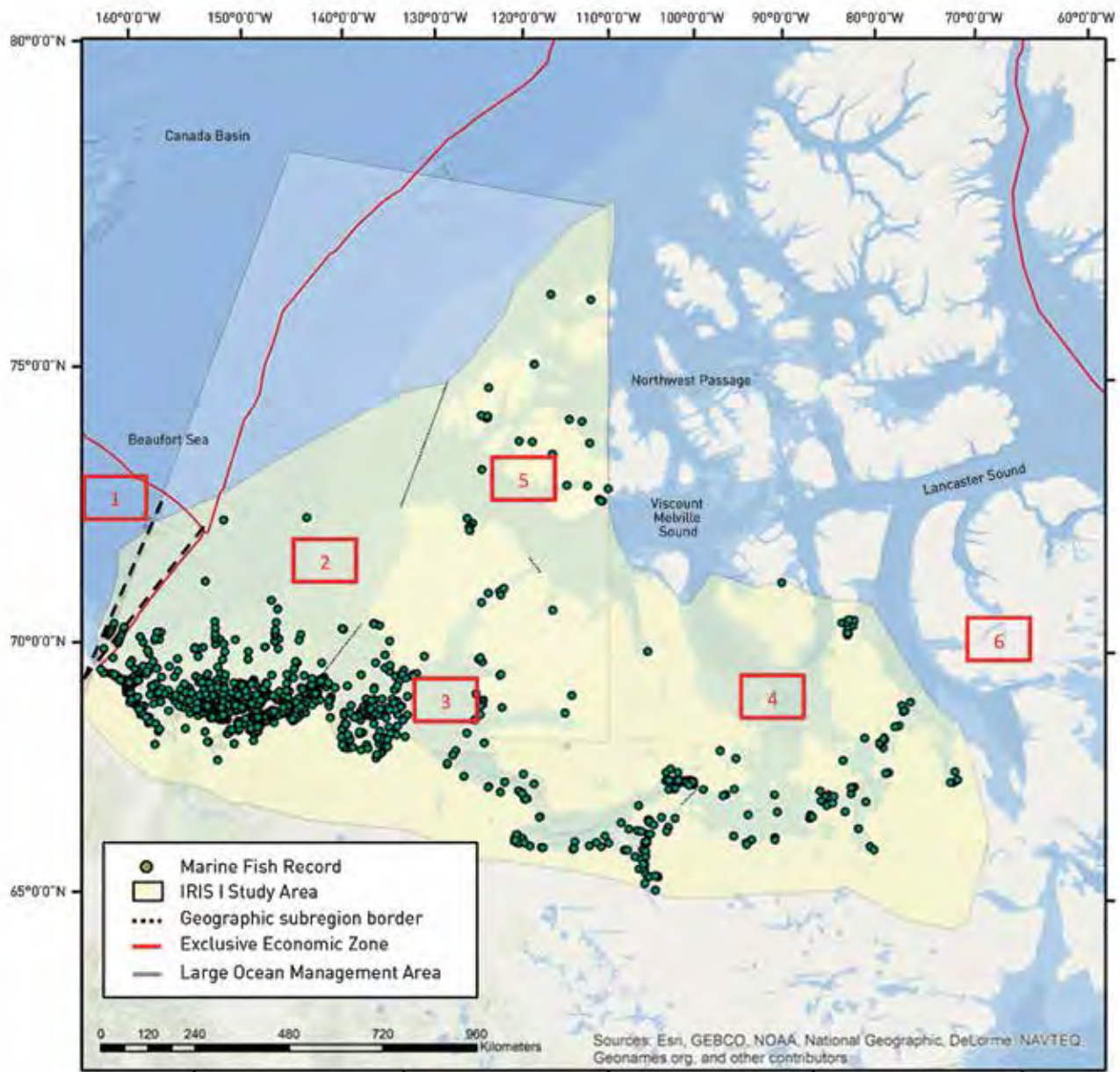


FIGURE 3. Map of all known point occurrences of anadromous and marine fishes in marine habitats of the ISR and the Kitikmeot region of Nunavut (yellow polygon). Note the significant biases towards nearshore and coastal embayments, which reflect accessibility (particularly in the past) and affect overall knowledge regarding fish distributions and diversity. Point distributions are from an unpublished database underlying Coad and Reist (2004) based upon all known and verifiable literature records, museum specimens and collection records for the area (e.g. Ocean Biogeographic Information System). The concentration of points in the southern Beaufort Sea and Amundsen Gulf represents recent work conducted by Fisheries and Oceans Canada under the NCMS Program (2007-2010) and the Marine Fishes Project of the BREA Program (2011-2013) (Reist et al. unpublished data). Geographic sub-areas referred to in the text are: (1) Alaskan Beaufort Sea, (2) Canadian Beaufort Sea, (3) Amundsen and Coronation gulfs, (4) Central Arctic Archipelago, (5) Northwestern Arctic Archipelago, and (6) Eastern Canadian Arctic. The triangular area enclosed by heavy dashed lines extending offshore along the 141°W meridian represents the disputed trans-boundary zone between Canada and the United States.

data). Similarly, for the Amundsen Gulf and Coronation Gulf area, ~50 species are known to occur, of which two are not in common with those of the Canadian Beaufort Sea. The known diversity in the central Arctic Archipelago is substantively lower (n=25 species) and that of the northwestern Arctic Archipelago lower still (n=14). This paucity likely reflects the tendency for diversity to decrease with increasing polar latitude (Christiansen et al. 2013). Additionally, low overall diversity likely results from low habitat diversity in waters of the Archipelago (e.g. limited deep-water habitats). The overall weak sampling effort in the central and northwestern Arctic Archipelago may also explain the low number of species. Figures for both areas are likely to increase as additional work is conducted. Forty-eight species known to occur in the Alaskan Beaufort Sea are shared in common with those of the Canadian Beaufort Sea (Appendix A). Total diversity is slightly higher in the former (Mecklenberg et al. 2002, 2011). About 44 species are known to occur in both the ISR and the Kitikmeot region and more easterly Arctic areas (Appendix A), but once again the latter area has much greater overall diversity (Coad and Reist 2004; Mueter et al. 2013).

4.3.2 The habitats of different marine fish species

The Canadian Beaufort Sea and other sub-areas are characterized by water masses of different origin (e.g. Mackenzie River plume, surface, Pacific, Atlantic, and Arctic) that define several distinct habitats for pelagic fish species (Figure 4). Similarly, depth, distance from shore, and bottom type (e.g. mud, sand, gravel, rock) will dictate different habitats for benthic species, particularly at the local scale.

Marine species in coastal/estuarine and inner shelf areas (depths from 0 to 20-50 m) generally have a wide tolerance to the large variations in temperature, salinity, light and ice that characterize these nearshore habitats. Fishes that occupy such habitats include: Arctic alligatorfish; many sculpins - hameçon, Arctic hooker sculpin and fourhorn sculpin; cods - Arctic cod and saffron cod; nearshore

eelblennies – slender eelblenny and Arctic shanny; and some eelpouts – fish doctor and Canadian eelpout. Hard-bottom habitats (i.e. rock or gravel substrates) are rare in the southern Canadian Beaufort Sea (Figure 3 sub-area 2) particularly in areas that receive sediments from the Mackenzie River (Carson et al. 1998), although gravel patches are known from western areas (Cobb et al. 2008). Deeper benthic areas offshore of Herschel Island in the West appear to be hard-bottom habitats (Jerosch 2013). Further east in Amundsen Gulf (e.g. Darnley Bay) and the Archipelago, hard-bottom habitats are more widespread. Hard-bottom habitats often provide stable areas for kelp and invertebrates that attach to rocks, especially at depths below ice scour. In general, hard-bottom habitats exhibit fewer and different fish species from those found over soft-bottom habitats such as the fish community associated with kelp on the ‘boulder patch’ in the Alaskan Beaufort Sea (Dunton et al. 1982). Species such as herrings, kelp snailfish and fish doctor are associated with kelp beds but also occur in association with mud, sand and cobble bottoms. Local knowledge indicates the possible presence of a kelp community in the vicinity of the western margin of Darnley Bay (DFO 2011) and similar habitats likely exist in the northern and eastern portions of the ISR and the Kitikmeot region (Martin and Gallaway 1994; Reist et al. unpublished data). Fish communities in these areas have seldom been studied.

Species in deeper areas where conditions are stable exhibit narrower tolerances to variations in temperature, salinity and light. Examples of such species include bigeye sculpin, Atlantic spiny lump sucker, Greenland halibut and the pale eelpout. Sand lances (northern sand lance and Pacific sand lance) associate with sand and small-diameter gravel. The banded gunnel and fourline snakeblenny inhabit cobble and rock habitats. The largest number of species is found over mud bottoms (i.e. silt and clays), which dominate much of the southern Beaufort Sea. However, most of these species are also found in other habitats (e.g. sand/gravel, cobble/bedrock). Zones >20 m deep can be further sub-divided into surface (including ice if present), pelagic and benthic habitats, all of which may be used by different species or groups of fishes. Arctic cod occurs in all such habitats

(i.e. within ice cracks and crevasses, in the water column, and also on or near the seafloor generally in depths <1000 m). Other species tend to occupy a narrower range of habitats.

Mixing zones between adjacent water masses, and areas where distinct water masses interact with the bottom (i.e. along the shelf break and the slope), appear to have somewhat distinct marine fish communities. For instance, early findings from the BREA Marine Fishes Project (Reist

et al. unpublished data) suggest species originating from the Alaskan Beaufort and/or Chukchi Seas occupy mid-depth offshore zones influenced by waters of Pacific origin (e.g. Polar sculpin, a species newly identified in the area). Similarly, deeper zones influenced by Atlantic-origin waters that circle around the pole and reach the Beaufort Sea Slope around 400-700 m depths appear to be habitats preferentially used by Atlantic species such as the Greenland halibut (Chiperzak et al. 1995).

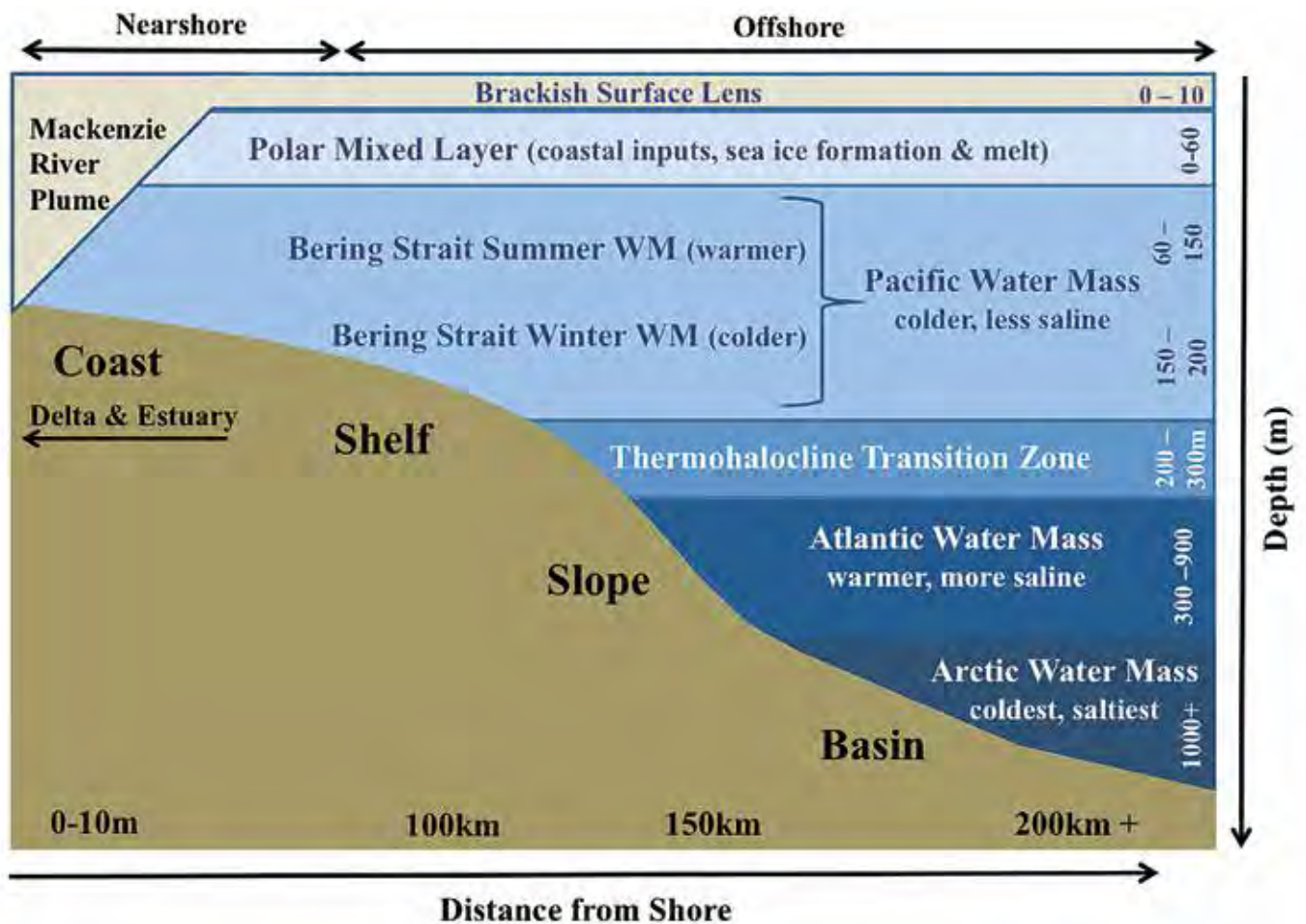


FIGURE 4. General water mass structure and bathymetric (depth) regions that define fish habitats in the southern Canadian Beaufort Sea, after Carmack and MacDonald (2002) and Carmack et al. (1989).

4.3.3 Fish diversity, abundance and biomass

Preliminary results from the BREA Marine Fishes Project (Reist et al. unpublished data; note that species identifications require formal taxonomic verification) indicate that overall species richness is about the same between the shelf (20 species from 13 genera) and the upper slope (24 species, 15 genera) zones, however, the species composition differs (Figure 5). Species richness is much lower (15 species, 10 genera) in the deeper (>500 m) zone and the composition is substantially different from that in shelf areas.

A few species are found across all habitats such as Arctic cod, some eelpouts and a snailfish. Arctic cod numerically dominate the catches in the shelf and slope zones. For benthic species, eelpouts exhibit the highest species richness (9 species), three of which are present across all habitats. Larger-bodied species such as Greenland halibut and Arctic skate are associated with deeper slope and off-slope waters.

Most species present on the shelf tend to be small-bodied and, despite high abundances, their overall biomass remains small (Figure 6; Reist et al. unpublished data). Biomass increases with depth; it is intermediate on the upper slope,

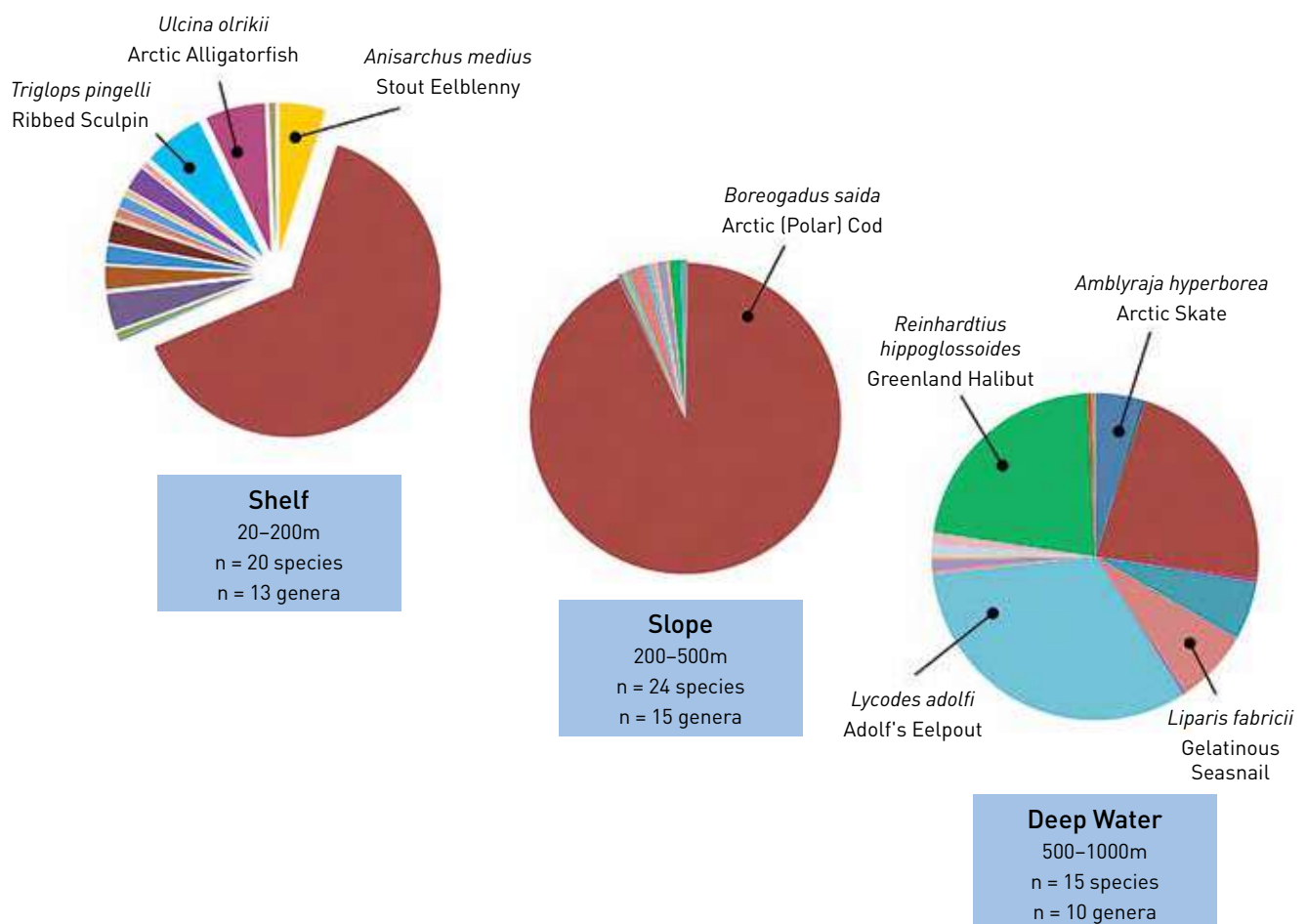


FIGURE 5. Preliminary results from the BREA Marine Fishes Project conducted by DFO in 2012 (Reist et al. unpublished data). Relative diversity of taxa across depth zones; the colours of pie segments indicate species and the size of the segments indicate relative abundance integrated across all stations in the southern Canadian Beaufort Sea.

which hosts larger bodied fish and a generally higher absolute biomass than the shelf. Biomass is largest in deeper areas (500-1000 m) where large individuals of several large-bodied species are captured (e.g. Greenland halibut and Arctic skate).

The high relative and absolute abundances of Arctic cod on the shelf and the slope underscore the pivotal role this pelagic-demersal forage fish plays in the Beaufort Sea marine ecosystem, particularly as a staple for key marine mammals such as ringed seals and beluga whales (Loseto et al. 2009; Asselin et al. 2012). Flatfishes, eelpouts and Arctic skate clearly dominate the deeper waters in terms of fish diversity and biomass although their absolute abundance may be low. Despite the overall numerical dominance of Arctic cod in the region, the diversity of benthic fishes in all sub-ecosystems is suggestive of significant roles for this group. Whether deepwater sub-ecosystems operate independently of those on the shallower slope and shelf is unknown at this time.

A further look at Arctic cod

Given its importance as a forage fish for other fish, seals, whales and seabirds, much research has focused on the distribution and ecology of Arctic cod over the annual cycle in the Beaufort Sea. Benoit et al. (2008) detected large Arctic cod aggregations in winter in Franklin Bay based on the continuous operation of an echosounder from the overwintering Canadian Coast Guard Ship (CCGS) *Amundsen* in 2003-2004. A second overwintering of the *Amundsen* in 2007-2008 extended the mapping of the Arctic cod winter distribution to the entire Amundsen Gulf (Geoffroy et al 2011). Large spawning aggregations were observed at depth under the ice cover from early December until late April (Figure 7). The dispersion of the last aggregation in late April coincided with the development of the spring phytoplankton bloom under the ice (Forest et al. 2011) and the migration of zooplankton prey towards the surface (Geoffroy et al. 2011). No Arctic cod school was detected in the absence of ice-cover waters. We hypothesized that this aggregation pattern was driven by the need for Arctic

cod to avoid its main predator the ringed seal (*Pusa hispida*). In winter, the ice cover provides ringed seals with a platform from which to dive. As the ice forms, the Arctic cod aggregations develop with the largest fish remaining in the deepest layer, and the smaller fish moving down in daytime and up at night but never above the 140 m depth horizon. In winter, large adult cods sport a very large, lipid-rich liver. Interestingly, it appears that diving seals target the large livers of these large, deep-dwelling cod. Remaining at depth limits predation by increasing the distance seals have to dive to reach the largest fish/livers. Also, Arctic cod spawn in winter and the buoyant eggs hatch into larvae near the surface from January to early July. The ice and snow cover shields the young fish from seabird predators and likely reduces vulnerability to pelagic fish and other visual predators by reducing light in the surface layer.

Together, the Active Acoustic Mapping of Fish and the Marine Fishes projects of BREA have documented the summer distribution of fish in the offshore Canadian Beaufort Sea. Acoustic records validated by trawls confirmed the concentration of adult Arctic cod (age 1+) on the slope over bottom depths ranging from 200 to 400 m (Figure 8a). This distribution of adults overlaps extensively with several oil exploration lease blocks (Figure 8b). The survey also indicated that juvenile Arctic cod (age 0) are distributed near the surface (0-100 m) over the shelf and the shelf slope.

4.3.4 Effects of human-caused stresses on fish populations

The effect of human activities on marine fish populations in the western and central Canadian Arctic have not been documented to any extent. No commercial exploitation of any marine species takes place presently in the area (Chapter 9, section 9.3.4), although coastal fishing targeting anadromous species also captures marine species (Chapter 3). In terms of overall effects, exploitation through subsistence fishing is restricted to a small suite of coastal marine species and has had no discernible impact on their populations.

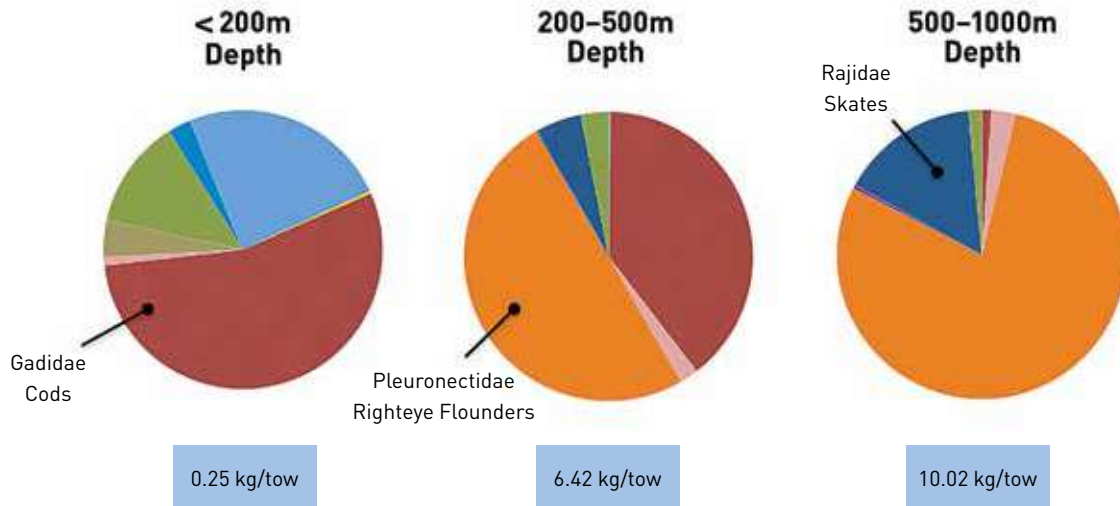


FIGURE 6. Average relative biomass of benthic fishes associated with depth zones (preliminary results from the BREA Marine Fishes Project conducted by DFO in 2012, Reist et al. unpublished data). Overall biomass per standardized tow by benthic gear is relatively low on the shelf (<200m), intermediate on the slope (200-500 m) and high in deeper waters (500-1000 m). These results reflect the finding that most fish present in zones <500 m depths are smaller bodied than those found in deeper water. On the shelf, most biomass is present as Arctic cod (>50%, reddish brown colour), followed by sculpins (lighter blue) and eelpouts (green). While still a significant component of biomass on the slope, Arctic cod are replaced by flounders (orange colour) as the dominant contributor to biomass on the upper slope (200-500 m). Flounders, particularly Greenland halibut, and skates (dark blue) dominate the biomass in deeper areas. Other colours represent other fish families.

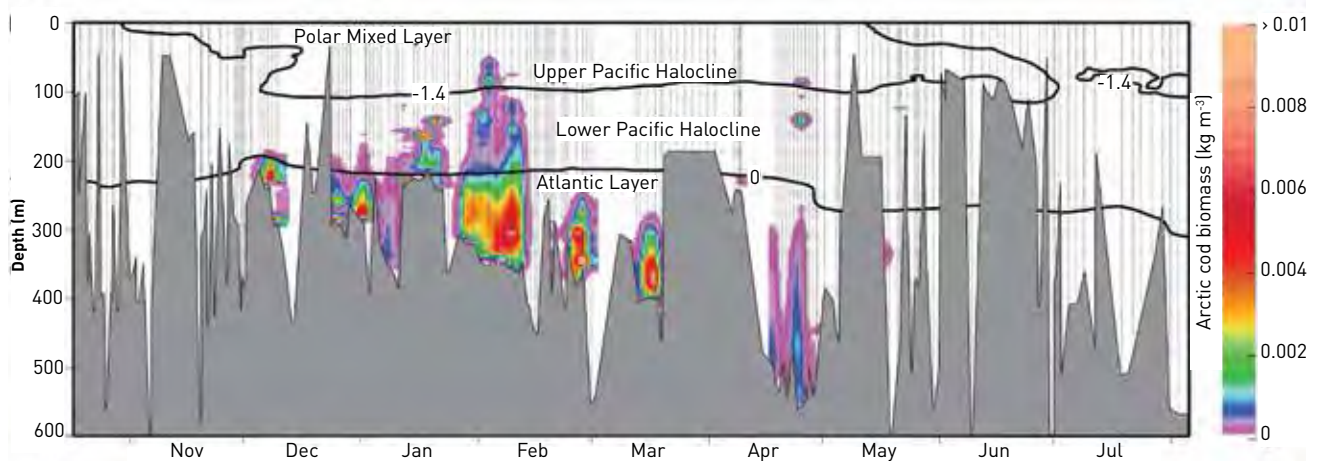


FIGURE 7. Time-depth section of Arctic cod biomass along the track of the CCGS *Amundsen* in the Amundsen Gulf from 18 October 2007 to 4 August 2008. The -1.4°C isotherm indicates the boundary between the upper and lower layers of the Pacific Halocline. The 0°C isotherm separates the Pacific Halocline and the Atlantic layer. Greyish vertical lines correspond to acoustic profiles. The grey area represents sea bottom. From Geoffroy et al. (2011).

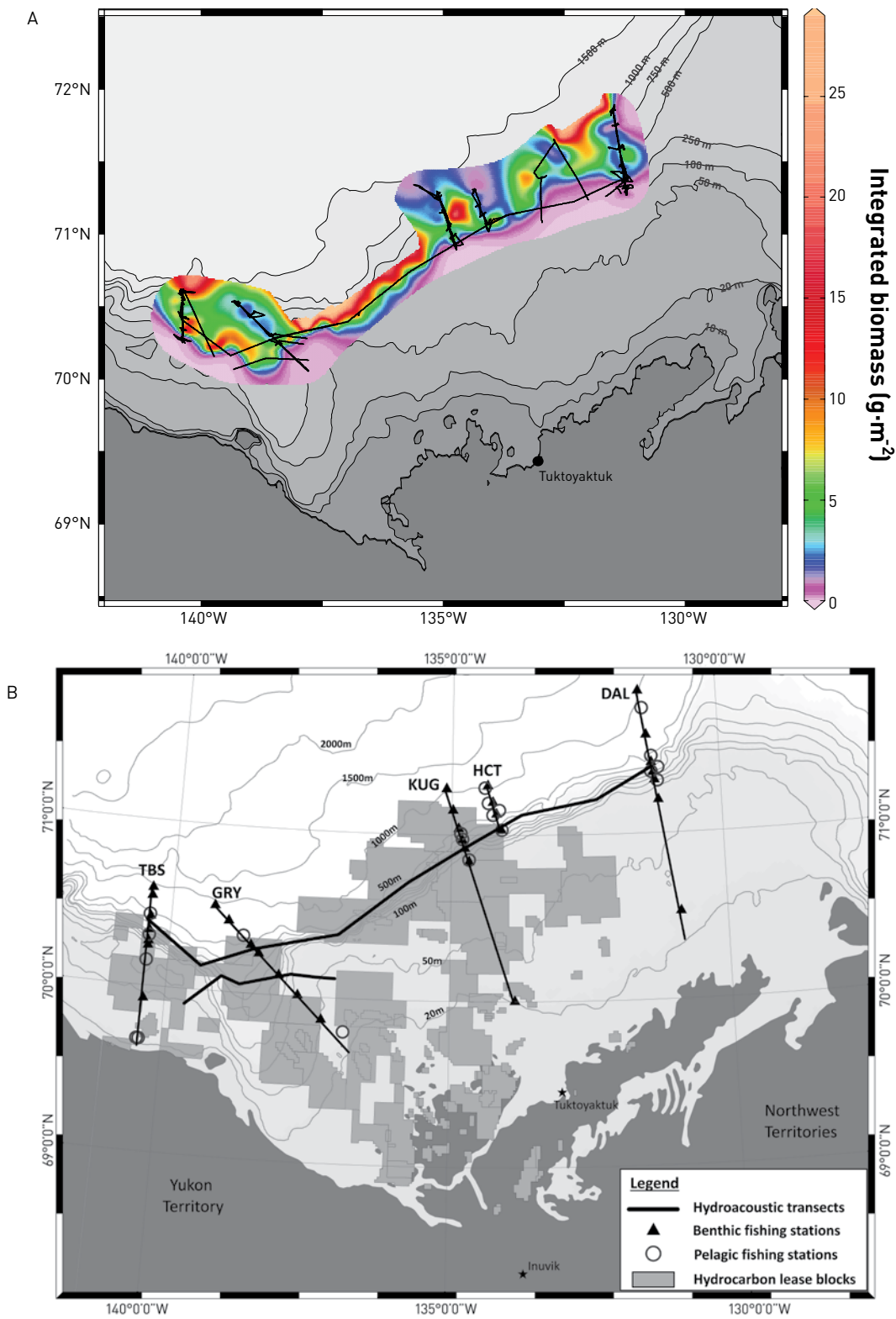


FIGURE 8. (a) Integrated biomass of late juvenile and adult Arctic cod (age 1+) in the Canadian Beaufort Sea during the BREA survey in August 2012. (b) Acoustic transects (solid lines), sampling stations (black dots), and oil exploration lease blocks in the area (hatched polygons). Base map showing lease blocks provided by Aboriginal Affairs and Northern Development Canada.

Recent exploratory research has increased our understanding of how species associate with particular habitats and has documented overall diversity (Reist et al. unpublished data). Two years of sampling (2012, 2013) have suggested an additional 13-14 species of fish occur in the Canadian Beaufort Sea than were previously known. Since previous sampling was restricted to ice-free shallow coastal zones and may have missed such rare offshore species, these specific findings cannot be attributed with any certainty to stressors such as climate change that would facilitate the invasion of the region by fish from the Pacific and/or Atlantic Oceans.

The recent inventory by the BREA Marine Fishes Project (Reist et al. unpublished data) is the first significant and comprehensive census of fish species to be conducted in the Beaufort Sea, especially in deeper waters. It represents a new baseline against which future change can be assessed. The census clearly documents the greater species richness and biomass of the community of benthic fish relative to the pelagic community. Based on the response of ecosystems to climate warming in the nearby Bering Sea (Grebmeier et al. 2006; Grebmeier and Maslowski 2014) it can be anticipated that by stimulating phytoplankton production to the detriment of ice-algae production, a reduction of the sea-ice cover will increase food retention in the surface layer of the Beaufort Sea and reduce the amount of food sinking to the benthos. This could in turn result in a rapid increase of pelagic fish and whale populations, and the simultaneous decrease of benthic production as observed in the Bering Sea (Grebmeier et al. 2006).

With respect to Arctic cod specifically, at this stage there is no indication that population dynamics have been impacted yet by climate change or human activities in the southeastern Beaufort Sea. However, as spawning aggregations occur only under the ice, and as the young fish likely depend on sea ice as a refuge, in the long term, the possible future reduction of summer ice cover could limit the hatching season (presently late January to early July) to winter months. The decrease of summer sea ice may also affect the standing stock of large copepod species

contributing to the Arctic cod diet during the larval, juvenile and adult stages. Most importantly, a longer ice-free season will facilitate the invasion of Arctic seas by boreal fish species such as capelin and sand lance, which may potentially outcompete Arctic cod, a hyper-specialist species adapted to life under and within the ice cover. The displacement of Arctic cod by capelin and sand lance has already been documented both in southern and northern Hudson Bay where ice decline is intense; in the latter capelin and sand lance have replaced Arctic cod as the main prey brought back to feed thick-billed murre (*Uria lomvia*) nestlings (Gaston et al. 2003). In the southeastern Beaufort Sea, where ice retreat is also severe, a decadal study (2002-2011) of the larval fish assemblage suggests the recent intrusion of the Pacific sand lance within the offshore distribution area of juvenile Arctic cod (Falardeau et al. 2014; see Box 1). Again, given the shortness of the record and the lack of earlier sampling of offshore waters, there is no certainty that Pacific sand lance did not occupy the Beaufort Sea in the recent past. Nevertheless, we may be witnessing the first step in the displacement of Arctic cod by a boreal forage fish, and the concurrent shift of the pelagic marine ecosystem to a new state.

Offshore exploration for oil in the Canadian Arctic targets the edge and slope of the Beaufort Sea Shelf where leases have been awarded in 2007. From 2011 to 2014, two BREA projects (Active Acoustic Mapping of Fish and Offshore Fish Population, Habitat and Ecosystems) focused on the baseline description of fish migrations, distribution and abundance on the shelf, slope and deep waters of the Canadian Beaufort Sea. In particular, the results revealed the importance of the continental slope as a habitat for the Arctic cod (Figure 8). They also confirmed the segregation of the early juveniles (20-35 mm, age 0 year) that occupy the surface waters (<100 m) in summer from the adult fish (age 1+ year) that live at depth (200-400 m) over the slope throughout the year (Geoffroy et al. 2012; Majewski et al. 2013a). This information is invaluable to help anticipate the potential impacts of an oil spill in the offshore Beaufort Sea. In case of an oil spill, crude oil mixed with seawater would potentially spread over the

BOX 1. Will Pacific sand lance compete with Arctic cod in the warming Beaufort Sea?

As elsewhere in the Arctic Ocean, the duration of the ice-free season and sea-surface temperatures are increasing in the Beaufort Sea (Wood et al. 2013). These rapid changes favour the northward migration of fish species normally restricted to temperate and subarctic seas. For instance, in 2011 Pacific sand lance (*Ammodytes hexapterus*) larvae were the second most abundant after those of the ice-adapted Arctic cod (*Boreogadus saida*) in the southeastern Beaufort Sea. Until then sand lance was seldom captured north of the Chukchi Sea. A recent study on the possible consequences of a sand lance invasion on Arctic cod in the Beaufort Sea demonstrated that in 2011, there was no competition among the larvae of both species as sand lance hatched after Arctic cod (Falardeau et al. 2014). However, as sand lance larvae grew 3.7 times faster than Arctic cod larvae they reached a similar length by the end of the summer and then started to compete for the same zooplankton prey species. Competition was limited by the fact that juvenile Arctic cod generally fed on bigger prey and sand lance on smaller ones. Rapid climate change in the Beaufort Sea is predicted to amplify the on-going reduction in the size of zooplankton prey (Falk-Petersen et al. 2007). Based on their 2011 results, Falardeau et al. (2014) foresee an increase in the abundance of Pacific sand lance in the southeastern Beaufort Sea, which could impact the abundance and distribution of Arctic cod.

Arctic cod (*Boreogadus saida*)

seafloor, affecting benthic fishes and aggregations of adult Arctic cod on the slope. Oil and/or dispersant in the surface waters would impact the buoyant eggs and the juvenile Arctic cod. The numerous marine mammal and seabird predators attracted by Arctic cod aggregations would also be at risk of exposure to oil.

4.4 Benthos

The Arctic Ocean seafloor hosts unique benthic fauna dominated by invertebrate organisms that live either within the mostly muddy sediment (endobenthos, e.g. polychaetes, clams) or on the sediment (epibenthos, e.g. brittle stars, mussels, crabs). Benthic animals provide services to humans as food (e.g. shellfish) and indirectly as the food of exploited marine species such as crabs, seals, toothed whales and seabirds (Bluhm and Gradinger 2008) (Figure 9). For instance, the bearded seal (*Erignathus barbatus*), the main benthic-feeding marine mammal

species in the Beaufort Sea, consumes whelks, shrimps, clams, anemones, sea cucumbers and polychaete worms (Cameron et al. 2010).

The Arctic benthic ecosystem is strongly influenced by the strong seasonality of its food supply, which consists essentially of sinking ice algae and phytoplankton (Piepenburg 2005; Carmack and Wassmann 2006; Link et al. 2011; Figure 9). As the Arctic climate warms, the ice melts and, in some regions, this may result in an increase in the algal food sinking to the benthos (Arrigo et al. 2008) (see section 4.2).

In other regions however, such as the deeper regions of the western Canadian Arctic, less ice could favour the interception of sinking algae by the zooplankton and result in a reduction of the food supplied to bottom-dwelling animals. Forest et al. (2011) have shown that microalgae produced in the Amundsen Gulf are intercepted to a large extent by microbes and zooplankton before the material reaches the seafloor. Such a regime shift has been observed in the

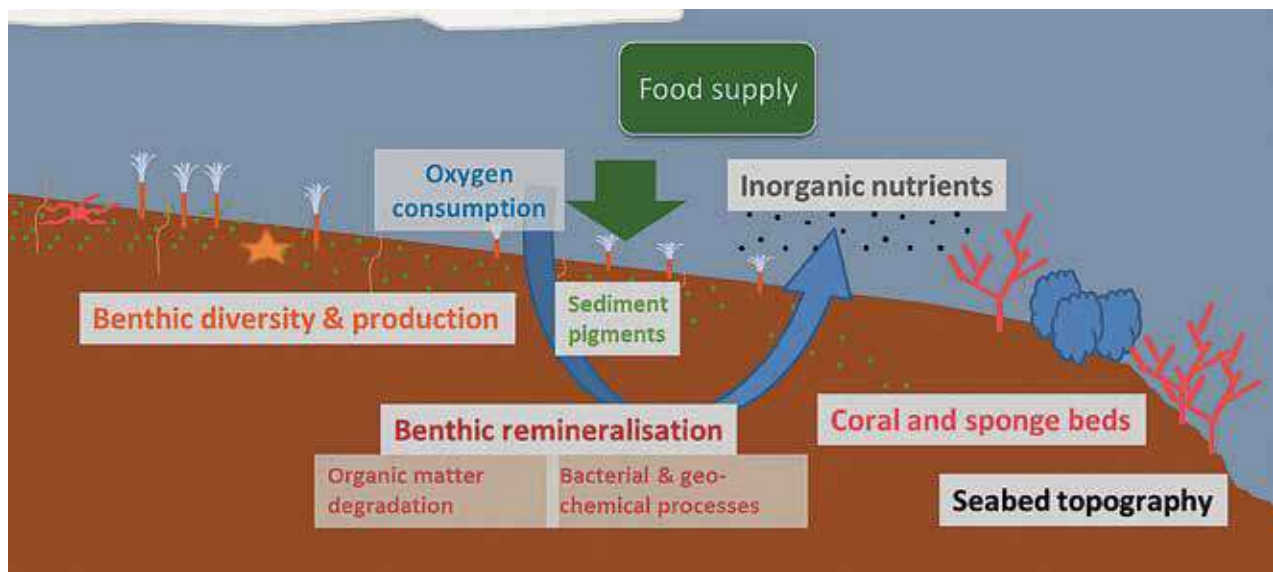


FIGURE 9. Schematic illustration of benthic ecosystem functioning in Arctic soft-bottom habitats. From Kenchington et al. (2011), Fisheries and Oceans Canada. Available online at http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2011/2011_071-eng.pdf

Bering Sea, where the reduction of sea-ice cover translated into the rapid increase of pelagic fish and whale populations, and the simultaneous decrease of benthos production (Grebmeier et al. 2006). In shallow coastal areas, food availability to the benthos may increase with increased production of algae (Tremblay et al. 2011), due to the lower abundance of zooplankton grazers inshore (Darnis et al. 2012). In addition to the expected shift in ecosystems, the invasion of the Arctic Basin by boreal species from the Bering Strait may spell the displacement of several Arctic bottom-dwelling species (ACIA 2004).

Knowledge of benthic processes in the western Canadian Arctic has increased tremendously during the past decade, thanks to several national and international research programs such as ArcticNet, CASES, IPY-CFL, BREA, the Malina Project, NCMS/Nahidik Program, and Canadian Healthy Oceans Network (CHONe). Yet, the biodiversity of many taxonomic groups and their contribution to the recycling of organic matter at the seafloor remain poorly documented (Archambault et al. 2010), but see Link et al. (2013a). A better understanding of benthic processes will improve our ability to predict the future health of Arctic

marine ecosystems. Here, we present a synthesis of our understanding of benthic diversity and some sediment processes at the seafloor gained through the ArcticNet-CHONe campaigns of 2006–2011 and BREA campaigns of 2012–2013. Finally, we evaluate the possible impacts of climate change on the health of the benthic ecosystem and on the services it provides.

4.4.1 Benthic diversity

Although the equivalent of only ~52 m² of seafloor had been sampled in the Canadian Arctic until 2003, no less than 992 species of benthic animals had been identified (Cusson et al. 2007). From 2003 onward, extensive sampling and improved identification based on DNA allowed for the increase of this number to 1,307 species (Snelgrove et al. 2011). For instance, Piepenburg et al. (2011) described 185 species of polychaetes (bristle worms) and 364 species from four common groups (molluscs, crustaceans, sea stars and urchins, and annelid worms) from a total of 131 sites sampled in the western Canadian Arctic. A recent study based on DNA revealed 407 bristle worm (polychaete) species for

the western Canadian Arctic only (Carr 2011), tripling the number of species previously identified based on morphology. Using a simple model (rarefaction curves), Carr (2011) also predicted that bristle worms in the Canadian Arctic might comprise as many as 897 species. Overall, bristle worms diversity may actually be higher in the Canadian Arctic than in the Canadian Atlantic where the model predicts a total of 550 species.

Studies conducted since 2007 have reported a relatively high diversity of large (≥ 5 mm) epibenthic animals for the western Canadian Arctic (Figure 10). A total of 718 taxa were identified. Most areas were characterized by 20-40 epibenthic species per site. The Mackenzie Shelf break shows the

highest species richness. This area has been identified by Roy et al. (2014) as a specific community in the Arctic, with a high faunal distinctiveness. The different species of several groups such as sponges, ribbon and peanut (sipunculid) worms have not been described and discriminated. Thus, unexplored habitats such as intertidal flats (a source of food for Inuit that needs further study in a context of climate and sea-ice regime change), rocky seafloor and the abyss of the deep Canada Basin likely harbour many undiscovered species. Furthermore, despite high abundance, many groups such as hydrozoans, sponges and cold-water corals have not been inventoried for the Canadian Arctic (Kenchington et al. 2011).

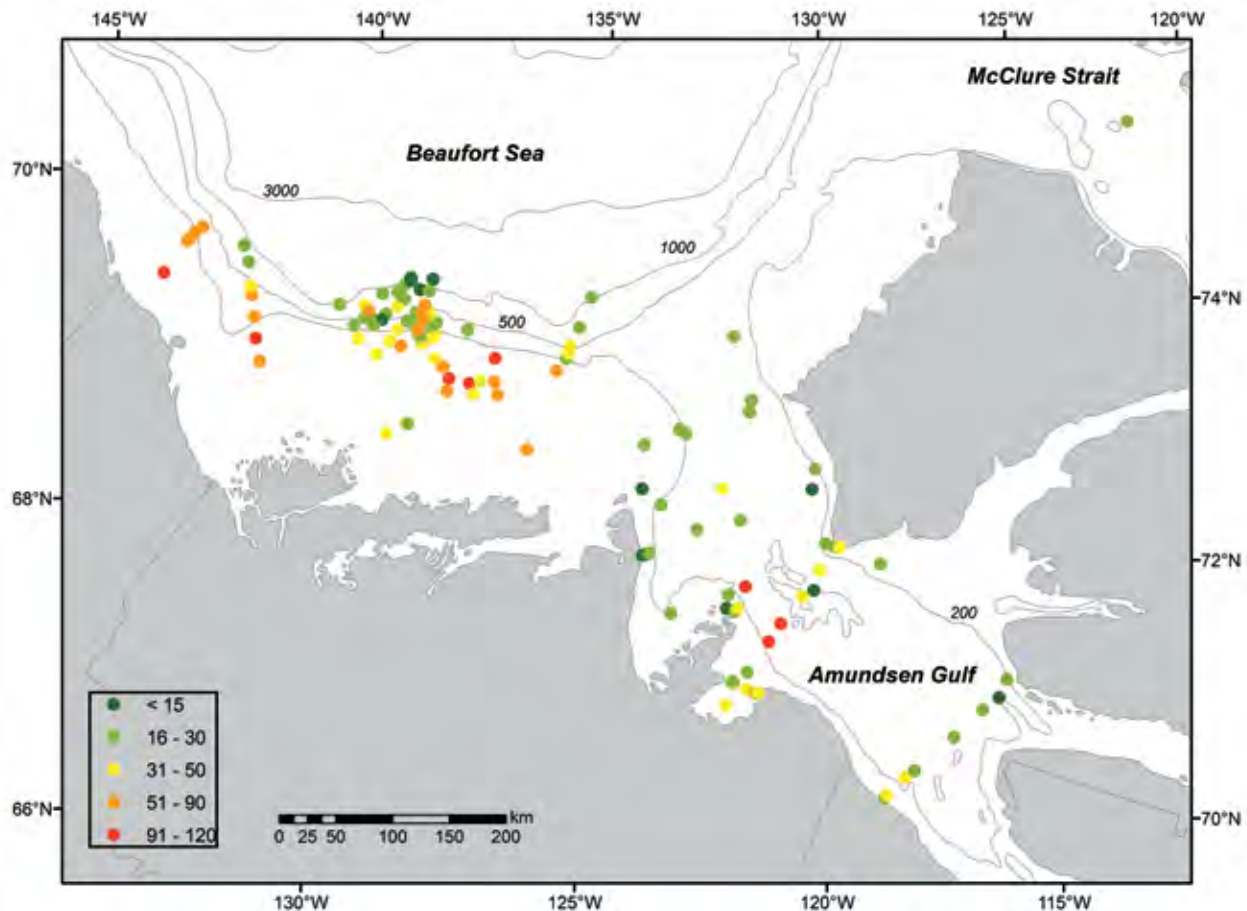


FIGURE 10. Species richness (total number of taxa) of the epibenthic fauna collected in the western Canadian Arctic from 2007 to 2013.



Above: Recovery of the Agassiz trawl, used to sample epibenthic species. Top right: *Margarites costalis*. Bottom right: *Pteraster obscurus*.

The importance of benthic biodiversity is recognized at all governance levels up to the United Nations General Assembly (UNGA). UNGA Resolution 61/105 “States to take action immediately, individually and through regional fisheries management organizations and arrangements, and consistent with the precautionary approach and ecosystem approaches, to sustainably manage fish stocks and protect vulnerable marine ecosystems, including seamounts, hydrothermal vents and cold water corals [...] recognizing the immense importance and value of deep sea ecosystems and the biodiversity they contain” (UNGA 2007). This resolution directly targets some groups such as the cold water corals, which are recognized as important nursery grounds for fish and many mobile epibenthic species. The recent assessment of biodiversity in the western Canadian Arctic (Josefson et al. 2013) highlights that the benthic fauna appears surprisingly diverse and that much work remains to inventory species in several important groups. It is necessary to pursue and extend the census of benthic species in the western Canadian Arctic to understand the role these unresolved groups play in the ecosystem.

4.4.2 Projected impacts of climate change on benthic ecosystem services

The production of microalgae in the western Canadian Arctic is expected to increase in the mid-term, but this will not necessarily benefit the health and services of the benthic ecosystem. In areas where small phytoplankton cells dominate, grazing by zooplankton will allow only a small fraction of the organic matter to reach the seafloor (Forest et al. 2011). In coastal and ice-covered areas, larger phytoplankton cells and sea-ice algae sink more rapidly to the bottom and the benthos (Tremblay et al. 2011). With the decreasing sea-ice cover, small phytoplankton are expected to prevail (Arrigo et al. 2008), thus limiting food supply to the benthos in deep areas of Amundsen Gulf and of the Mackenzie Shelf. This will most likely result in reduced abundance and diversity of benthic organisms (Smith et al. 2008; Blicher et al. 2010) and decreased nutrient recycling at the seafloor (Link et al. 2013b).

In shallow coastal areas and in upwelling areas where deep nutrients are brought up to the surface such as the Mackenzie Delta and the Cape Bathurst Polynya, an increase in microalgal growth will likely lead to an increase in the food reaching the benthos (Tremblay et al. 2011). The higher abundance of food may facilitate invasion by boreal species, thus shifting the nature and diversity of benthic ecosystems (Wassmann et al. 2011). The overall abundance of benthic organisms, including shellfish, should increase, which may not only benefit benthic-feeding marine mammals, but also local communities as a direct food resource (e.g. mussels, clams, crabs). The recycling of nutrients at the seafloor should also increase, leading to increased oxygen demand. In areas such as the Mackenzie Delta a strong input of organic matter due to increased microalgal growth and/or erosion could deplete oxygen at the seafloor and impact the benthic ecosystem. However, this scenario is based on only two years of nutrient recycling measurements in the western Canadian Arctic. The impact of climate change on benthic communities will need to be further assessed with longer time series of data. The response of benthic ecosystems to changes in the ice regime in shallow

inland marine waterways (e.g. Coronation Gulf, McClure Strait, McClintock Channel, Queen Maud Gulf, etc.) remains conjectural as scientific information on these systems and the ecosystems they support is generally lacking.

4.5 Seabirds

The potential impacts of climate change on Arctic animals are diverse. For example, changes in temperature and precipitation patterns could alter distributions and migrations, increase exposure to contaminants and pathogens, reduce habitat availability, increase competition, and decrease survival and recruitment of top predators (Learmonth et al. 2006). Many of these concerns are directly related to changes in the timing of sea-ice formation/break-up, declining sea-ice thickness/extent, and increasing sea surface temperatures (ACIA 2004; Kovacs et al. 2011).

Predicting long-term impacts of climate change on seabird populations is difficult and will vary from species to species. Nevertheless, there is mounting evidence of modifications in Arctic seabird biology and behaviour due to a decreasingly stable Arctic climate. Climate-related impacts have already occurred for most Arctic seabird species. For example, one of the rarest Arctic seabirds, the ivory gull (*Pagophila eburnea*), has faced severe population declines (>80%) in the Canadian Arctic during the last few decades (Gilchrist and Mallory 2005), likely associated with climate change and sea-ice declines (Karnovsky et al. 2009). Short-term, yearly sea-ice patterns have similarly affected northern fulmars (*Fulmaris glacialis*) and black-legged kittiwakes (*Rissa tridactyla*) at Prince Leopold Island, NU by reducing nestling survival when open water is distant from breeding colonies (Gaston et al. 2005). Additionally, breeding times of thick-billed murres and glaucous gulls (*Larus hyperboreus*) occur increasingly earlier at Coats



MARTIN FORTIER/ARCTICNET

Island, NU coinciding with earlier ice break-up (Gaston et al. 2009).

It is evident that recent climate trends influence the population status of seabirds in the Arctic. Biological patterns such as population declines, altered breeding times, and reduced nestling survival are largely associated with access to prey and changes in marine food supplies. Consequently, to understand the extent to which climate change can affect seabird populations, it is critical to investigate how food sources are impacted. In the Canadian Arctic, Arctic cod is the most frequent and numerous prey item of top predators with about five billion individuals consumed annually in the central Canadian Arctic alone (Welch et al. 1992, 1993). It is consistently the main prey item of seabirds in the Arctic (e.g. Bradstreet 1976; Bradstreet and Cross 1982), and thus has a critical role influencing the success of seabird colonies. Despite the ecological value of Arctic cod in the western and central Canadian Arctic, little is known how this small forage fish will respond to a changing environment. One of the main climate change projections for marine organisms indicates that temperate species will shift their distribution northward and compete for resources with species endemic to the Arctic. Distributional changes can have widespread repercussions for predators because typical prey may be adversely affected by competition with more robust species that may not be as energetically profitable (Orlova et al. 2009). Perhaps the most compelling evidence of the effect distributional shifts of prey can have on seabird foraging was demonstrated in northern Hudson Bay where the diet of thick-billed murre switched from Arctic cod to capelin over a 20 year period (Gaston et al. 2003). The observed change in diet composition was attributed to the expansion of capelin to warming northern waters, and reduced Arctic cod abundances as a result.

Interestingly, current climate patterns, particularly reduced sea-ice extent and earlier ice-breakup, appear to benefit seabirds, at least in the short-term. This hinges on access to open water especially near breeding colonies to provide for chicks (Gaston et al. 2005, 2009). However, open water is only valuable if prey are present and accessible to

predators. Consider Allen Bay, NU, a relatively shallow (rarely >30 m deep) coastal area located at the southern part of Cornwallis Island. Allen Bay is frequented by schools of Arctic cod during the open water season which provide a substantial energetic source for several seabirds including glaucous gulls, black-legged kittiwakes, and northern fulmars (Matley et al. 2012c). Unlike thick-billed murre, these species are unable to make deep foraging dives and are restricted to capturing prey <3 m from the surface. Accordingly, they are reliant on Arctic cod swimming to the surface. It is unknown why billions of Arctic cod leave depths >200 m and place themselves at risk of predation from shallow-diving seabirds each summer. The most likely causes are to forage for prey at the surface (Moulton and Tarbox 1987; Matley et al. 2012a) and to seek out warmer temperatures (Benoit et al. 2008; Crawford et al. 2012). Current climate trends could significantly influence both scenarios and ultimately the vertical distribution of Arctic cod. For example, Arctic cod consume ice-associated organisms near the surface (Bradstreet and Cross 1982; Lønne and Gulliksen 1989), and as the ice melts these prey sink towards the bottom (Grainger 1991) but remain important components of the Arctic cod diet during summer (Matley et al. 2013). Therefore, the timing of ice break-up influences the vertical distribution of foraging Arctic cod. Similarly, Arctic cod that aggregate at the surface in warmer waters to optimize physiological conditions may alter vertical distributions as sea surface temperatures increase. For example, surface layers of the water column may exceed optimal thermal ranges (e.g. increased oxygen consumption adversely affects growth efficiency and weight loss; Hop and Graham 1995) causing Arctic cod to remain in deeper cooler layers. Both cases would impact seabird access to Arctic cod in Allen Bay and abroad.

The future success and persistence of seabird populations facing climate variability in the western and central Canadian Arctic will depend on their ability to adapt to change. Seabirds have no shortage of behavioural adaptations to forage efficiently and minimize potential impacts of environmental change. In Allen Bay, seabirds use a variety of methods to capture prey while reducing energetic costs.

Glaucous gulls display diverse foraging strategies including kleptoparasitism (food stealing) which enables them to consume up to eight times more Arctic cod than northern fulmars and black-legged kittiwakes (Matley et al. 2012c). By contrast, northern fulmars optimize energetic gains by associating with schools of Arctic cod (Matley et al. 2012a) and by gorging themselves when schools are near the surface (Matley et al. 2012c). Black-legged kittiwakes are able to supplement their restricted energetic capacity (Piatt et al. 2007; Welcker et al. 2010) by foraging effectively on both schooling and non-schooling Arctic cod (Matley et al. 2012c). Even common ravens (*Corvus corax*) supplement their diet by scavenging on discarded Arctic cod (Matley et al. 2012b). Physiological adaptations are also common in seabirds. For example, thick-billed murres are able to reallocate energetic stores in response to declining prey density (Piatt et al. 2007).

As sea-ice regimes continue to change in response to climate warming, changes in the physical environment and in the marine ecosystems of the Canadian Arctic will increasingly impact seabirds. Short-term benefits such as increased access to open water may in turn adversely affect breeding and foraging efficiency. How seabird populations will be affected is largely dependent on access to marine food sources. Perhaps new food sources will replace Arctic cod in the diet or maybe seabird breeding colonies will move to retain access to energy-rich prey. In any case, seabirds must be able to adapt to changing conditions.

4.6 Marine mammals

Marine mammals are more difficult to study and usually considered more at risk than their terrestrial counterparts (Mace and Purvis 2008). In particular, there is special concern for those adapted to living in Arctic marine ecosystems, being highly dependent on the presence and persistence of sea ice (Laidre et al. 2008). Loss of sea ice through climate change will likely affect all marine mammal populations in the Beaufort Sea, but the impacts are difficult to predict. The ice-adapted marine mammals that

regularly inhabit the Canadian Beaufort Sea include the beluga whale, a medium-sized toothed whale; the bowhead whale, a large baleen whale; the ringed seal, the smallest of the true seals; the bearded seal, a larger benthic-feeding seal; and the polar bear, a carnivorous bear that feeds on both seal species (Thiemann et al. 2008). Both whale species seasonally migrate from the Bering Sea to the Beaufort Sea region, spending the ice-free season throughout the southeastern Beaufort Sea, Amundsen Gulf (Richard et al. 2001; Harwood and Smith 2002). Beluga and bowhead whales have also been tracked into Viscount Melville Sound in summer (Richard et al. 2001; Quakenbush et al. 2013). In the Kitikmeot region, beluga, bowhead and narwhal whales migrate from their eastern wintering grounds to their summering grounds which include the Gulf of Boothia and Peel Sound (Department of Fisheries and Oceans 2002, 2007; COSEWIC 2009). The polar bear and its two main food sources, ringed and bearded seals, remain year-round within the western and central Canadian Arctic area, although seasonal migration by certain age groups occurs (Harwood et al. 2012a). These three species depend on sea ice for survival and reproduction.

The five marine mammal species found in the Beaufort Sea are important to Inuvialuit and Inuit who, to varying degrees, depend on marine mammal harvesting for subsistence. For example, 55% of participants from the Inuvialuit Settlement Region (ISR) are reported in the Inuit Health Survey (2007-2008) to eat beluga meat (Egeland et al. 2010a). Similarly, in Nunavut, 74% and 45% of participants in the Inuit Health Survey (2007-2008) reported eating ringed seal meat and beluga mattaaq, respectively (Egeland et al. 2010b).

In addition to the Arctic species, two sub-Arctic ice seals, the spotted seal (*Phoca largha*) and ribbon seal (*Phoca fasciata*) are found peripherally in the Beaufort area (Burns 1981), and three whale species, grey whale (*Eschrichtius robustus*), narwhal and killer whale (*Orcinus orca*), occur occasionally in the region (Harwood and Smith 2002). There are numerous data gaps in basic information about western and central Canadian Arctic species, making

it difficult to assess status and trends related to climate change. Greater knowledge of population sizes, densities, and distributions are necessary to understand the relationships with predictions for sea-ice loss and climate change.

As major consumers of zooplankton and fish (in particular Arctic cod), marine mammals strongly influence the structure and function of marine ecosystems (Bowen 1997), and provide important cultural and socio-economic value to local people (Harwood and Smith 2002). The known or predicted accelerated changes in sea ice, temperature (Chapter 2), biodiversity (this chapter), and human activity (Chapters 6-9) underscore the importance of understanding marine mammals and their habitats in the western and central Canadian Arctic to inform management and conservation.

4.6.1 Whales

Beluga whales

The beluga whale is the most common whale in the Beaufort Sea (Bockstoce and Botkin 1983; Harwood and Smith 2002) and Inuvialuit have hunted belugas for over 500 years (McGhee 1970; Byers and Roberts 1995). For the past two decades, communities in the ISR have participated in marine mammal research and monitoring efforts. These programs are harvest-based, and key projects have focussed on beluga harvests in the Mackenzie Estuary since 1980, and ringed seal harvests in Ulukhaktok, NT (formerly Holman, NT) since 1992. Both projects have focussed on the consistent extensive sampling and measuring of specimens taken in the subsistence harvests.

The number of beluga whale landing in the Mackenzie Estuary has averaged 90 whales annually, and consists mainly of adult males which are selected for by the hunters. The harvest is managed by the Fisheries Joint Management Committee (FJMC) under the Beaufort Sea Beluga Management Plan, available at www.fjmc.ca. The annual average take of beluga appears to be declining by about 10 beluga per decade, which is thought to reflect a reduction



GRETCHEN FREUND



JEFF HIGDON



GRETCHEN FREUND

Beluga whales (top), bowhead whale (middle), and killer whales (bottom).

in the number of Inuvialuit that are actively hunting and consuming beluga products, not a change in the size of the stock. The Beaufort Sea beluga population is considered to be stable or increasing and is estimated to number at least 40,000 animals (Department of Fisheries and Oceans 2002; COSEWIC 2004). Results of the 2007-2009 offshore aerial surveys for belugas in the Beaufort Sea indicated there were more than three times the amount of surfaced whales in late August compared to survey results in this area and season during 1982 and 1984-1985 (Harwood and Kingsley 2013). Although a rise in beluga population may explain part of this observation, a more plausible explanation could be that either (1) a decline in industrial activity in the offshore Beaufort Sea since the 1980s has made the area more attractive to belugas, (2) climate change has altered the marine ecosystem to the extent that belugas could be foraging a greater distance and/or a longer time period for prey in the offshore region, or (3) both scenarios have occurred (Harwood and Kingsley 2013).

The main finding of the beluga harvest community-based monitoring study, which has possible links to climate-induced changes in the ecosystem, is that there appeared to be a slight trend toward decreased growth rates/body condition in recent years. Further analysis of these data is underway and targeted for primary publication. Sampling for contaminants and disease are undertaken at one of the beluga monitoring locations, Hendrickson Island, where a technical, multi-disciplinary study of beluga health has been continually underway annually since 2000.

Habitat use analyses of satellite tracking data collected during the summer and fall revealed belugas sexually segregate in the Beaufort Sea and Amundsen Gulf (Loseto et al. 2006). The largest males selected heavy sea ice concentration habitats over deeper waters in the Canada Basin and smaller males and females with calves preferentially used open water habitats near the shoreline. Asselin et al. (2011) used a historical dataset to examine the spring distribution of belugas in the Beaufort Sea. Through five years of surveys (1975-1979), belugas consistently selected areas with heavy ice concentrations (80 to 100%) and 200-500

m water depths in spring (Asselin et al. 2011). Only during the lightest ice concentration year of the study (1975) did beluga select fast-ice edges (Asselin et al. 2011). Prey distributions are believed to play a role in the routing of beluga spring migrations, in particular, the availability of Arctic cod (Asselin et al. 2011). Arctic cod has been identified as the main prey of belugas in various Arctic locations (Kleinenberg et al. 1964; Dahl et al. 2000), including the eastern Beaufort Sea in spring-summer (Loseto et al. 2009). Arctic cod are often associated with sea ice (Sekerak and Richardson 1978), particularly within or just under the sea ice (Bradstreet 1982; Gradinger and Bluhm 2004), and belugas have morphological adaptations, including the ability to purse their lips to suction-feed, which would enable them to capture cod from the under surface of the sea ice (Kane and Marshall 2009). Large aggregations of Arctic cod were detected by Geoffroy et al. (2011) in the Amundsen Gulf in ice-covered waters and at depths greater than 220 m from December 2007 to April 2008 (see section 4.3). The distribution of these Arctic cod aggregations likely overlaps with the areas selected by beluga during spring as reported by Asselin et al. (2011), although the two studies were conducted several decades apart.

Bowhead whales

The Western Arctic bowhead whale stock was reduced considerably by commercial whaling from the mid-1800s to early 1900s (Bockstoe and Botkin 1983; Harwood and Smith 2002) from ca. 10,000 to 23,000 down to between 1,000 and 3,000 (Allen and Angliss 2011). The stock has subsequently recovered, with the 2001 estimate indicating at least 10,000 whales in the population (George et al. 2004). Whales from the East Canada – West Greenland stock, which summer partly in the eastern Kitikmeot region (specifically the Prince Regent Inlet and Gulf of Boothia), number at least 6000 (COSEWIC 2009); additionally, traditional knowledge indicates that whales from this population have largely increased over the last few decades (NWMB 2000). Despite the growth of the bowhead whale population, they are sensitive to potential impacts from climate change, such as changes in

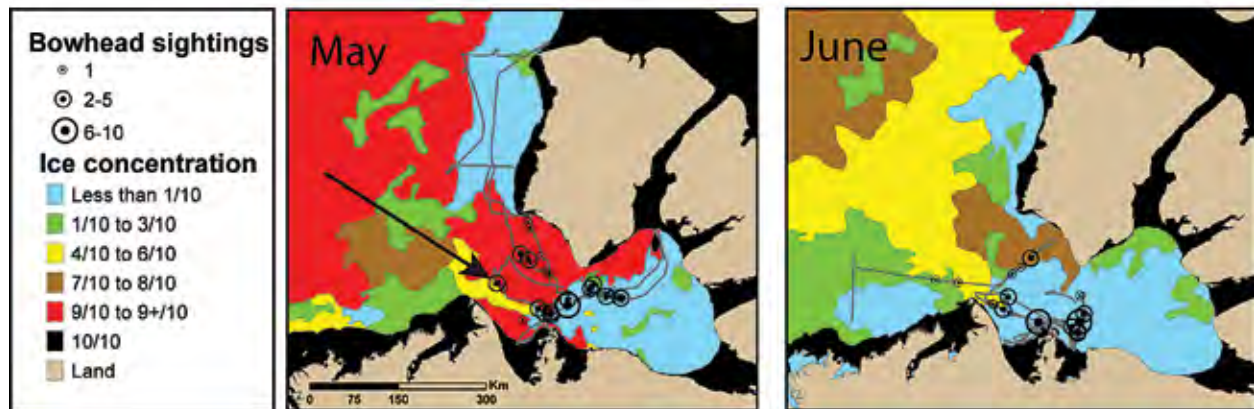


FIGURE 11. May 2008 (left) and June 2008 (right) bowhead sightings from the CCGS *Amundsen* and ice conditions for May 19, 2008 (right) and June 16, 2008 (left) [Canadian Ice Service, available at <http://ice-glaces.ec.gc.ca>]. The grey line represents the ship track and the arrow indicates the location of the first bowhead sighting in spring on 7 May 2008.

prey quality or quantity. The bowhead was identified by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) as a species of “Special Concern” (COSEWIC 2009).

Each summer, bowhead whales from the Western Arctic population aggregate in the southeastern Beaufort Sea, where they feed mainly from early August through late September or early October. They utilize several different areas for feeding, moving amongst these locations to some extent over the course of the summer (Walkusz et al. 2012; Quakenbush et al. 2013). Sightings of bowheads in the southeastern Beaufort Sea during the International Polar Year Circumpolar Flaw Lead Study in spring-summer 2008 were in general accordance with historical reports of their arrival in early to mid-May (Braham et al. 1980) but were noted as arriving earlier than in one case reported 30 years ago (mid to late May; Fraker 1979) (Figure 11). Up to 50% of the population may use the Canadian Beaufort Sea at any one time (Harwood et al. 2010), and of those in Canadian waters, the majority tends to feed on the continental shelf offshore the Tuktoyaktuk Peninsula in waters 20-50 m deep. Availability of suitable zooplankton densities in summer is important for bowheads to meet their annual energy requirements. Climate change may impact the quality and quantity of available pelagic prey needed by

bowhead whales. The expected/observed increase in zooplankton (section 4.2) may explain the apparent increase in the number of bowheads using the Canadian Beaufort Sea compared with the 1980s. The longer-term impact and role of ecosystem changes on bowheads is difficult to predict and quantify (Laidre et al. 2008).

The beluga and bowhead feeding activity observed at the Franklin Bay ice edge (Asselin et al. 2012) indicates the importance of the circumpolar flaw lead habitat to marine mammals as they return to the Amundsen Gulf in spring. Ice-edge phytoplankton blooms start the summer season of biological production (Perrette et al. 2011). Increases in phytoplankton production lead to increases in food availability to higher trophic levels including whales (Croll et al. 2005). Thus, in the early spring of years with low ice coverage, belugas and bowheads may feed more at fast-ice edges that dependably provide concentrations of prey (Asselin et al. 2012).

Killer whales

Killer whale sightings are rare and widely distributed throughout the Beaufort Sea region, ranging from Ulukhaktok, NT in the East to Herschel Island, YT (and further on into Alaska) in the West, and are most common in

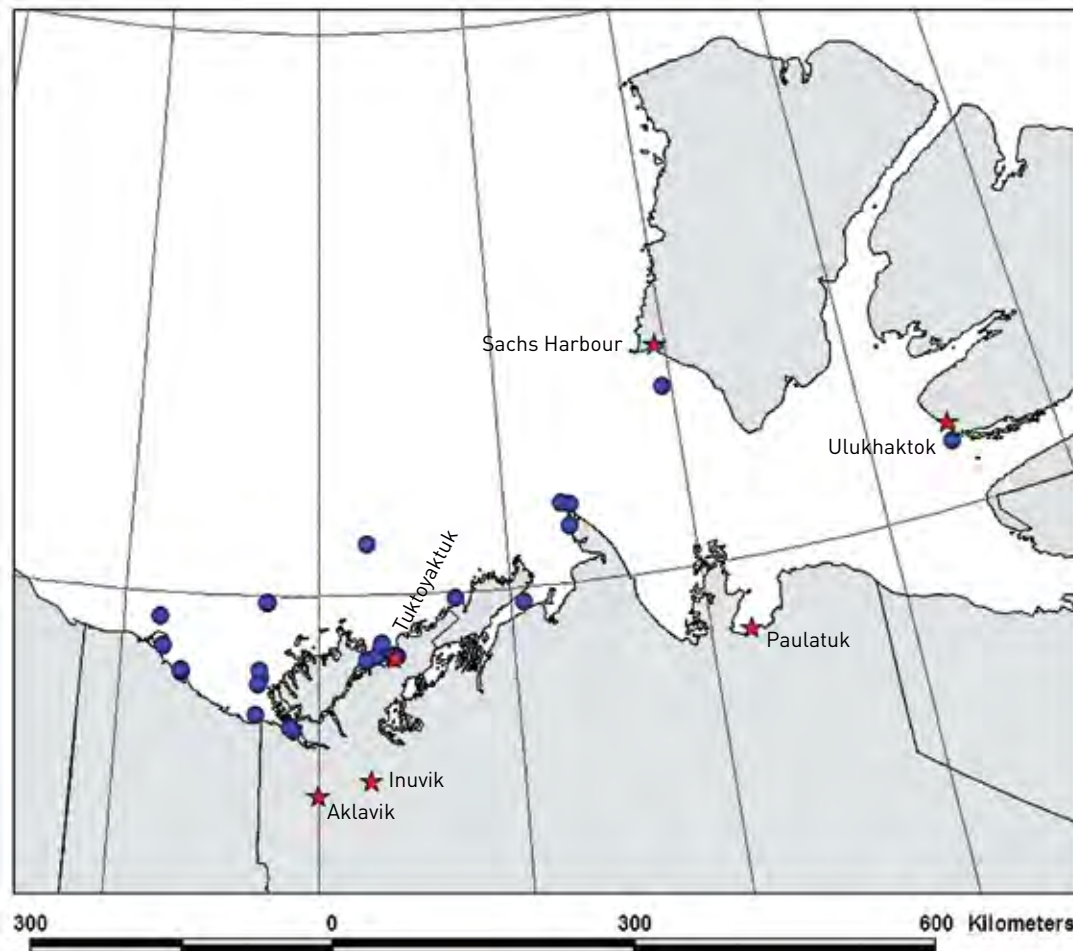


FIGURE 12. Approximate locations of 30 killer whale observations (blue circles) reported for the Canadian Beaufort Sea. Locations of Inuvialuit communities are shown as red stars.

the Mackenzie Delta area (Higdon et al. 2012) (Figure 12). Killer whales do not appear to make regular movements into the Canadian Beaufort and thus COSEWIC (2008) considers sightings in this region to be out of their typical range, and likely originating from the Bering Sea population (Dahlheim 1997; Baird 2001). However, killer whales have been observed in the eastern Kitikmeot region, and some Inuit are concerned about the repercussions of competition between these whales with beluga and bowhead whales (NWMB 2000).

4.6.2 Seals

Harwood et al. (2012b) examined the relationship between ringed seal body condition (fatness) and reproduction, and spring sea-ice conditions in prime ringed seal habitat in Canada's western Arctic during 1992-2011. Since 1970, ice conditions in east Amundsen Gulf and west Prince Albert Sound have shown only a slight trend toward earlier ice clearance (break-up) in spring (3-7 days per decade), and no trend toward later freeze up or increased variability in timing of spring ice clearance. A subsistence

harvest-based sample of 2281 ringed seals was obtained during 1992-2011 from a traditional hunting camp located in east Amundsen Gulf. Results showed there was (1) a temporal, statistically significant trend of decreasing mean annual body condition of ringed seals, both in adults and subadults, over the last two decades of study, and (2) a negative correlation between mean annual body condition of adults and subadults and timing of fast ice clearance in spring. Failure to ovulate (necessary for pregnancy) was obvious in the most extreme late ice clearance year, 2005, when only 30% of the mature adult females sampled ovulated. This came at a time when seal body condition indices and percent pups in the harvest were among the lowest annual values, and when spring ice clearance was 38 days later than the 1992-2011 average. While the seal population appears to have recovered from natural and extreme-year fluctuations over four decades of study, the possible magnified effect of several consecutive extreme ice years, compounded by the simultaneous occurrence of the temporal decline in seal body condition, all in the context of a changing climate, is of particular concern.

While current climate change models predict an increase in pelagic productivity, they also predict a decrease in benthic productivity, which could in turn affect bearded seals. This species is the main benthic-feeding marine mammal species in the Beaufort Sea. The bearded seal, more difficult to study because harvested specimens are rarely available, is one of the Beaufort species most likely to be impacted by climate change, yet little is known of its life history parameters, prey and habitat preferences.

4.6.3 Polar bear

Polar bears in the Beaufort Sea region have demonstrated shifts in summer and fall distribution in recent decades. As sea ice recedes or breaks up earlier, more polar bears are arriving on land earlier, staying for longer periods, and appearing in areas they had not previously used (Gleason and Rode 2009). These changes in distribution and possible abundance have been attributed to sea-ice loss and have

been documented in the Beaufort Sea where polar bear denning locations have shifted in some regions in response to changing ice conditions, with more dens appearing on shore (Fischbach et al. 2007).

The status of the polar bear population in the north Beaufort Sea suggests stability in terms of ecosystem productivity and sea ice in the north Beaufort Sea/Amundsen Gulf region (Stirling et al. 2011). Ice availability and conditions have remained relatively suitable (or having not reached some lower threshold yet) for north Beaufort Sea polar bears feeding largely on seals in summer and fall (Stirling et al. 2011). This was not the case for the south Beaufort Sea bear population (Stirling et al. 2008), which has fluctuated, likely as a result of changes in sea-ice coverage and the concomitant availability of seals. Specifically, Stirling et al. (2008), based on findings of cannibalized and starved bears in the south Beaufort Sea, found that polar bears were nutritionally stressed from 2004 through 2006. One possible explanation was a decadal-scale downturn in seal productivity (Stirling et al. 2008), which was indeed apparent in our Ulukhaktok seal monitoring study (Harwood et al. 2012b). Inuvialuit traditional knowledge holders consider the abundance and the physical condition of polar bears across the Canadian Beaufort Sea region to have remained stable over the years; however, (1) changing ice and environmental conditions are making it difficult to track bear movements, and (2) bears today are not as fat as they were before the mid-1980s (Joint Secretariat 2015). A comprehensive study by York (2014) noted that conflicting perspectives on polar bear population estimates between traditional knowledge holders and scientists appears to stem from unreliable sampling methodologies (e.g. under/overestimating populations) used by scientists. York (2014) further advocates the reliance of traditional knowledge of polar bear populations as an accurate and reliable measure with which to compare scientific results. With that said, the enhanced knowledge sharing of both scientific and traditional knowledge is needed to benefit resource management regionally and across the nation.



ANDRÉ ROCHON/ARCTICNET

Traditional ecological knowledge (TEK) on polar bear

The hunting of polar bear is an activity closely tied to Inuit identity. Polar bear meat is a delicacy. Skins used to be shared for clothing, bedding and tools, but in more modern times the skins have become a source of cash revenue, which can either be shared with extended families or help offset the cost of the hunt (Keith 2005).

A recent report by the Joint Secretariat (2015) in the ISR draws upon interviews from 72 traditional knowledge holders from all Inuvialuit communities plus follow-up workshops. Summarizing a wealth of traditional knowledge of polar bears, sea ice and Inuvialuit hunting of polar bears, the report is an impressive contribution towards furthering the management and research of polar bears in the Canadian Beaufort Sea region. While some of the highlights of this report have been referenced in this chapter, the main take-away message is that ice conditions, climate change effects and polar bear behaviour are complexly intertwined. While sea ice is important to polar bear abundance, distribution and condition, changes in annual sea ice conditions do not dictate the maintenance of polar bear habitat or survival (Joint Secretariat 2015).

Ideal ice conditions for polar bears to hunt seals include pressure ridges and open leads (Keith 2005; Slavik and Wildlife Management Advisory Council 2009). First year ice appears to be an ideal hunting habitat for polar bear relative to multi-year ice as it is thinner and characterized by pressure ridges, allowing seals to make their breathing holes.

Inuvialuit hunters report no longer seeing multi-year ice (Slavik and Wildlife Management Advisory Council 2009; Joint Secretariat 2015); hunters in Gjoa Haven also report a decrease in multi-year ice in addition to fewer and smaller icebergs since the 1970s and 1980s (Keith 2005). While multi-year ice remains off the west coast of Banks Island, it is no longer as close to shore (Slavik 2013). Inuvialuit are quick to point out that although multi-year ice is disappearing as a result of climate change, annual sea ice will still be available for polar bears (Canadian Wildlife Services 2010; Slavik 2013; Joint Secretariat 2015). Canadian Wildlife Services (2010) summarized Olokhoktokmiut comments as: “*Polar bears don’t use multi-year ice because they cannot find seals there. They are found more frequently around annual ice. Annual ice is rough; with more pressure ridges and areas of open water; that is where seals are found*”. While this is generally agreed upon, hunters from Sachs Harbour have also seen bears on the multi-year ice pack west of Banks Island, and hunters encourage population surveys in this area (Slavik 2013). Inuvialuit knowledge suggests that large males prefer to stay out on the pack ice, whereas juveniles as well as females and cubs usually remain close to shore and on land-fast ice (Slavik and Wildlife Management Advisory Council 2009).

Inuvialuit and Kitikmeot Inuit communities are observing impacts of climate change in the western and central Canadian Arctic. Wind and currents are key natural drivers that shape polar bear habitat by opening leads and causing pile-ups (Hart and Amos 2004; Slavik and Wildlife Management Advisory Council 2009). People from all coastal Inuvialuit communities have either noticed a decline in the number and the size of pressure ridges, which is attributed to thinner ice and increased ice movement, or that these ridges no longer form predictably in the same areas each year (Reidlinger 2001; Slavik and Wildlife Management Advisory Council 2009; Canadian Wildlife Services 2010; Joint Secretariat 2015). Some hunters have observed a change in direction of prevailing winds (Slavik and Wildlife Management Advisory Council 2009; Slavik 2013; Joint Secretariat 2015). According to recent observations, there has been a lot more open water in the last few

years, with the exception of 2008-09 (Canadian Wildlife Services 2010; Joint Secretariat 2015). For example, in the vicinity of Gjoa Haven, sea ice cleared in August in the 1950s, but in the 1980s and 1990s it has typically cleared at least a month earlier (Keith 2005). Changing ice conditions attributed to climate change include a decrease in the thickness and strength of ice in some areas, making it more difficult to predict the safety of the ice and therefore limiting the range of search effort and polar bear harvesting (Keith 2005; Slavik and Wildlife Management Advisory Council 2009; Slavik 2013; Joint Secretariat 2015). Polar bears also depend on deep snow for denning (November-February), but local observations in Gjoa Haven indicate that snow is arriving later and melting earlier than in the past, and that there is also less snow than there used to be (Keith 2005). Inuvialuit hunters have noticed changing wind and snow conditions also, but they have not necessarily observed any differences in the number of maternity dens (Joint Secretariat 2015).

Polar bear movements are dictated largely by locating migratory seal populations and can cause polar bear numbers in certain areas to fluctuate annually as they follow their food (Slavik and Wildlife Management Advisory Council 2009; Slavik 2013): “*Where the seals are, that’s where the polar bears are - and the polar bears know the country! They know where their food is, that’s why we don’t see them much anymore*” (F. Wolki, Slavik and Wildlife Management Advisory Council 2009). Inuvialuit believe that polar bears are adjusting their range further north and further out on the multi-year ice in response to changes in ice conditions and distribution of seals related to climate change (Slavik and Wildlife Management Advisory Council 2009; Canadian Wildlife Services 2010). Moreover, they recently observed that the condition and abundance of seals are being impacted by climate change, as relatively few and skinny seals have been reported in recent years (Reidlinger 2001; Slavik 2013).

Several threats to polar bears and their habitat have been identified through traditional and community knowledge. The most serious and immediate threats to polar bears are the cumulative effects of climate change on sea ice and the Arctic ecosystem. Offshore oil and gas exploration and

development is an important threat and can be compounded by climate change. Marine traffic such as ice-breakers, submarines, cargo ships, and cruise ships could travel through open leads, preventing the leads from re-freezing properly, and hence contribute to the decline in multi-year ice (Slavik and Wildlife Management Advisory Council 2009; Canadian Wildlife Services 2010). As polar bears are a sensitive species with excellent senses, Inuvialuit believe that disturbances from increased development (sound, smoke, etc.) could impact their migrations and behavior (Berger 1976; Slavik and Wildlife Management Advisory Council 2009). Inuit in Gjoa Haven consider the decrease in snow and ice to be partly associated with the decline in the polar bear population in the Kitikmeot region, but other factors include human activity (aircraft, snowmobiling, erecting new infrastructure), and selective hunting of mature males (Keith 2005).

4.6.4 Anticipated impacts of climate change and other stressors on marine mammal populations

As large, wide-ranging species, belugas, bowheads, ringed seals and bearded seals can have important spatial and temporal trophic impacts related to the Arctic marine ecosystem. Climate change is expected to affect these whales and seals by altering their ecosystem and habitat. As a result of climate-related changes to the ecosystem, prey quality and quantity may be affected and this in turn could impact marine mammal migration routes, patterns of habitat use, body condition, fitness and ultimately reproduction. As a major predator, 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 belugas and bowheads may result in distributional changes of prey and changes to the Beaufort Sea marine food web.

Ice-dependent marine mammals, such as polar bears and some seals, are possibly threatened by reductions in duration of the sea-ice season and in the spatial extent of

summer ice. The Beaufort Sea marine mammal populations may be at risk of decline over the next few decades. A coordinated marine mammal monitoring plan needs to be developed and implemented across a coordinated spatial and temporal pattern.

The diverse marine mammal research projects in the eastern Beaufort Sea have contributed to a baseline of information on their respective distributions and habitat use. A better understanding of beluga, bowhead, ringed seal and bearded seal habitat use can inform management, assist with effective mitigation of the impacts of human activity and help Northerners adapt to a changing Arctic. As belugas and bowheads migrate into seasonally ice-covered regions in the spring, the changes in sea ice associated with climate change will likely impact their migration and distribution and, in turn, their foraging success. By ensuring continuation of community-based monitoring programs, we can further the current state of knowledge on Arctic marine mammals into the future. Our understanding of the direct and indirect effects of climate change and other stressors on Arctic marine mammal ecosystems is in its infancy and will require a concerted effort to improve.

Increasing disturbance to marine mammals will likely occur with oil/gas and mining industries. In the Beaufort Sea region, exploration, development, and production phases of the hydrocarbon industry may cause displacement of marine mammals from important feeding habitat, changes to their underwater acoustic environment, impact calving and migratory habitats, and result in direct mortality due to oil spills or contamination. The risks of population declines for marine mammals can be addressed, and perhaps mitigated, through rigorous environmental assessments, controlling the timing, intensity and type of exploration and development activities, and dedicated work with local communities to ensure local harvests are sustainable. Future mining development in the western and central Canadian Arctic could impact marine mammals through increased shipping and activity in coastal zones, and increase the potential for contamination of run-off. Knowledge on how to assess and predict impacts of not only one development

but the cumulative impacts of numerous developments in the region is required. Also, managers need to understand the multiple scales of potential impacts over space and time as well as the use of novel scientific and traditional knowledge approaches to reduce the potential for negative impacts on marine mammals.

Impact of development on marine mammals

Industrial development in the Beaufort Sea impacts marine mammals primarily by increasing underwater noise, increasing the risk of collision with vessels, increasing the risk of chemical contamination, and by degrading their habitat.

Noise

Several activities associated with industrial development (shipping, dredging, construction, seismic survey airguns, sonar and aircraft) emit noise that disturbs marine mammals (Richardson et al. 1998). Noise differs in its energy level at the source; louder noises are more likely to cause physiological damage to marine mammals than quieter noises. Noise varies in its frequency band (i.e. pitch). Low-frequency noise travels longer distances underwater than high-frequency noise. Transient noise is brief in duration (e.g. airguns and sonars) while continuous noise persists over a long period of time (e.g. noise from shipping or drilling).

Marine mammals produce sound that they use to navigate, hunt and communicate. In addition, they use naturally occurring sounds to gain information about their environment. Thus, industrial noise affects marine mammals in several different ways. Noise can mask important environmental sounds and communication calls, and as a result, navigation and intra-specific communication can be compromised or made impossible (Clark et al. 2009). Noise can disrupt important behaviours of marine mammals (e.g. feeding, breeding, resting, migration; Richardson et al. 1998) and, as a result, change their energy budget. Noise can change the habitat of marine mammals by displacement of potential

prey and can cause marine mammals to leave a region (Richardson et al. 1998). Finally, loud noise can also cause temporary or permanent hearing loss (Finneran et al. 2002).

The impact of noise from oil and gas exploration on bowhead whales has been examined in the Bering, Chukchi, and Beaufort seas. In general, bowhead whales avoid areas with high industrial noise levels (for a review see Gordon et al. 2003). Moreover, when industrial noises were played to bowhead whales during an experiment in the Beaufort Sea, they decreased their vocalisation rate, ceased feeding, and changed their surfacing and dive patterns (Richardson et al. 1990). Bowhead whales in the Alaskan Beaufort Sea, in the vicinity of seismic activity (41-415 km range), decreased their calling rate after airguns were fired (Blackwell et al. 2013). In the Canadian Beaufort Sea, they avoided areas with seismic noise louder than 160 dB (Richardson et al. 1986). Bowhead whales reacted to airplanes flying at less than 305 m above the water by changing their behaviour and swimming away (Richardson et al. 1985), as well as to helicopters flying at less than 150 m above the water (Patenaude et al. 2002).

Belugas are common in captivity and have been used as test-subjects to examine the different effects of noise. For example, the masking (i.e. drowning out) of beluga calls has been investigated with playback experiments (Johnson et al. 1989; Erbe and Farmer 1998; Erbe 2008). These studies showed that industrial noise can mask beluga communication calls and the extent of masking depends on the type of noise and its frequency band. Also, based on captive trials, there is a high probability that noises from seismic airguns can cause temporary hearing damage to belugas (Schlundt et al. 2000; Finneran et al. 2002).

The impact of noise on belugas in the Beaufort Sea has also been investigated through simulation studies (Erbe and Farmer 2000). Based on sound propagation models for an ice-breaker and the known hearing capacity of belugas, a model suggested that belugas within 35-78 km would hear the noise from the ice-breaker and could be disturbed by it (Erbe and Farmer 2000). Masking of beluga calls was

estimated to occur at 14-71 km from ice-breakers (Erbe and Farmer 2000). Lastly, temporary hearing damage was predicted if belugas stayed for more than 20 minutes within 1-4 km of the ice-breaker (Erbe and Farmer 2000).

The impact of industrial noise on pinnipeds has also been examined in the wild. In the Beaufort Sea, ringed and bearded seals avoided airgun noise that was 150 m away (Harris et al. 2001). In a study performed during the construction of Northstar Island in the Alaskan Beaufort Sea, industrial activities did not have a significant effect on the density of seals on landfast ice even within 1 km from the construction (Moulton et al. 2005).

Collisions with vessels

The bowhead whale is susceptible to vessel strike because it is a slow-swimmer and it swims at shallow depths (Krutzikowsky and Mate 2000). About 1% of bowhead whales that were harvested in the Bering, Chukchi, and Beaufort Seas between 1976 and 1992 had scars that resulted from collisions with vessels (George et al. 1994). Right whales are comparable to bowhead whales for their swimming speed and behaviour, and, per capita, they have been involved in the most vessel strikes among all whale species (Vanderlaan and Taggart 2007). Of 45 documented mortalities of right whales in the western North Atlantic Ocean between 1970 and 1999, 35% were attributed to vessel strike (Knowlton and Kraus 2001).

Oil spills

With increased shipping traffic, the chance of accidental oil spills as well as oil contamination through ballast water will increase, which has many Inuit concerned (e.g. NWMB 2000). Oil that comes into contact with whales through either skin exposure, inhalation, or ingestion can have serious negative impacts on whales by fouling baleen plates, damaging eyes and interfering with olfactory (i.e. sense of smell) cues (Geraci and St Aubin 1990). Moreover, if polar bears come into contact with oil, their fur may become less insulating (Hurst and Øritsland 1982; Derocher and Stirling

1991). The *Exxon Valdez* oil spill likely killed 41% of the killer whale population in southern Alaska (Matkin et al. 2008). Moreover, it has been estimated that the *Deepwater Horizon*/BP oil spill in the Gulf of Mexico led to the mortality of up to 5000 marine mammals (Williams et al. 2011).

Habitat degradation

Industrial activities can also affect marine mammals by degrading or reducing their habitat, and/or reducing the availability of space to move about and find their prey. Avoidance distances to industrial activities extrapolate to reduce the available area for marine mammals to conduct life processes (Morton and Symonds 2002). Many fish species rely on sound to communicate and mate, and thus, industrial noise could alter their mating success (Bass and Ladich 2008). In addition, fish have been documented to avoid noise (Slabbekoorn et al. 2010).

Water quality may be negatively affected as a result of ballast water and other chemical spillage. Marine mammals are the top predators of marine ecosystems and they are sensitive to the bioaccumulation of chemicals (Muir et al. 1999; Loseto et al. 2008b).

Traditional Knowledge

Local hunters near St. Lawrence Island, in the Bering Sea, have noticed that bowhead whales are sensitive to noise, and as a result, use sailboats when hunting the whales (Noongwook et al. 2007). In 2008, interviews with whaling captains based out of Wainwright, Alaska expressed concerns about the effect of oil and gas exploration on bowhead whales in the Chukchi Sea. Specifically, after seismic testing offshore in 1968, they reported that bowhead whales did not perform their yearly migration and passed Wainwright in the spring (Quakenbush and Huntington 2010).

Hunters from the villages of Sireniki, Novoe Chaplino, Yanrakinnot, and Uelen (Chukotka, Russia) recounted that belugas in the northern Beaufort Sea avoid big ships and areas where motors are operating on shore (Mymrin

and Huntington 1999). Hunters from the Alaskan villages Norton Bay, Buckland and Point Lay have also noticed shifts in the distribution of belugas that they attribute to noise from fishing vessels (Huntington 1999).

4.7 Contaminants in wildlife of the western Arctic

In the same manner that carbon and energy are transferred from microalgae to fish, marine mammals, birds and man via planktonic grazers, so too are human-made chemical contaminants that associate with lipids. Unlike carbon and energy, however, the concentrations of particular contaminants, especially organochlorines and methyl-mercury (MHg), are enhanced moving up to the top of the food web through biomagnification. Even though emissions of these contaminants have been addressed through international agreements (2004 Stockholm Convention on persistent organic pollutants (POPs); 2013 Minamata Convention on mercury), we must maintain vigilance in observing contaminant distributions in the Arctic ecosystem because not all regions will respond in the same way. Also, the dramatic change in climate now underway will alter the fate, transport, exposure pathways and vulnerabilities to the health of top predators that are most at risk (Macdonald et al. 2005; Stern et al. 2012). Most of the recent change in the Arctic can be directly linked to melting ice and thawing permafrost both of which alter contaminant pathways and ecosystem structure (e.g. Callaghan et al. 2004; Letcher et al. 2010). Recent research has shown that change in sea ice means change in wildlife exposure to organohalogen compounds (OHCs) (McKinney et al. 2009, 2010, 2012) and Hg (Gaden et al. 2009). Accordingly, contaminant research over the past decade has focused on OHCs and Hg because they are persistent, bioaccumulative and toxic (PBT), and because these chemicals present the greatest risk to Northerners who depend on aquatic food webs for much of their diet (e.g. AMAP 2010, 2011; Letcher et al. 2010). Chapter 3 (section 3.6) summarizes the sources and biological effects of persistent and bioaccumulative organohalogen contaminants as well as metals such as Hg.

4.7.1 Organohalogen Compounds

OHCs include industrial chemicals (e.g. polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs)) and pesticides (e.g. DDT, chlordane, toxaphene), which have been released in large quantities for at least the past 50 years. The present distribution of these chemicals is a result of historical release patterns and environmental processes, which have produced a variety of distributions and trends in environmental media. For example, HCH (hexachlorocyclohexane), which was largely phased out

by the 1990s, is dwindling toward clearance (Pućko et al. 2013), while PCBs and more recently introduced PBDEs are still found at high concentrations in the fatty tissues of top predators like polar bears and seals (Letcher et al. 2010). The ocean, ice and soils have the capacity to store large amounts of OHCs (and Hg), and therefore the replacement of multi-year pack ice by first-year ice promises to widely alter the entry pathways for these compounds into biological systems as mediated through melt ponds (Pućko et al. 2010a, b, 2011, 2012), and then accumulate into seals and bears via food web processes (e.g. Letcher et al. 2009;

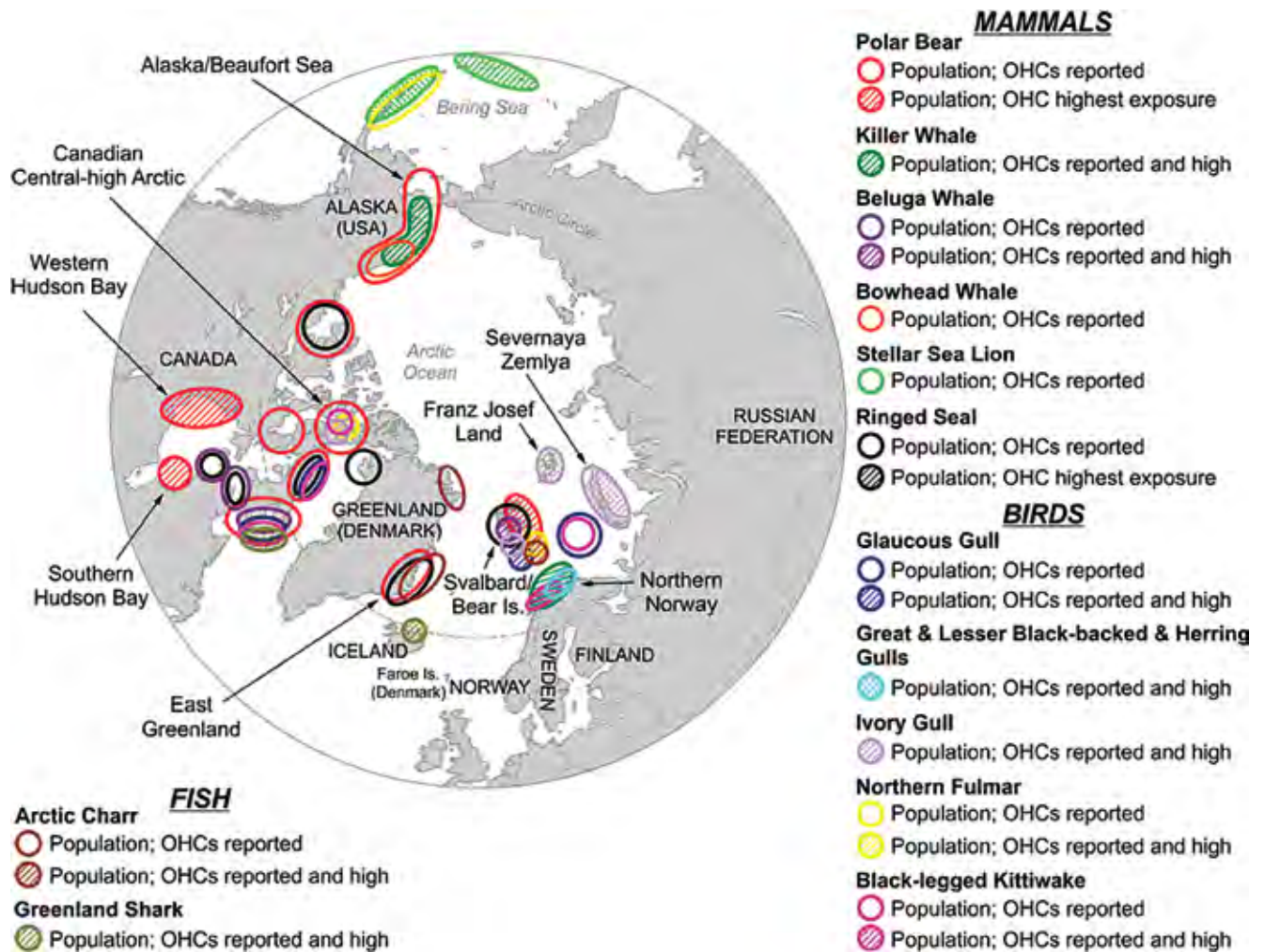


FIGURE 13. Arctic species and populations (“hotspots”) of concern based on “weight of evidence” of stress and effects related to OHC exposure and other environmental stressors. Adapted from Letcher et al. (2010).

McKinney et al. 2009, 2010). Transient/subarctic species often have higher tissue OHC levels likely due to higher expenditures of energy during migration and, possibly, the consumption of more contaminated prey in distant regions (McKinney et al. 2012).

The likelihood of OHCs affecting animal populations will increase with stress from climate variability or change that affects predation, pathogens or food availability and quality (Gill and Elliott 2003; Sih et al. 2004; Bustnes et al. 2006, 2008). Indeed, stress from OHCs may hinder an animal's capacity to adapt to such change (Jenssen 2006; Noel et al. 2014). Unfortunately, there remains little understanding of such interactions except that they will worsen as the Arctic warms (Boonstra 2004). The weight of evidence for POPs (e.g. Letcher et al. 2010) suggests that we ought to be especially vigilant for "hotspot" species and populations which include polar bears from Hudson Bay, East Greenland and Svalbard, as well as for killer whales from Alaska (western Arctic Ocean) (Figure 13). In general, and compared to the eastern Canadian Arctic, Greenland and Svalbard/Norway, there is a lack of OHC data for wildlife from the western and central Canadian Arctic. This is due to a number of factors including the accessibility and abundance of wildlife populations (e.g. polar bears) and the fact that OHC levels tend to be lower in environmental compartments in the western Arctic. However, the opening up of oil and gas and other development in the western Arctic (e.g. Beaufort Sea) signals that more contaminant monitoring should be prioritized in these areas.

Marine mammals

Based on polar bear data, it has generally been shown that the concentrations of Σ PCBs \approx Σ CHLs (chlordanes) \approx Σ PFSA (perfluorinated sulfonic acids, and essentially all perfluorooctane sulfonate (PFOS)) $>$ 1 ppm $>$ Σ DDTs (dichlorodiphenyltrichloroethane) $>$ Σ chlorobenzenes (CBzs) \approx Σ hexchlorocyclohexanes (HCHs) \approx Σ Toxaphenes \approx Σ PFCA (perfluorinated carboxylic acids) $>$ Σ PBDEs $>$ hexabromocyclododecane (HBCDD). Furthermore, metabolites of these OHCs (e.g. hydroxylated-PCBs (OH-PCBs))

may contribute concentrations comparable to Σ DDTs, Σ CBzs and Σ PCBs. The exceptions are for PBDE metabolites and pentachlorophenol, which have been reported at very low parts-per-billion wet weight or non-detectable concentrations, and limited to bears sampled in 1999-2001 in East Greenland, in 1997 in the Resolute Bay area of the Canadian high Arctic, and showing no western versus eastern Arctic trends (Sandau et al. 2000; Sandala et al. 2004; Gebbink et al. 2008).

Bowhead whales, belugas, harbour porpoises (*Phocoena phocoena*) and ringed seals are especially valuable sentinel species. Recent OHC data, most of which are for beluga whales and ringed seals from Hudson Strait in the Canadian Arctic, west and east Greenland, and Svalbard, exhibit tissue concentrations similar to those of polar bears (Σ PCB $>$ Σ CHL \approx Σ DDT \approx Σ PFSA $>$ Σ CBz \approx Σ HCH \approx Σ Toxaphene \approx Σ PFCA $>$ Σ PBDE $>$ HBCDD) (Letcher et al. 2010 and references therein).

More recently emerged contaminants like PFOS have been reported in polar bear and ringed seal livers at levels as high as Σ PCBs. In polar bears, PFOS levels have been reported to be higher in Hudson Bay animals relative to animals from the western Arctic (Beaufort Sea) (Butt et al. 2010; Houde et al. 2011). As reported for ringed seals from Baffin Bay and west and east Greenland, PFOS levels tend to be lower in the liver than for polar bears (Butt et al. 2010; Rigét et al. 2013). These sorts of perfluorinated compounds (PFSA and PFCA) released as their precursors enter the environment through many commercial uses such as stain repellents and fire-fighting foams (Tomy et al. 2009; Houde et al. 2011).

Marine and terrestrial birds

Birds exhibit varied diets, ecology, metabolism and fat reserves, leading to high variability in OHC distributions. Aquatic birds tend to have the highest exposures of OHCs ($>$ 1 ppm) and metabolic products (Letcher et al. 2010). As reviewed in Butt et al. (2010), for recently emerged OHCs, PFSA (PFOS) and PFCA have been reported in the livers of black guillemot (*Cephus grylle*) from east Greenland,

herring gulls (*Larus argentatus*) from northern Norway, thick-billed murres and northern fulmars from the Canadian central Arctic, and glaucous gulls from the eastern Canadian Arctic. In general, PFOS and PFCA temporal trends in thick-billed murre (1975, 1993, and 2004) and northern fulmar (1975, 1987, 1993, and 2003) liver samples from Prince Leopold Island (Lancaster Sound) in the Canadian Arctic showed increasing levels over the entire study period. Presently, little is known about the effects of OHCs on these birds (de Wit et al. 2004; Fisk et al. 2005; Letcher et al. 2010), thus requiring extrapolation from studies conducted elsewhere.

Marine and freshwater fish

OHCs and metabolites in fish are relatively low (Braune et al. 2005; de Wit et al. 2006), probably due to relatively short lives and/or low trophic positions. Where high contaminant levels have been found, PCBs usually dominate with lower levels of *p,p'*-DDT (de Wit et al. 2004; Evenset et al. 2005; reviewed in Letcher et al. 2010). There are hotspots, for example in Arctic char from Lake Ellasjøen, Bjørnøya (Bear Island) (Figure 13). Data on the effects of OHCs on Arctic fish are few (Letcher et al. 2010), possibly reflecting an unwarranted assumption that these animals are universally less at risk.

4.7.2 Mercury

Hg in tissues of top predators (e.g. polar bears, beluga whale, ringed seals, a few seabird species, and landlocked Arctic char) sometimes exceeds thresholds for effects (Dietz et al. 2013). Toothed whales appeared to be among the most vulnerable due to their high trophic position and high intake of protein (polar bears feed on fatty tissue that has trace levels of Hg).

Two factors contribute to the Arctic's vulnerability to Hg: the Arctic Ocean is a sink for Hg (Leitch et al. 2007; Andersson et al. 2008; Outridge et al. 2008; Douglas et al. 2012), and methylation of Hg occurs within the

Arctic's aquatic environments leading to biomagnification (Macdonald and Loseto 2010). MHg, the most toxic form of Hg, predominates in top predators due to its bioaccumulative and biomagnitative properties (e.g. see Loseto et al. 2008a; Macdonald and Loseto 2010; Stern et al. 2012).

Recent research has revealed that MHg is both formed (e.g. St. Louis et al. 2007; Lehnher et al. 2011; Wang et al. 2012) and destroyed (Lehnher et al. 2011) in the Arctic Ocean. This, together with varied food chains, leads to high variance in MHg exposure at the bottom of the food web (Stern and Macdonald 2005; Foster et al. 2012). Variation in foraging contributes further variance at the top of the food web (Loseto et al. 2008a, b; Gaden et al. 2009). The complexity of MHg formation along with food web processes means that climate change and variability may contribute to the wide variations in time and space observed for whales, seals, bears and birds (Stern and Macdonald 2005). Canada's western Arctic has exhibited the highest exposures of Hg in predators based on data originating from long monitoring partnerships between the local communities and Fisheries and Oceans Canada.

Marine mammals

The polar bear has some of the highest observed Hg concentrations in the Arctic (Dietz et al. 1989; Rigét et al. 2011; Dietz et al. 2013). Hg concentrations in Beaufort Sea polar bears are unusually high (Routti et al. 2011) (Figure 14), possibly due to local sources (river, atmosphere) and processes (methylation, biomagnification) (e.g. Leitch et al. 2007; Loseto et al. 2008a, b; Cardona-Marek et al. 2009; Gaden et al. 2009; Horton et al. 2009; St. Louis et al. 2011). Recent change in sea-ice climate for this region may also contribute to Hg cycling (Loseto et al. 2014, in press), especially given that MHg is a dynamic balance between local production (e.g. Wang et al. 2012) and destruction (e.g. Point et al. 2011).

Temporal trends and the effect of emission controls are of wide interest. Evidence suggests that Hg emissions have been declining globally since ~1980 and deposition has

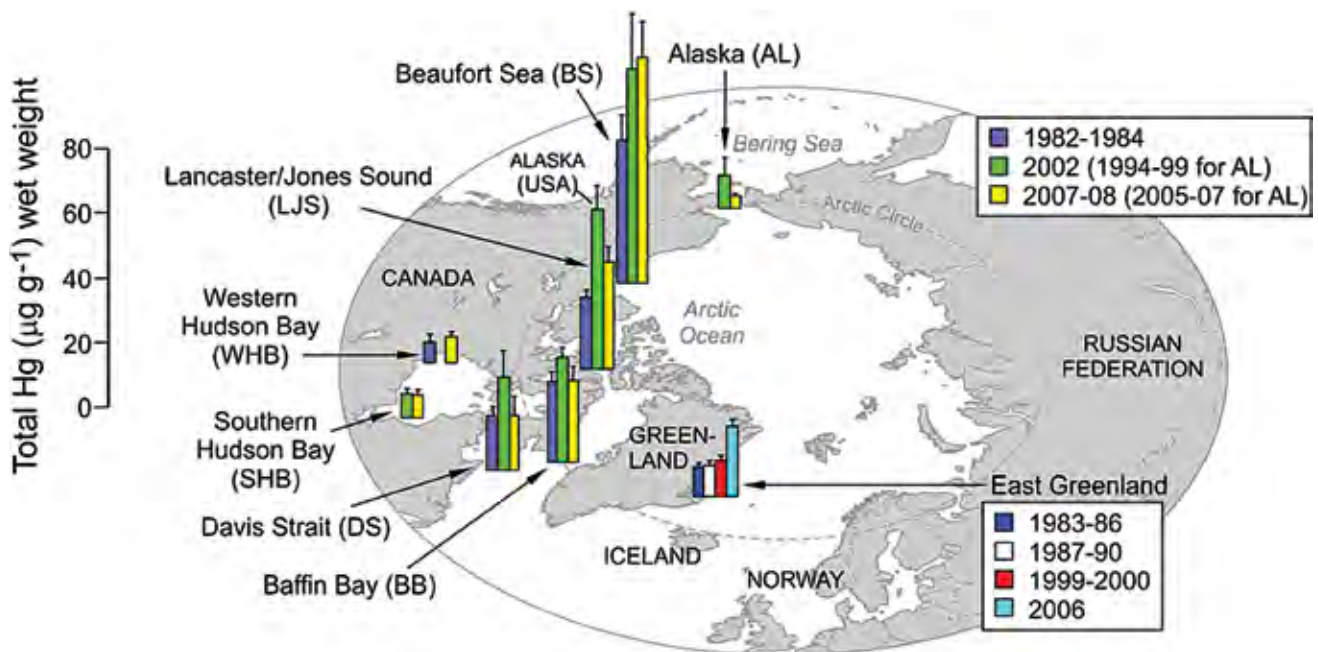


FIGURE 14. Concentrations ($\mu\text{g g}^{-1}$ ww; geometric mean \pm standard error) of THg in polar bear liver from Alaska in 1994 to 2007, Canada in 1982 to 2008, and East Greenland in 1983 to 2006. Adapted from Routti et al. (2011). AL: Alaska (Chukchi/Bering seas); BS: Beaufort Sea; LJS: Lancaster/Jones Sound; WHB: Western Hudson Bay; SHB: Southern Hudson Bay; DS: Davis Strait.

declined since \sim 1990 (Goodsite et al. 2013). THg in polar bear livers from the Beaufort Sea increased slightly between the 1980s and 2002 (Rush et al. 2008) with no change after that up to 2008 (Routti et al. 2011). The most recent data indicate that Chukchi and Canadian Arctic (excepting the Beaufort Sea) subpopulations' THg levels have declined relative to levels in 2002.

Due to the lower trophic level of bowhead whales that feed on zooplankton, Hg concentrations remain low (Dehn et al. 2006) and thus of minimum concern. Ringed seals in the western Arctic have not shown changes over many years of monitoring, yet a closer evaluation considering ice-free days and food availability demonstrated a link between feeding exposure and alteration in sea ice (Gaden et al. 2009).

Beluga whales, at a higher trophic level, demonstrated some of the highest Hg concentrations in the western Arctic (Lockhart et al. 2005). The western beluga population has

one of the largest home ranges, with males and females occupying different habitats during summer (Loseto et al. 2006). This segregation affects feeding ecology and energetic requirements thus spelling the potential for widely different Hg exposures over space and time (Loseto et al. 2008a; Loseto et al. 2009).

Hg concentrations in estuarine, pelagic and epibenthic food webs

Few studies have measured Hg in zooplankton and there are no published data on phytoplankton from the Beaufort Sea. The latter can be estimated from the Northwater Polynya where ice algae had Hg levels at \sim 0.015 mg g^{-1} dw ($n=1$) (Campbell et al. 2005). Copepods (e.g. *Calanus glacialis* and *C. hyperboreus*) and phytoplankton had lower Hg levels in the Mackenzie Estuary (0.025 mg g^{-1} dw) compared with offshore Beaufort Sea (0.032 mg g^{-1} dw) (Geynrikh 1986; Auel and Hagen 2002; Loseto

et al. 2008a). Levels of Hg in copepods from the Beaufort Sea vary seasonally and spatially (Stern and Macdonald 2005), but are similar to those of the Northwater Polynya (Campbell et al. 2005) and Lancaster Sound (Atwell et al. 1998).

Mercury in fish and predatory invertebrates vary between regions and within species. For example, Arctic cod collected beneath the ice in Amundsen Gulf and Franklin Bay in the spring averaged $0.37 \text{ mg THg g}^{-1} \text{ dw}$ compared to $0.16 \text{ mg THg g}^{-1} \text{ dw}$ in cod collected over the Beaufort Shelf (Loseto et al. 2008a). Concentrations in Arctic cod from the shelf region were low ($<0.2 \text{ mg THg g}^{-1} \text{ dw}$) (Loseto et al. 2008b) and similar to other fish collected nearby (e.g. rainbow smelt (*Osmerus mordax*), Pacific herring (*Clupea pallasii*), Arctic cisco (*Coregonus autumnalis*) and least cisco (*C. sardinella*)). This, together with biodilution during rapid growth (Kidd et al. 1999; Karimi et al. 2007) highlights the challenge of assigning the sources of variation among species and locations when assessing trends. Representative benthic species eaten by beluga had Hg levels ranging from $0.2 \text{ mg g}^{-1} \text{ dw}$ in flounders and shrimp to $0.5 \text{ mg g}^{-1} \text{ dw}$ in sculpins (Loseto et al. 2008b). Hg levels in sculpins ranged from $0.24 \text{ mg THg g}^{-1} \text{ dw}$ in Lancaster Sound to $0.34 \text{ mg g}^{-1} \text{ dw}$ in West Greenland (Atwell et al. 1998; Rig et et al. 2007).

Observations in the Beaufort Sea demonstrated that the increase of Hg up food webs reflects biomagnification of approximately ten times at each trophic level, implying that a small increase in bioavailable MHg at the bottom of the food web will drive a large change at the top (Loseto et al. 2008a; Douglas et al. 2012). Although differences in Hg uptake among shelf/estuarine, pelagic and benthic food webs may reflect trophic structure, species specific process or regional sources at the base of the food web (Loseto et al. 2008b), the high influx of Hg and MHg to the Mackenzie Delta (Leitch et al. 2007) apparently did not lead to high levels in the estuarine-shelf food web, and belugas feeding there had the lowest Hg levels (Loseto et al. 2008b). This does not negate the importance of the Mackenzie River as a source of Hg: rather, it emphasizes the importance

of determining pathways into the food web after the Hg reaches the estuary.

4.7.3 Conclusions

In the study of food web contamination, a major challenge is to link the effects/responses observed in wildlife to specific causative agents, such as exposure to bioaccumulative contaminants and their precursor and/or degradation products (top left boxes in Figure 15), and enhanced vulnerability due to environmental stress due to climate variability and change (right hand box in Figure 15). Many studies correlate tissue concentrations of contaminants and biomarkers, which provide a measure of the impacts of contamination on the health of the organism. Several factors potentially limit the value of such correlations: study site, season, time window during the life cycle, limited knowledge of life histories, and the representativeness of randomly-captured animals. The adverse effects of contaminants may be expressed as changes in animal performances, including impaired reproduction, altered response and stress responses (to infectious agents), but this remains to be established in Arctic wildlife and fish.

Climate change may dictate an animal's exposure to contaminants and may augment its vulnerability to such exposure. For example, western Hudson Bay polar bears were observed to exhibit nutritional stress due to change in sea ice climate (McKinney et al. 2009, 2010). In turn, several chlorinated and brominated OHC levels increased faster (e.g. ΣPBDE), or shifted from decreasing to increasing (i.e. ΣCHLs and ΣPCBs), relative to levels associated with unchanged diets. Trends associated with changes in diet can be projected to continue and expand in scale as temperatures rise and the multi-year pack ice diminishes (Johannessen et al. 2004).

There is a need to investigate more fully the interrelationships between climate change, contaminant pathways and vulnerabilities, to arrive at a robust weight of evidence in

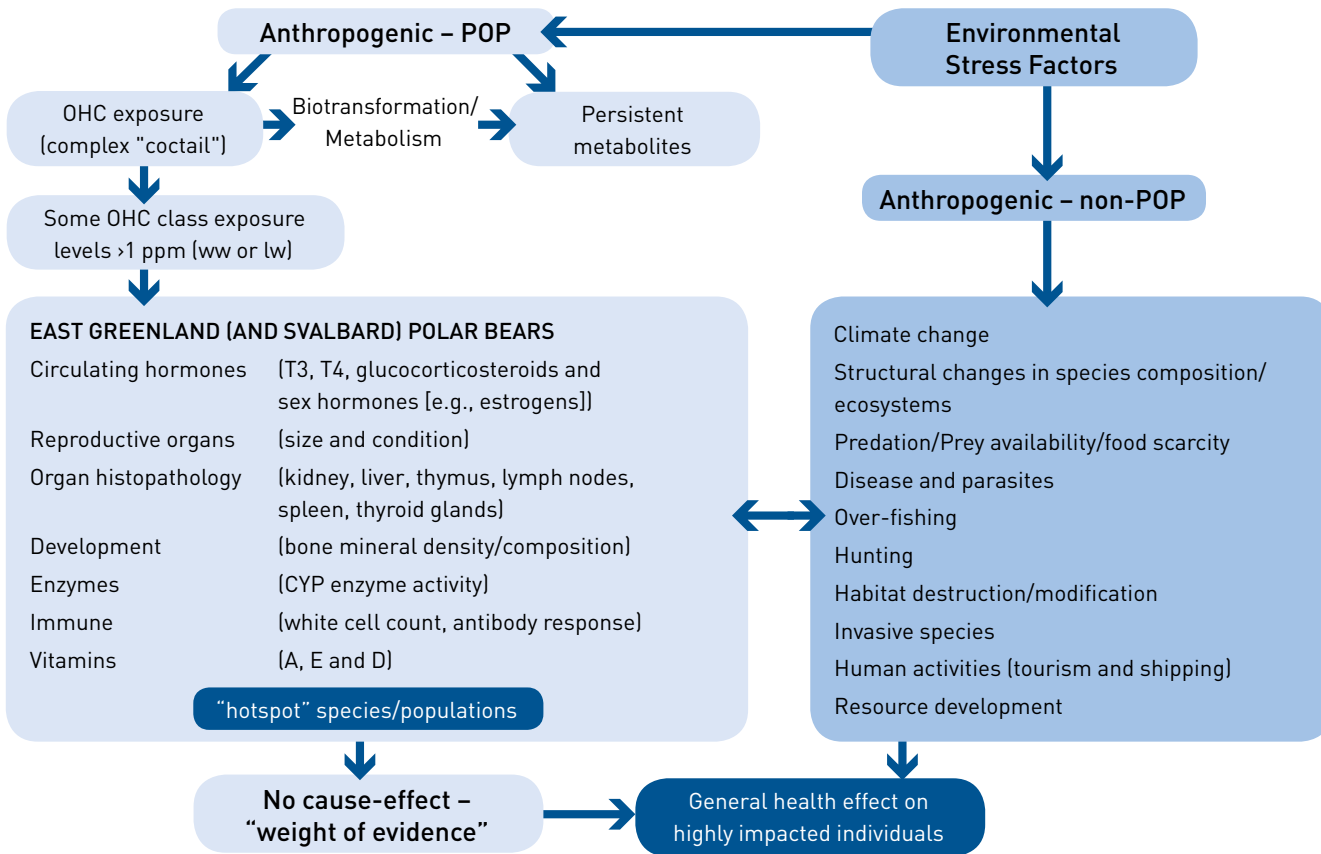


FIGURE 15. A schematic diagram showing the interaction between exposure to chemicals (top left), stress from climate change (right panel) and manifestation of effects (left panel). Adapted from Letcher et al. (2010).

determining which individuals/populations of the marine ecosystems are at risk, and why.

Recognizing that climate change and its cascading impacts on the ecosystem can alter trophic levels and thus exposure to contaminants (Figure 15), efforts must focus on characterizing both contaminant and climate change mediated contaminant effects. Contaminant-mediated effects data are lacking for vulnerable species (e.g. glaucous gull and polar bears) and for most species during periods of physiological sensitivity (e.g. growth period, reproductive and fasting periods).

There is insufficient basic ecological and physiological information for Arctic wildlife, which makes it difficult to assess the specific effects of contaminants or other anthropogenic stresses be they local or global (Letcher

et al. 2010). Basic information is required, for example, for baseline levels of hormones, vitamins, blood variables, immune function and other factors that might affect these (e.g. time of day, time of year, reproductive state, health status, fasting, etc.). Without such information it is impossible to infer whether such changes imply increased risk.

4.8 Conclusions and points for policy

4.8.1 Conclusions

Consistent with Inuvialuit expertise, recent scientific studies in the offshore Beaufort Sea and elsewhere in the western Canadian and US Arctic have confirmed the pivotal role of

sea ice in shaping Arctic marine ecosystems by dictating (1) the amount of light penetrating the surface layer of the ocean, and the upwelling of nutrients by wind from the deep layer to the surface layer; (2) the relative and absolute magnitude of ice algae and phytoplankton production; (3) the relative richness of pelagic and benthic ecosystems including their respective fish communities; (4) the ecology and abundance of key species such as the large copepods *Calanus glacialis*, the Arctic cod and several seabirds; (5) the abundance and health of resident ice-dependant seals and polar bears; (6) the migration patterns of, and the interactions among, migratory species such as the beluga, the bowhead whale and the killer whale; and (7) the cycling of waterborne and airborne contaminants and the exposure of marine organisms to these contaminants. In addition, the on-going reduction of the sea-ice cover and lengthening of the ice-free season contribute towards opening the region to industrial activities (e.g. oil exploration, shipping, tourism), which often have direct impacts on specific components of the marine ecosystems and the services they provide.

Lengthening of the ice-free season will shift the present Arctic environmental conditions toward sub-arctic conditions. Considering that observed changes often occur faster than model projections, it is reasonable to expect that the transformation of the present ecosystem of the Beaufort Sea into a more productive sub-arctic ecosystem should occur by the end of the century. However, although we know this transition is likely and can report on its first symptoms, we cannot anticipate with any certainty the pace at which it will unfold over the present century.

To summarize this chapter, the following inferences and tentative predictions can be made:

- (1) At this time, the marine ecosystems of the western Canadian Arctic are essentially intact. We are barely witnessing the very first symptoms of their expected shift towards sub-arctic boreal ecosystems in response to the on-going reduction of sea ice. The most convincing of these symptoms is an increase in the upwelling of nutrients that stimulates phytoplankton production, and the arrival of new species (e.g. salmon, Pacific sand lance). It must be emphasized however that, in the Bering Sea, a shift in sea-ice regime has resulted in a spectacular shift in the relative importance of pelagic and benthic ecosystems in less than 20 years (Grebmeier et al. 2006);
- (2) In the mid-term (2020-2049?), the progressive relaxation of extreme conditions (e.g. milder sea-ice regime, higher surface temperatures, localised enrichment of the surface layer by vertical mixing) will continue to stimulate increased phytoplankton production in the Beaufort Sea area, resulting in a greater abundance of pelagic animals, from copepods to fish, marine mammals and seabirds;
- (3) Simultaneously, reduced production of ice-algae and increased interception of sinking microalgae by pelagic grazers could stifle the vertical flux of food towards the bottom, resulting in a reduction of the abundance and diversity of bottom-dwelling invertebrates and fish, especially in offshore areas;
- (4) In the longer term (end of century?), we foresee the partial to near-complete replacement of the present fauna of resident Arctic specialists of the Beaufort Sea (e.g. Arctic cod, ice-seals, polar bear) by generalists from the North Pacific (e.g. Pacific sand lance, walleye pollock, king crab, new seabirds), with the persistence and likely expansion of less specialized migratory species (e.g. beluga, bowhead whale, killer whale, seabirds);
- (5) On the same time horizon, a general improvement of pelagic productivity and potential localised increases in some ecosystem services (e.g. traditional fisheries, mammal and bird populations, tourism) may develop where nutrient renewal occurs. It must be stressed however that, given the persistence of seasonal ice cover and low temperatures, there is no scientific basis for the expectation that rich fisheries will develop in the near future in the Beaufort Sea;
- (6) Offshore oil exploration leases in the Beaufort Sea overlap with the reproduction grounds and larval nursery areas of Arctic cod and other fish, as well as with the richest

benthic ecosystems and some marine mammal distribution areas and migration routes;

(7) Organohalogen contaminants (OHCs) and mercury (Hg) include persistent, bioaccumulative and toxic (PBT) compounds that are transferred from microalgae to fish, marine mammals, birds and man, in the same manner as carbon and energy, in the Arctic marine food web.

Unlike carbon and energy, the concentrations of particular PBT contaminants such as PCBs, PBDEs, PFOS and methyl-Hg (MHg) are enhanced toward the top of the Arctic marine food web through biomagnification.

Climate change stresses Arctic ecosystems, and can affect biotic exposure to contaminants and augments the vulnerability of species to the effects from such exposure.

Information is lacking on detailed interrelationships between climate change, contaminant pathways and exposure risks of individuals/populations of wildlife and fish. Generally, the higher the trophic level for a given species, the higher the vulnerability to PBT contaminants and adverse effects.

Data on the direct effects of PBTs on vulnerable species (e.g. glaucous gull and polar bears) are lacking. There is even greater uncertainty about the effects of PBTs on all species during periods of physiological sensitivity. Overall, there is insufficient basic ecological and physiological information for Arctic wildlife, which makes it difficult to assess the specific effects of contaminants or other anthropogenic stresses be they local or global.

Many studies rely on correlations between tissue concentrations of contaminants and response biomarkers to indicate cause and effect. However, confounding factors and other challenges mask connections between exposure and biological responses.

Adverse effects due to contaminants may potentially be observed as changes in animal performances, including

impaired reproduction, avoidance of predators and response to stress (e.g. infectious agents), but this remains to be established in Arctic wildlife and fish.

Even though emissions of these contaminants have been addressed through international agreements (expanded 2014 Stockholm Convention on POPs; 2013 Minimata Convention on mercury), we must maintain vigilance in observing contaminant distributions in Arctic wildlife and fish and ecosystems because not all regions will respond in the same way.

4.8.2 Recommendations

The above conclusions, inferences and tentative predictions translate into several recommendations for the management and stewardship of the marine ecosystems of the Canadian Western Arctic in a context of climate change and exploration for oil:

(1) The observed symptoms of the transformation of marine ecosystems in the ISR and the Kitikmeot region are expected to amplify in the near future. The monitoring of these ecosystems during the coming crucial decades must be maintained and intensified. It will be particularly important to measure (1) the annual variability and trends in the activity of the benthic ecosystem in relation to the amount and nature of microalgal production, (2) the abundance and migration of marine fishes including key species such as Arctic cod, (3) the invasion of the Beaufort Sea by new species, including seabirds, and (4) changes in the abundance, distribution and migrations of marine mammals;

(2) This monitoring of the marine ecosystems would greatly benefit from community-based observations and research. Furthermore, improved coordination of harvest effort and reporting could provide precious insight into fluctuations of the abundance, health and distribution of important species;

(3) There is an urgent need for an inventory and expansion of existing information on the marine ecosystems of the Kitikmeot region. A meeting of scientists and Inuit experts for

this region is needed to collate and synthesize existing data, to identify knowledge gaps, and to propose research avenues;

(4) Until we have a better understanding of the quantitative response of the benthic and pelagic ecosystems to sea-ice reduction, a precautionary approach that protects existing traditional fisheries must be used. The moratorium on commercial fisheries in the ISR should be expanded to the rest of the Canadian Arctic (including the Kitikmeot region);

(5) The risks of serious impacts on the benthic and pelagic ecosystems associated with oil exploration are real and must be taken into account to develop scenarios and models of oil dispersion. There is an urgent need to consolidate our scientific understanding of the impacts of an oil spill in ice-covered conditions – before any spill happens;

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Appendix A

Geographic distribution of marine fishes within the western and central Canadian Arctic

In the following table, numbers 1-6 (header) correspond to geographic sub-areas in Figure 2; occurrences for sub-areas 1 and 6 represent only those species actually present in the study area (i.e. are not reflective of total overall diversity for these sub-areas). Sub-areas 2-5 are inclusive. Table entries: ✓ = Confirmed record; ✦ = Not reported from the area, but occurrence is highly likely given presence from areas immediately adjacent; ✕ = Not reported to occur from the area. Occurrences within Canadian waters are based on Coad and Reist (2004), Lowdon et al. (2011), Majewski et al. (2006, 2009a,b, 2011, 2013); those for Alaska are from Mecklenberg et al. (2002, 2011) and Rand and Logerwell (2010). Species believed to be new to the area are not listed pending the confirmation of their identifications.

FAMILY	SCIENTIFIC NAME	COMMON NAME	1. ALASKAN BEAUFORT SEA	2. CANADIAN BEAUFORT SEA	3. AMUNDSEN GULF	4. CENTRAL ARCTIC ARCHIPELAGO	5. NORTHWEST ARCTIC ARCHIPELAGO	6. EASTERN CANADIAN ARCTIC
Agonidae (n=2)	<i>Aspidophoroides olrikii</i> ¹	Arctic alligatorfish ¹	✓	✓	✓	X	X	✓
	<i>Leptagonus decagonus</i>	Atlantic poacher	✓	✓	✓	X	X	✓
Ammodytidae (n=2)	<i>Ammodytes dubius</i>	Northern sand lance	X	✓	✓	X	X	✓
	<i>Ammodytes hexapterus</i>	Pacific sand lance	✓	✓	✓	X	X	✓
Anarhichadidae (n=2?)	<i>Anarhichas denticulatus</i> ²	Northern wolffish ²	✓	✓	✓	X	✓	✓
	<i>Anarhichas orientalis</i>	Bering wolffish	✓	✦	✓	X	X	X
Clupeidae (n=2)	<i>Clupea harengus</i>	Atlantic herring	X	X	X	✓	X	✓
	<i>Clupea pallasii</i>	Pacific herring	✓	✓	✓	✓	X	X
Cottidae (n=11)	<i>Arteidiellus scaber</i>	Hameçon	✓	✓	✓	✓	X	✓
	<i>Arteidiellus uncinatus</i>	Arctic hookear sculpin	X	✓	✓	X	X	✓
	<i>Gymnocanthus tricuspis</i>	Arctic staghorn sculpin	✓	✓	✓	✓	✓	✓
	<i>Icelus bicornis</i>	Twohorn sculpin	✓	✓	✓	✓	✓	✓
	<i>Icelus spatula</i>	Spatulate sculpin	✓	✓	✓	X	X	✓
	<i>Myoxocephalus quadricornis</i>	Fourhorn sculpin	✓	✓	✓	✓	✓	✓
	<i>Myoxocephalus scorpioides</i>	Arctic sculpin	✓	✓	✓	✓	✓	✓
	<i>Myoxocephalus scorpius</i>	Shorthorn sculpin	✓	✓	✓	✓	X	✓
	<i>Triglops murrayi</i>	Moustache sculpin	X	✓	✦?	X	X	✓
	<i>Triglops nybelini</i>	Bigeye sculpin	✓	✓	✓	X	X	✓
	<i>Triglops pingelii</i>	Ribbed sculpin	✓	✓	✓	✓	X	✓
Cyclopteridae (n=2)	<i>Eumicrotremus derjugini</i>	Leatherfin lumpsucker	✓	✓	✓	✓	✓	✓
	<i>Eumicrotremus spinosus</i> ³	Atlantic spiny lumpsucker ³	X	✓	✓	✓	✓	✓
Gadidae (n=6)	<i>Arctogadus glacialis</i> ⁴	Polar cod ^{4,5} Ice cod	✓	✓	✓	✓	✓	✓
	<i>Boreogadus saida</i> ⁵	Arctic cod ⁵	✓	✓	✓	✓	✓	✓
	<i>Eleginus gracilis</i>	Saffron cod	✓	✓	✓	✓	X	X
	<i>Gadus chalcogramma</i> ⁶	Walleye pollock ⁶	✓	✓	X	X	X	X
	<i>Gadus morhua</i>	Atlantic cod	X	X	X	✓	X	✓
	<i>Gadus ogac</i>	Greenland cod	✓	✓	✓	✓	X	✓

FAMILY	SCIENTIFIC NAME	COMMON NAME	1. ALASKAN BEAUFORT SEA	2. CANADIAN BEAUFORT SEA	3. AMUNDSEN GULF	4. CENTRAL ARCTIC ARCHIPELAGO	5. NORTHWEST ARCTIC ARCHIPELAGO	6. EASTERN CANADIAN ARCTIC
Liparidae (n=4)	<i>Careproctus reinhardtii</i>	Sea tadpole	+	✓	✓	X	X	✓
	<i>Liparis fabricii</i>	Gelatinous seasnail	✓	✓	✓	✓	X	✓
	<i>Liparis gibbus</i>	Variiegated snailfish	✓	✓	✓	✓	X	✓
	<i>Liparis tunicatus</i>	Kelp snailfish	✓	✓	✓	✓	X	✓
Osmeridae (n=1)	<i>Mallotus villosus</i>	Capelin	✓	✓	✓	✓	X	✓
Pholidae (n=1)	<i>Pholis fasciata</i>	Banded gunnel	+	X	✓	X	X	✓
Pleuronectidae (n=5)	<i>Hippoglossoides robustus</i>	Bering flounder	✓	+	✓	X	X	X
	<i>Limanda proboscidea</i>	Longhead dab	✓	X	✓	X	X	X
	<i>Platichthys stellatus</i>	Starry flounder	✓	✓	✓	X	X	X
	<i>Pleuronectes glacialis</i>	Arctic flounder	✓	✓	✓	✓	X	X
	<i>Reinhardtius hippoglossoides</i>	Greenland halibut	✓	✓	✓	X	X	✓
Rajidae (n=2?)	<i>Amblyraja hyperborea</i>	Arctic skate	✓	✓	✓	X	X	✓
	<i>Bathyraja spp.</i>	Unidentified skate (egg case only)	X	✓	X	X	X	X
Stichaeidae (n=6)	<i>Acantholumpenus mackayi</i>	Blackline prickleback	+	✓	X	X	X	X
	<i>Anisarchus medius</i>	Stout eelblenny	✓	✓	✓	X	X	✓
	<i>Eumesogrammus praecisus</i>	Fourline snakeblenny	✓	X	✓	X	X	✓
	<i>Leptoclinus maculatus</i>	Daubed shanny	✓	✓	✓	X	X	✓
	<i>Lumpenus fabricii</i>	Slender eelblenny	✓	✓	✓	✓	X	✓
	<i>Stichaeus punctatus</i>	Arctic shanny	✓	✓	✓	X	✓	X
Zoarcidae (n=13)	<i>Gymnelus hemifasciatus</i> ⁷	Halfbarred pout ⁷	✓	✓	✓	X	✓	X
	<i>Gymnelus viridis</i> ⁸	Fish doctor ⁸	✓	✓	✓	✓	X	✓
	<i>Lycodes jugoricus</i>	Shulupaoluk	X	✓	✓	✓	X	X
	<i>Lycodes lavalae</i> ⁹	Newfoundland eelpout ⁹	X	✓	X	X	X	✓
	<i>Lycodes marisalbi</i> ¹⁰	White Sea eelpout ¹⁰	X	✓	✓	X	✓	X

FAMILY	SCIENTIFIC NAME	COMMON NAME	1. ALASKAN BEAUFORT SEA	2. CANADIAN BEAUFORT SEA	3. AMUNDSEN GULF	4. CENTRAL ARCTIC ARCHIPELAGO	5. NORTHWEST ARCTIC ARCHIPELAGO	6. EASTERN CANADIAN ARCTIC
Zoarcidae (n=13) <i>(continued)</i>	<i>Lycodes mucosus</i>	Saddled eelpout	✓	✓	✓	✓	X	✓
	<i>Lycodes pallidus</i> ¹⁰	Pale eelpout ¹⁰	✓	✓	✓	X	✓	✓
	<i>Lycodes polaris</i>	Canadian eelpout	✓	✓	✓	X	✓	✓
	<i>Lycodes reticulatus</i> ¹¹	Arctic eelpout ¹¹	✦	✓	X	X	X	✓
	<i>Lycodes rossi</i> ¹¹	Threespot eelpout ¹¹	✓	✓	✓	X	X	X
	<i>Lycodes sagittarius</i>	Archer eelpout	✓	✓	X	X	X	X
	<i>Lycodes seminudus</i>	Longear eelpout	✓	✓	✓	X	X	✓
	<i>Lycodes vahlii</i>	Checker eelpout	X	X	X	X	✓	✓
Totals (n=59)			48	53	50	25	14	44

¹ Recently returned to the genus *Aspidophoroides* from *Ulcina* (Mecklenburg et al. 2011).

² Record unconfirmed and point distribution not included in Figure 3; record in the Canadian Beaufort Sea based on a partially eaten specimen (Coad and Reist 2004).

³ Includes eggvin lump sucker (*Eumicrotremus eggvinii*) as a junior synonym of Atlantic spiny lump sucker (*Eumicrotremus spinosus*) (Byrkjedal and Høines 2007).

⁴ Includes toothed cod (*Arctogadus borisovi*) as a synonym of polar cod (*Arctogadus glacialis*) (Jordan et al. 2003).

⁵ Polar cod as a common name sometimes is used to refer to both Arctic cod (*Boreogadus saida*) and a northeastern Atlantic stock of Atlantic cod (*Gadus morhua*); to reduce ambiguity *A. glacialis* is referred to here as ice cod.

⁶ Previously in the genus *Theragra*, recently returned to the genus *Gadus* (Mecklenburg et al. 2011).

⁷ Includes Knipowitsch's pout (*Gymnelus knipowitschi*) as a synonym of halfbarred pout (*G. hemifasciatus*) (Chernova 1999).

⁸ Includes *Gymnelus bilabrus* as a synonym of fish doctor (*G. viridis*) (Anderson and Federov 2004; Mecklenburg et al. 2011).

⁹ Record from the Royal Ontario Museum, accessed at <http://www.iobis.org/> July 2013; occurrence is suspect since outside typical distribution.

¹⁰ Pale eelpout (*Lycodes pallidus*) may actually be White Sea eelpout (*Lycodes marisalbi*) in the Beaufort Sea (Rask et al. 2001).

¹¹ Arctic eelpout (*Lycodes reticulatus*) and threespot eelpout (*L. rossi*) may be synonymous (Møller et al. 2010).



Chapter 5. Inuit Health Survey

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ABSTRACT

The Inuit Health Survey of 2007-08 covered all Inuit communities in the Inuvialuit Settlement Region and the Kitikmeot region of Nunavut, with the aim to assess the state of health among Inuit to serve as a baseline against which the impact of future social, economic and climate change can be monitored and the effectiveness of health intervention programs be evaluated. A large amount of data based on interviews, clinical measurements and laboratory tests were collected from 802 adults from 595 households in the Inuvialuit Settlement Region and Kitikmeot region. 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.

5.1 Background, design and methods

The Inuit Health Survey (hereafter IHS, named *Qanuqitpit* in the Inuvialuit Settlement Region and *Qanuippitali* in Nunavut, meaning “How Are We?”) was conducted across the Canadian Arctic over two summers in 2007 and 2008, covering all Inuit communities in the Inuvialuit Settlement Region (ISR), Nunavut, and Nunatsiavut. The data collected are compatible with, and will contribute to, the proposed International Inuit Health in Transition Study which is being discussed with Inuit organizations and governments in Canada, Greenland and Alaska.

This report covers only communities within the boundaries of the western and central Canadian Arctic, namely, those in ISR and the Kitikmeot region of Nunavut.

The overall objective of IHS is to provide a broad-based assessment of health among Inuit adults. 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 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.

5.1.1 Planning and consultation

The survey was developed through a participatory process involving extensive consultations with stakeholders and formation of steering committees in each of the three jurisdictions. 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. To date, a final agreement with one of the land claims organizations has not yet been finalized.

5.1.2 Funding

The major contributor was the Canadian IPY Program of the federal government. Supplementary funding (both in cash and in kind) was provided by the Canadian Institutes of Health Research, Health Canada, ArcticNet, Northern Contaminants Program, and the territorial governments and regional health authorities.

5.1.3 Sampling

Six communities in the ISR participated: Aklavik, Inuvik, Tuktoyaktuk (Figure 1), Sachs Harbour, Paulatuk, and Ulukhaktok. Five communities in the Kitikmeot region of Nunavut participated: Kugluktuk, Cambridge Bay (Figure 2), Gjoa Haven, Taloyoak, and Kugaaruk.

Participants were chosen in a two-stage procedure: the household, and individuals within the household. A total of 595 households (288 in the ISR and 307 in the Kitikmeot region) were selected, from which a final sample of 802 adult participants aged 18+ were selected (362 in the ISR and 440 in the Kitikmeot region). Women predominated, accounting for 64% of the sample. Over half (55%) were aged 40 and above.

5.1.4 Data collection and logistics

All coastal communities were reached by the Canadian Coast Guard Ship (CCGS) *Amundsen*, while the two inland communities (Inuvik and Aklavik) were visited by air by separate research crews. 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 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



STEPHANIE MACDONALD/INUIT HEALTH SURVEY

FIGURE 1. Tuktoyaktuk, one of the participating communities of the IHS.



STEPHANIE MACDONALD/INUIT HEALTH SURVEY



STEPHANIE MACDONALD/INUIT HEALTH SURVEY

FIGURE 2. A feast was held in Cambridge Bay to introduce the survey team and crew of the CCGS *Amundsen* to the community.



STEPHANIE MACDONALD/INUIT HEALTH SURVEY

FIGURE 3. The barge picking up survey participants in Ulukhaktok (top) and bringing them back to the CCGS *Amundsen*, where they are lifted onto the ship (bottom).

officers, and 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 CCGS *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 CCGS *Amundsen*.

After the ship's arrival in the community, participants were brought on board the ship by a shuttle (barge) or a helicopter. Between 40 and 50 participants were seen daily and visits lasted up to three hours (Figure 3).

5.1.5 Questionnaires, clinical measurements and laboratory tests

A variety of survey procedures were conducted on board the CCGS *Amundsen* (Figure 4).

Household questionnaire: 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 questionnaire: 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 questionnaire: 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 questionnaire: Use of selected medication, vitamins, and nutritional supplements

Dietary questionnaires: Food frequency and quantity of selected country and market foods consumed, using food models; 24-hour recall of food intake

Holter monitoring: To measure heart rate and detect irregular cardiac rhythms

Ultrasonography: Carotid arteries – to measure thickness and patency; abdomen – to measure intra-abdominal fat deposits

Anthropometry: Height and weight; waist circumference; sitting height; bioelectrical impedance to measure body fat

Venous blood tests: Fasting and 2-hour post-challenge plasma glucose, insulin; vitamin D, parathyroid hormone and osteocalcin; total, high-density-lipoprotein, and low-density-lipoprotein cholesterol, 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 including heavy metals (e.g. mercury, cadmium, lead) and persistent organic pollutants (such as PCBs, toxaphenes, and organochlorines).

Capillary blood tests: Hemoglobin

Blood pressure: Diastolic (DBP) and systolic (SBP)

Bone density: Measured in forearm and heel bone, among women 40+ years only, who are at risk for osteoporosis

Toenail samples: To measure selenium level, as a marker of country food consumption

5.2 A portrait of the population's health

5.2.1 Self-rated health

A useful index of overall health is a respondent's self rating of health as "excellent", "very good", "good", "fair" or "poor". Only a small minority (about 5%) of respondents rated themselves as in poor health (Figure 5). 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. Overall there is little difference in the responses between participants from the ISR and Kitikmeot region.

5.2.2 Pre-existing health problems

Respondents were also asked if they had ever been told by a doctor or nurse that they had certain health conditions (Figure 6). About 20% of adults were affected by



FIGURE 4. Different survey procedures conducted on the CCGS *Amundsen*: (a) interviewers reviewing questionnaires; (b) nurse collecting blood sample; (c) blood pressure measurement; (d) ultrasonography of the carotid arteries; (e) lab technicians preparing blood samples; (f) measuring heart rate and rhythm with the Holter monitor.

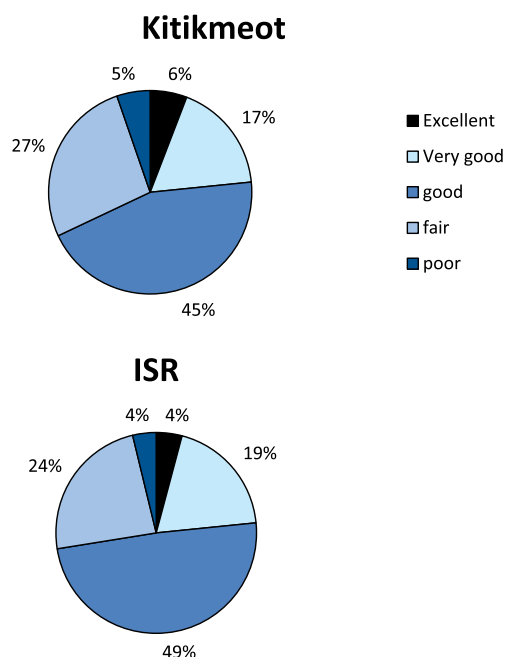


FIGURE 5. Self-rated health among survey participants in the Kitikmeot region and the ISR.

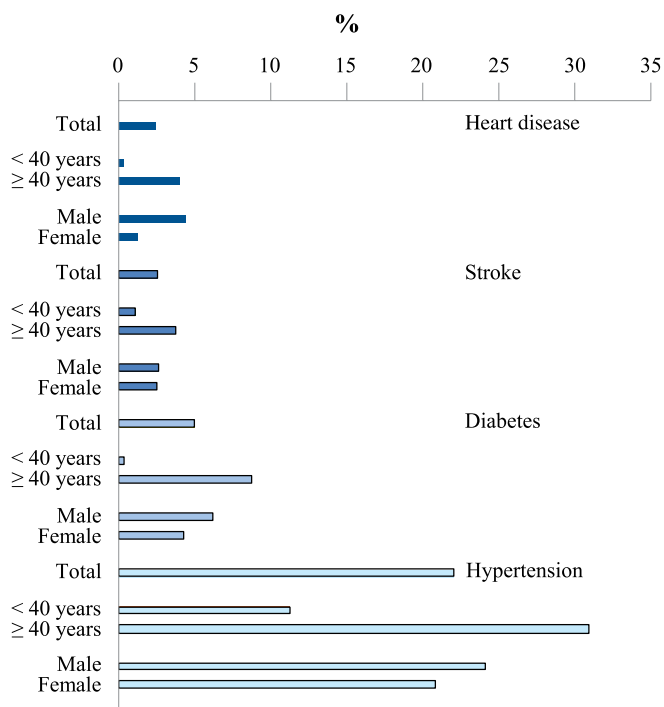


FIGURE 6. Prevalence of self-reported chronic conditions.

hypertension (high blood pressure), while just under 5% had diabetes. The survey question did not distinguish between type-1 and type-2 diabetes, which requires detailed clinical history and additional blood tests; however, the great majority of diabetes cases among Inuit, as in other populations, are type-2. 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.

TABLE 1. Prevalence (%) of self-reported past health conditions.

	KITIKMEOT	ISR	BOTH REGIONS
Heart attack			
Total	2.8	1.9	2.4
Male	3.5	5.9	4.4
Female	2.3	0	1.3
<40 yrs	0.6	0	0.4
40+ yrs	4.8	3.1	4.0
Stroke			
Total	2.5	2.7	2.6
Male	2.1	3.5	2.6
Female	2.7	2.2	2.5
<40 yrs	1.1	1.0	1.1
40+ yrs	3.8	3.7	3.7
Diabetes			
Total	4.9	4.9	4.9
Male	7.0	4.7	6.2
Female	3.7	5.0	4.3
<40 yrs	0.6	0.0	0.4
40+ yrs	9.4	8.0	8.7
Hypertension			
Total	21.3	23.6	22.3
Male	22.7	26.2	24.0
Female	20.4	22.3	21.3
<40 yrs	12.9	9.3	11.6
40+ yrs	29.7	32.1	30.8

TABLE 2. Prevalence (%) of selected social, economic and cultural characteristics.

	KITIKMEOT	ISR	BOTH REGIONS
Education			
<Secondary completion	63.4	53.4	59.2
Completed secondary	23.0	31.8	26.7
Any post-secondary	13.6	14.8	14.1
Income			
Received income support	49.8	20.5	35.6
Annual personal income of <\$20,000	54.1	40.8	48.4
Annual personal income of \$20-60,000	29.4	37.2	32.8
Annual personal income of \$60,000+	16.5	22.0	18.9
Housing			
Living in public housing	70.0	48.8	59.7
Home in need of major repairs	60.2	40.1	50.5
Provided shelter to homeless	13.9	21.4	17.5
Language and culture			
Use Inuit language at home*	38.6	12.3	25.9
Active hunter in household	79.1	58.7	69.2
Shared game meat with community	86.0	71.0	78.8

Note: *An Inuit language or dialect used at home either exclusively or in combination with another language such as English.

Table 1 compares the responses from Kitikmeot participants with those from the ISR. As expected, pre-existing chronic diseases are more likely among older than younger people; however, there is no clear pattern of gender differences.

5.2.3 Cultural and socioeconomic determinants

Lower educational attainment has been shown to be associated with the presence of many health problems. Approximately 60% of adults did not complete secondary school (Table 2). However, among the younger generation (under 40 years of age), the proportion is lower, at 49%, compared to 67% of those 40 years of age or older (Figure 7). There is no substantial difference between men and women (Figure 7).

Approximately 36% of respondents received income support. About half of the individuals (48%) had a total personal income of less than \$20,000 per year (Table 2). Adults 40 years of age or older tend to have higher incomes than younger adults, and men tend to receive more income than women (Figure 8). ISR residents in general tend to have higher level of educational attainment and annual income than those in the Kitikmeot region.

About 60% of households occupied public housing (Table 2). About half of the homes were considered to be in need of major repairs or had problem with molds. Approximately 18% of households reported having provided lodging to a homeless person, with a median of 61 days of stay. As a measure of crowding, 24% of homes had more than one person per room – the proportion was higher (1/3) among homes with children. On average there were 2.76 persons per bedroom.

As a measure to understand the vitality of Inuit culture, the use of one of the Inuit languages was reported from 26% of households. Hunting and fishing are also important traditional activities – just over 69% of households had an active hunter, and 79% distributed game meat to other members of the community. Table 2 compares the ISR with the Kitikmeot region. Overall, based on these indicators, participants from the Kitikmeot region are more engaged in traditional cultural activities than those from the ISR.

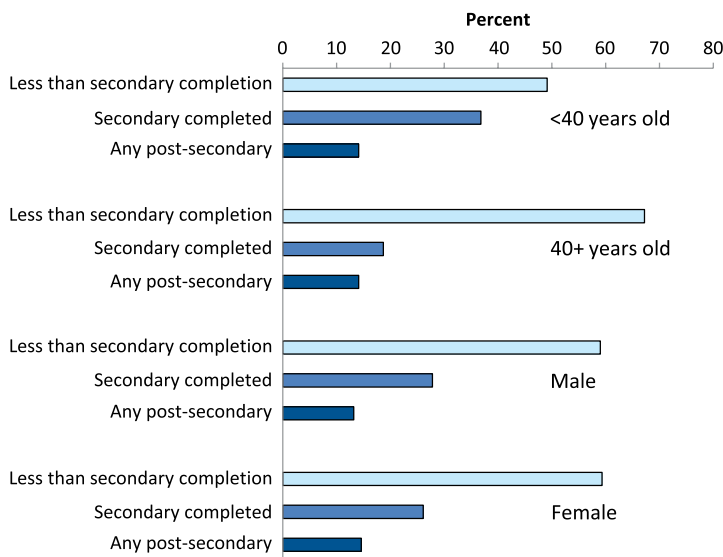


FIGURE 7. Educational attainment among the ISR and Kitikmeot participants of the IHS.

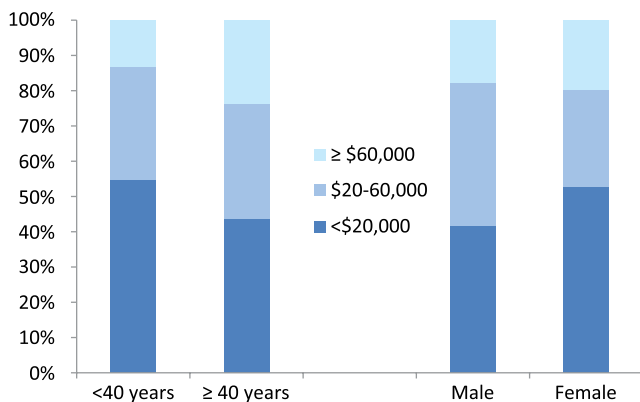


FIGURE 8. Total annual personal income of participants of the IHS.

5.2.4 Health-related behaviours

Smoking is an important risk factor for a variety of diseases, including lung cancer, chronic respiratory disease, heart disease and stroke. Table 3 compares participants from the ISR with those from the Kitikmeot region. Smoking is more common in the Kitikmeot region than it is in the ISR. Unlike other Canadians, where the proportion of smoking among men is higher than in women, the reverse is true among Inuit. About 70% of adults are current smokers, while 96% had smoked at some point in their life. Among smokers, the average number of cigarettes smoked per day was 10.2. The average age when smokers began smoking was 15.2 years. Exposure to environmental (second-hand) smoke was almost universal in homes – 87% of households had at least one smoker, and the proportion was even higher (90%) 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 (76% did so) and if they engaged in vigorous activities for at least 20 minutes on three or more days in the past week (46% did so) (Table 3).

5.2.4 Diet and nutrition

Inuit across the Arctic are undergoing rapid dietary transition, from one based on traditional “country” foods obtained from hunting and fishing (Figure 9), to one that is based on market foods imported from the South and purchased in stores (Figure 10). Chapter 8 discusses in detail the emerging issue of food insecurity, which has become a significant public health issue in the North.

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. As expected, older adults consumed more traditional foods than younger ones. Land mammals and fish accounted for the great majority of daily consumption of traditional foods by weight (see also Chapter 8, Figure 2).

TABLE 3. Prevalence (%) of selected health-related behaviours among participants of the IHS.

	KITIKMEOT	ISR	BOTH REGIONS
Smoking			
At least one household member a smoker	91.4	82.1	86.9
Currently a smoker:			
Total	73.0	65.4	69.8
Male	68.5	62.4	66.8
Female	75.9	66.9	71.8
<40 yrs	81.4	77.5	79.9
40+ yrs	65.1	57.9	61.7
Physical activity*			
Walking:			
Total	77.6	74.0	76.1
Male	72.1	72.3	72.2
Female	81.1	74.9	78.3
<40 yrs	77.8	79.4	78.4
40+ yrs	77.4	70.5	74.3
Vigorous activity:			
Total	47.6	44.8	46.4
Male	60.7	61.9	61.2
Female	39.0	36.7	37.9
<40 yrs	56.1	53.5	55.1
40+ yrs	39.6	39.4	39.5

Note: *Based on self-report of engaging in an activity of at least 20 minutes on three or more days in the past week.

Specific dietary deficiency can also be detected by blood tests. For vitamin D, 30% of adults (57% among the <40 and 10% among the 40+ age groups) were found to be deficient. Vitamin D is important for bone health, and its deficiency can lead to brittle bones; in children a severe form of deficiency is called rickets, which is associated with deformities of the leg bones. Anemia is determined by testing for hemoglobin (Hgb) in capillary blood. Hgb is an iron-containing protein molecule in red blood cells which carries oxygen. Overall 14% of men and 23% of women



STEPHANIE MACDONALD/INUIT HEALTH SURVEY



STEPHANIE MACDONALD/INUIT HEALTH SURVEY

FIGURE 9. Traditional foods (top) such as Arctic char (bottom) still play an important dietary role in the ISR and the Kitikmeot region.



STEPHANIE MACDONALD/INUIT HEALTH SURVEY

FIGURE 10. The prohibitive price of imported foods in an Aklavik store.

TABLE 4. Selected dietary indicators among participants of the IHS. Note: Mean energy intake values are derived from 24-hour recall while intake of specific food items are based on food frequency questionnaires.

	TOTAL	AGE <40 YRS	AGE 40+ YRS	MALE	FEMALE
Energy					
Mean total energy (kcal)	2287.4	2396.7	2199.1	2663.0	2070.8
% energy as fat	32.5	31.2	33.5	33.2	32.1
% energy as carbohydrates	45.7	51.0	41.4	43.1	47.2
% energy as protein	21.0	17.2	24.0	22.6	20.0
Traditional food consumption					
Mean daily intake of traditional foods (g)	227.4	186.9	256.8	297.6	185.4
Marine mammals	7.2	5.8	8.7	16.1	5.3
Land mammals	95.0	83.9	102.7	127.1	73.6
Fish	44.1	25.6	78.8	69.6	37.6
Birds	1.6	0.8	2.6	3.0	1.2
Soft drink consumption					
% drank soft drinks daily	81.9	90.7	74.7	81.7	82.0

were defined as anemic, (i.e. a Hgb level lower than 130 g L⁻¹). Additional blood tests such as serum ferritin, a measure of body iron stores, identified 4% of men and 29% of women as suffering from iron deficiency.

5.2.5 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, based on internationally accepted criteria. Table 5 summarizes key findings on the distribution of the population by categories of blood pressure and plasma lipids. Lipids are fatty substances in the blood, and different types can be measured: total cholesterol, HDL (High Density Lipoprotein, i.e. the “good” cholesterol) and LDL (Low Density Lipoprotein, i.e. the “bad” cholesterol), and triglycerides. These data indicate that a substantial proportion of the population have blood lipid levels that are known to be associated with higher risk for heart disease in the future. Health promotion strategies are thus needed to reduce these levels.

TABLE 5. Prevalence (%) of risk categories for plasma lipids and blood pressure.

“At risk” plasma lipid levels	
Total cholesterol	40.7
LDL-cholesterol	22.7
HDL-cholesterol	28.4
Triglycerides	27.8
Distribution of blood pressure level	
Normotensive	61.3
Pre-hypertension	27.1
Hypertension stage 1	9.6
Hypertension stage 2	2

Note: A person is considered “at risk” when total cholesterol ≥ 5.2 mmol L⁻¹; LDL-cholesterol ≥ 3.5 mmol L⁻¹; HDL-cholesterol ≤ 1.0 in men and 1.3 mmol L⁻¹ in women; or triglycerides ≥ 1.7 mmol L⁻¹.

“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 ≥10.

5.2.6 Mental health and well-being

The IHS also contains a confidential, self-administered questionnaire on several issues relating to personal mental health and community well-being. These questions are of a highly sensitive nature such as suicidal attempts, past sexual and physical abuse, and depressive symptoms. Regional summary reports on the extent of these problems have been compiled and presented to the communities, after extensive consultations with community representatives on the steering committees. These results will not be included in this report.

5.2.7 Environmental contaminants

A variety of contaminants were measured in the blood samples in the IHS. Data were analysed separately for ISR, Nunavut and Nunatsiavut. For this report, results are not broken down into regions within Nunavut (hence not for the Kitikmeot region separately), since the advice from the regional steering committee stipulated that results could be released to the public only for Nunavut as a whole.

Among Inuvialuit and Nunavummiut, concentrations of metals and organochlorines (e.g. PCBs, DDTs/DDEs, toxaphene, chlordane) were higher than the Canadian average values. The average concentrations of contaminants, however, were below the guideline levels established by Health Canada, suggesting that most of the IHS participants do not have a concern for contaminant-related adverse health effects. However, a percentage of heavy country food consumers can still be exposed to elevated levels of contaminants.

Blood concentrations of cadmium, lead, and mercury showed a significant decrease when compared to the concentrations reported in Nunavik in the early 1990s. Older males tended to have the highest blood concentrations of mercury, lead, PCBs, DDTs/DDEs, toxaphene, and chlordane. Cadmium was the only contaminant of concern for which young adults (18-40 years old) had the highest blood concentrations in all Inuit regions.

The primary dietary sources of mercury for Inuvialuit were Arctic char, caribou meat, whitefish, and fish eggs. In Nunavut it was ringed seal liver. The primary source of cadmium for Inuit in ISR and Nunavut was smoking. The primary sources of PCB and other organochlorines were beluga blubber and muktuk in the ISR, and beluga and narwhal blubber in Nunavut.

On the other hand, country foods are the primary dietary sources of key nutrients such as selenium (mainly from beluga muktuk and caribou meat) and omega-3 fatty acids (mainly from Arctic char).

In summary, the results indicate that country foods provide many essential nutrients that can lower the risk of chronic diseases. Most Inuvialuit should have minimum concern on effects of contaminants. Overall, the benefits of eating country foods outweigh the risk of contaminant exposure. However, smoking is a major problem for Inuit both in the ISR and the Kitikmeot region (Table 3).

5.3 Major scientific findings

The IHS 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.

The IHS can be compared with data collected earlier in other studies. Compared to 1999, the average body mass index (BMI) among Inuit has 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. Among men, the average BMI has remained stable, while that of women has increased from 27.2 to 29.1 (Sheikh et al. 2011) (Figure 11).

BOX 1. Addressing Inuit health concerns through participatory and collaborative research: the ISR *H. pylori* Project

In response to compelling calls for research on the stomach bacteria called *Helicobacter pylori* that Aklavik, NT residents had heard was linked to high rates of stomach cancer, University of Alberta researchers joined with Aboriginal leaders and organizations, and regional and territorial health authorities, to form the Canadian North *Helicobacter pylori* (CANHelp) Working Group in 2006. The CANHelp Working Group is a team of researchers, health officials, and community leaders and organizations who collaboratively investigate *H. pylori* infection and associated stomach diseases in the Yukon and Northwest Territories. CANHelp Working Group goals are to (1) investigate *H. pylori* infection in participating communities to identify determinants, consequences and effective treatment strategies, (2) develop health care policy recommendations that are ethically, economically, and culturally appropriate for northern communities, and 3) develop knowledge exchange strategies that help community members understand *H. pylori*-associated health risks as well as solutions and unsolved challenges for reducing these risks.

The Aklavik *H. pylori* Project (AHPP) started out as the CANHelp Working Group's pilot project. To develop specific participatory methods and research goals, university researchers worked closely with the locally-organized and managed Aklavik Health Committee, which serves as the AHPP planning committee. The CANHelp Working Group has extended this community-driven model, starting *H. pylori* projects in Old Crow, YK (2008), Tuktoyaktuk, NT (2010), and Fort McPherson, NT (2011). At the request of the Inuvialuit Regional Corporation, plans are in place to extend this work throughout the ISR communities.

Early in AHPP planning, university researchers learned Arctic residents had concerns about how research would be carried out. Researchers in the past have come and gone, never to return or report on their findings to the community (Huntington et al. 2009). Additionally, individuals working in Arctic health research and healthcare delivery often come from different cultural backgrounds than the communities they serve; bringing with them different perspectives on human health and the scientific research process. Meaningful knowledge exchange in both directions between researchers and project participants is crucial for informing the CANHelp Working Group's



research process at all stages including initial planning, data collection and analysis, reporting of results, and healthcare interventions (Colquhoun et al. 2013b). To facilitate this process, CANHelp university researchers work closely with community planning committees to plan all stages of research and data dissemination. Within each community *H. pylori* project, local residents are hired and trained to work alongside visiting researchers to recruit participants; administer *H. pylori* tests, epidemiological questionnaires, and ethnographic interviews; and work collaboratively in knowledge exchange and data dissemination.

Recently, the CANHelp Working Group formed an exchange program within the AHPP that brings Aboriginal residents together with university researchers to develop meaningful data dissemination materials for communicating microbiology research results to community members (Colquhoun et al. 2013a). Participating Aklavik residents traveled to Vancouver to present this project with the exchange program coordinators at the ArcticNet 2012 scientific meeting. The CANHelp Working Group is currently drafting proposals for expanding this exchange program to other community *H. pylori* projects, where we will recruit additional Aboriginal residents to become leading partners in our collaborative knowledge translation efforts.

Key findings: CANHelp Working Group research components include non-invasive screening for *H. pylori* infection, endoscopy clinics set up in participating communities to assess stomach health, pathological examination of stomach tissue biopsies, microbiological characterization of bacterial strains, trials to identify effective treatment, and long-term follow-up of participants. Breath-test screening yielded *H. pylori* prevalence estimates of 58% in Aklavik, NT, 57% in Tuktoyaktuk, NT, 59% in Fort McPherson, NT, and 68% in Old Crow, YT. Across participating communities, pathology results revealed a high prevalence of conditions associated with increased risk of stomach cancer amongst *H. pylori*-positive participants (Cheung et al. 2013). In the AHPP treatment trial, treatment was successful in less than 60% of participants who took the standard Canadian regimen (Morse et al. 2013), thus subsequent trials have been designed to identify more effective treatments (result in progress). Follow-up after the Aklavik treatment trial demonstrated that prevalence decreased amongst participants since initial screening; the estimated rate of new infections and re-infections combined was 2.4% per year (95% CI: 0.8-5.9% per year) amongst Aboriginal participants, while all non-Aboriginal participants remained free from infection during the study, as did all participants aged 55 years and older. These findings indicate that community-based screening and treatment has the potential to substantially reduce the prevalence of *H. pylori* infection in northern communities (Carraher et al. 2013).

In coming years, the CANHelp Working Group will continue to expand its *H. pylori* research in the ISR and to collaborate with research participants on the development of innovative knowledge translation strategies for residents of Arctic communities and for the practitioners and policy makers who provide their health care.

Is an excessive body mass index harmful to Inuit health? 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 Inuit. Although still uncommon compared to First Nations in southern Canada, diabetes was found to affect 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 waist line, who also has high levels of a blood lipid called triglycerides, is more likely to become diabetic. Among Inuit, such a person is almost nine times more likely to have diabetes than someone who

has a slim waist and normal blood triglycerides (Egeland et al. 2011a) (Figure 12).

The use of “universal” standards for obesity among Inuit may not be applicable to Inuit. Older literature indicates that Inuit have high trunk length relative to their legs (i.e. high sitting height ratio (SHR)). This may result in a higher BMI that does not reflect the amount of excess body fat, thus indicating an erroneously high prevalence of obesity in the population and creating a public health concern when in fact none exists. By re-calculating BMI “adjusting” for SHR, it was found that there is indeed little effect on the

BMI or the prevalence of obesity. The obesity problem among Inuit is thus “real” and not an artifact of their body proportions (Galloway et al. 2011).

The Inuit Health Survey provides a detailed description of the diet and food intake of Inuit today, with a special interest in the role of traditional foods. 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).

A disturbing trend is that food insecurity is widespread, while at the same time, the quality of the diet is deteriorating. Some 60% of households in the survey area experienced food insecurity. Diet quality can be measured using the Healthy Eating Index. Adults living in food-insecure households have lower scores than those living in food-secure households (fewer vegetables, fruits, grains and dairy products, and more high-sugar foods). These adults are also more obese. Food insecurity is associated with different indicators of poor socio-economic status such as crowding and housing quality, single adult households, and income support. However, households with an active hunter are less likely to be food insecure (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. Consumption of traditional foods appears to modulate the impact of food insecurity, elevating the blood levels of vitamin D and iron (Egeland et al. 2011b).

More detailed analyses are underway, and other important health issues, for example, mental health and suicidal risk, will be examined.

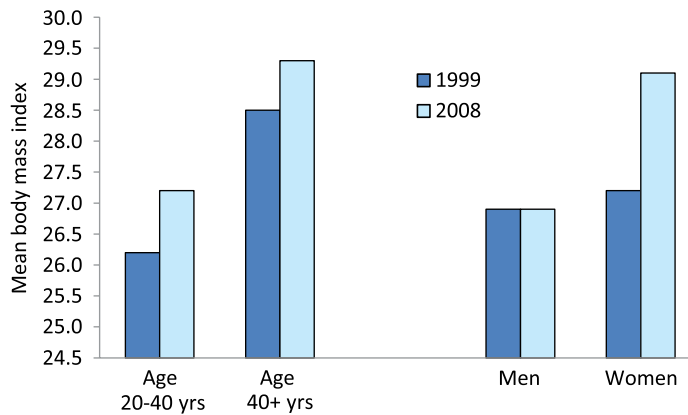


FIGURE 11. Mean body mass index in 1999 and 2008 by age group and sex among Inuit (data collected from the entire IHS). Note: Body mass index (BMI) = weight in kg/(height in cm)².

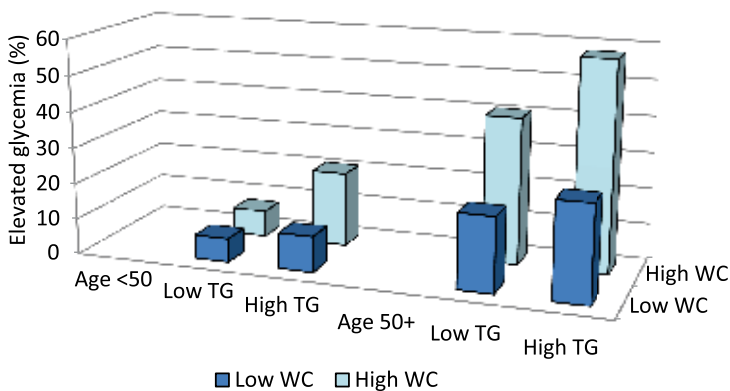


FIGURE 12. Prevalence of glycemia by age group, waist circumference, and fasting serum triglycerides (data collected from the entire IHS). Note: Glycemia = fasting glucose level ≥ 5.6 mmol L⁻¹ or taking medications for diabetes; WC = waist circumference; “high” defined as ≥ 102 cm for men or ≥ 88 cm in women; TG = triglycerides, “high” defined as ≥ 1.7 mmol L⁻¹.

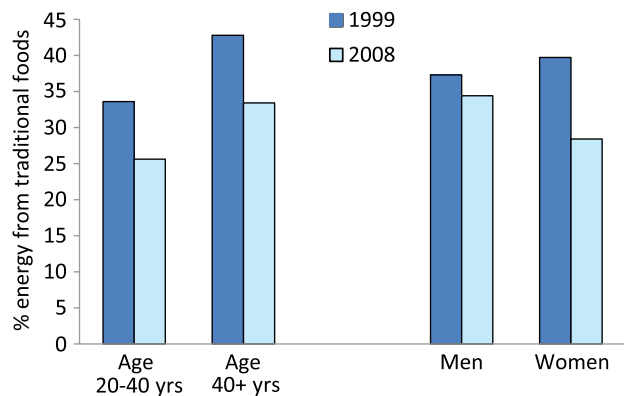


FIGURE 13. Proportion of energy derived from traditional foods among Inuit by age group and sex (data collected from the entire IHS). Note: Data based on 24-hour recalls.

5.4 Conclusions

The Inuit Health Survey was a landmark project which enabled the state of health of Inuit to be assessed comprehensively at a point in time. It was truly a partnership as representatives of Inuit organizations and communities actively participated and contributed to its design, implementation, analysis and dissemination. In addition to addressing important scientific questions, the results are particularly important for decision makers to plan and develop interventions targeted at important public health conditions such as the excessive level of smoking and emerging patterns of obesity which will likely lead to future increases in chronic diseases.

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Chapter 6. Safety in Travel and Navigation

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ABSTRACT

Safe passage in the Arctic provides a means for local subsistence activities, shipping, and adequate search and rescue capabilities. Northerners are facing variable seasons, weather, sea ice and permafrost conditions which are compromising the safety and access of travelling to harvesting grounds and limiting opportunities to pass on traditional land skills to youth. Increasing costs of fuel and travel equipment and resource development activities, which may deter animals from traditional hunting grounds, also affect subsistence activities. Improving the accessibility of food networks along with weather forecasting and communication may assist with adaptation efforts. With respect to shipping, approximately only 10% of the Archipelago waters, which were reliably ice-free under conditions of 30 years ago, have been charted to modern standards to date. With the increasing traffic as well as the potential for more open water areas, there is a need to expand the coverage of modern hydrographic data in support of safe charting to cope with the changing environment. This does not implicitly require that the waters of the entire Archipelago be surveyed, but that new and existing corridors need to be surveyed to modern standards. In the absence of sufficient resources to undertake the full scale of charting required, a prioritization scheme has been proposed by the Canadian Hydrographic Service. A complementary approach would be to increase the efficiency of existing Canadian Arctic mapping capabilities through multi-tasking of committed federal assets. These include the Canadian Coast Guard's 1200 class ice-breaker fleet as well as the upcoming Arctic Offshore Patrol Vessels. Another factor which can impede the safety of both local travellers and larger transient vessels is storm activity. Larger expanses of open water give rise to larger, more intense storms with increased wind speeds. The resulting waves and storm surges pose a safety risk to ships, ports and other coastal infrastructure. High-resolution studies are needed to research sensitive coastal areas, and to simulate trends and climate change projections for waves, storm surges, and sea ice.

6.1 Introduction

Climate change is impacting sea ice, winds, waves, currents, and coastal sediment transport in the Arctic (Chapter 2); these variables in turn influence access to Inuit harvesting grounds, search and rescue capabilities, marine transport, and present and future coastal infrastructure. Adequate resources, mapping and charting, facilities, support and science-based tools are required to enable harvesters and Arctic mariners to safely navigate the land, marine channels and harbours. This chapter presents an overview of how local and transient travellers are impacted by the effects of climate change and provides recommendations to support their safety, security and prosperity.

6.2 Travel on land

This section reviews the impacts to local travel in the North (e.g. snow mobile, boat, all-terrain vehicles (ATVs)). The impacts to harvested species, a means for travelling on the land, are covered in Chapters 3 and 4 of the assessment.

6.2.1 Significance of travelling on land and sea

Here the term ‘land’ refers to solid surfaces such as the ground, sea ice and lake-ice, in essence to how Inuit use this word (ICC 2008). The Inuit way of life depends on free movement on the land and sea to harvest local fish and wildlife (‘country foods’). Subsistence activities remain valued among Inuit in the Canadian Arctic as country foods are more nutritious, less expensive, and are preferred by Inuit in comparison to imported store foods (e.g. Nuttall et al. 2005; Kuhnlein and Receveur 2007; Mead et al. 2010; Chapter 8). Travelling and harvesting on the land are also important socially, culturally, spiritually and economically (e.g. guiding sport hunters) (e.g. Collings et al. 1998; Berkes and Jolly 2001; Nickels et al. 2005; Van Oostdam et al. 2005; Pearce et al. 2011b; Chapter 8).

6.2.2 Impacts

Climate change, modernization and other stressors are impacting travel and harvesting activities.

Climate change

The impacts of climate change to land travel, including changing sea-ice dynamics, increased frequency and intensity of storms, and changes in snow cover and levels of precipitation, have compromised the safety, access (e.g. to camps, harvesting grounds, routes) and overall success of hunts. In some cases hunters have had to travel longer distances to find game (Keith et al. 2005; Pearce et al. 2010, 2011a; Andrachuk and Smit 2012) or wait to travel later when conditions were safe (e.g. NTI 2001). A major challenge is associated with unpredictable weather. Critical to a successful hunting trip is the knowledgeable forecasting skills Inuit have developed over many generations. These days, due to sudden, unexpected weather, hunters have often had to return home prematurely or forgo trips altogether (Berkes and Jolly 2001; Pearce et al. 2010.)

In summer months hotter and more humid days have made travelling and living on the land relatively difficult both with respect to increased dehydration, insect harassment, and risk of sunburn/sunstroke (Thorpe et al. 2001; Nickels et al. 2005). Spring and summer temperatures are projected to rise an additional 2-4°C over the mainland and Canadian Arctic Archipelago (Chapter 2).

Over the last few decades Inuit in the western and central Canadian Arctic have witnessed thinning ice, less ice coverage, unpredictable ice conditions, and earlier break-up/late freeze-up of ice (Berkes and Jolly 2001; NTI 2001; Thorpe et al. 2001; Nichols et al. 2004; Keith et al. 2005; Nickels et al. 2005; Pearce et al. 2010; Knopp et al. 2011; Prno et al. 2011; Knopp et al. 2012). These ice conditions are unlikely to improve with fall temperatures expected to increase an additional 4-7+°C and winter temperatures an additional 4-5°C by 2050 in the ISR and Kitikmeot region (Chapter 2). Although some positive impacts have risen from this change



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in climate, including more fishing and boating opportunities and new tourism prospects (Zimmermann 1997; Thorpe et al. 2001; Stewart et al. 2007), most impacts experienced have been negative. Longer ice-free seasons and less ice coverage, along with windier and stormier conditions (Pearce et al. 2008; Pearce et al. 2010; Prno et al. 2011) have made the sea rougher and more dangerous for boat travel. In the past, easterly winds in Ulukhaktok assisted in clearing ice away from the community; now the wind patterns are variable, making the nature of break-up unpredictable and thus difficult to foresee safe travelling conditions. For example, changing wind dynamics has on several occasions resulted in broken sea ice being pushed back to the shoreline near the community and blocked marine access for hunters (Pearce et al. 2010). Shifts in the wind have also been observed around Gjoa Haven (Keith et al. 2005), which have had serious implications not only to safety but have also rendered snow drifts (which can be used to orient travellers by the direction the wind drifts the snow) useless as navigational aids. Community members at Ulukhaktok

and Kugluktuk have also observed water pooling on the sea ice, exposing travellers to wetness and freezing (Pearce et al. 2010; Prno et al. 2011).

Changes with respect to the snow and permafrost have also been impacted in a travel-unfriendly way. Less snowfall or early melting of snow and ice have often deterred travellers, and in other times these conditions have stranded or injured snowmobilers or resulted in lost or damaged equipment (Berkes and Jolly 2001; Pearce et al. 2008; Pearce et al. 2010). Permafrost degradation and increased rain in the summer and autumn have softened and water-logged the ground, discouraging ATV travel (Berkes and Jolly 2001; Prno et al. 2011). For the western and central Canadian Arctic, projected climate conditions indicate that snow will melt 1 to 13 days earlier in the spring, and summer precipitation will increase by up to 5-10% over most of the ISR and Kitikmeot region and by up to 25% offshore the Yukon North Slope (Chapter 2).

Modernization

Longer ice-free seasons coupled with increased resource development and tourism opportunities may encourage busier traffic in the Arctic's future. Already some communities in the Kitikmeot region have witnessed more ships through their ports in recent years (see Chapter 9, section 9.3.3). Inuit are concerned about associated environmental impacts which have indirect ties to the success of hunting trips. For instance, the residents of Ulukhaktok worry about the pollution aspects of increased boat traffic (e.g. sewage, contaminants) and their implications to animal habitat (Pearce et al. 2010). Inuit are also concerned that animals can move (and have moved) away from areas adjacent to shipping routes (Dumond 2007; ICC 2008).

With respect to the construction of the new, all-season highway connecting Tuktoyaktuk and Inuvik (see Chapter 7), the Environmental Impact Review Board (EIRB) under the Inuvialuit Final Agreement undertook a comprehensive study to examine all possible effects to the surrounding environment and Inuvialuit way of life. Regarding possible negative impacts to wildlife during the construction period (e.g. disturbance to caribou), EIRB concluded that such impacts must be mitigated, monitored and managed subject to the commitments made by the Hamlet of Tuktoyaktuk, Town of Inuvik, and Government of the Northwest Territories (collectively the Developer) (EIRB 2013). However, once complete, the highway is predicted to increase access to caribou harvesting grounds which may have implications on the abundance and health of the herd.



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Additional stressors

The success of a hunt is dependent not only upon environmental and climatic conditions but also on access to resources, knowledge and a healthy well-being. The necessities needed by harvesters can oftentimes be expensive to purchase and maintain. Snowmobiles, ATVs, fuel, heaters, safety equipment (e.g. navigational devices), food, and extra clothing are examples of such supplies. Although funds from harvester-assistance programs help to offset the costs associated with harvesting, wage-paying jobs, which are generally in short supply in northern Canada, are needed to support subsistence activities. With limited monetary resources, hunters will continue to face hardships in acquiring (or not acquiring) additional safety gear (e.g. satellite phone, beacon) needed for increasingly dangerous/unpredictable land conditions in the near future (Ford et al. 2008; Pearce et al. 2010).

The transmission and retention of traditional knowledge and land-based skills has become an increasing concern among Inuit (Pearce et al. 2010, 2011b). Hunting routes and techniques passed down by generations which have proven successful in the past are becoming less practical with respect to changing land and weather conditions today. The pace of these changes is forcing Inuit to adapt travelling and harvesting skills to relatively tight timeframes (e.g. single generation). With increasingly dangerous travel conditions, youth are experiencing fewer opportunities to learn these new ways. In response to changing distributions and timing of animal presence, some Inuit have adapted by switching the types of species harvested. However, not everyone has the appropriate transportation, equipment and skills to harvest different species, and sometimes there simply aren't other species to harvest (Pearce et al. 2010).

The effect of multiple stresses, including a lack of access to gear, knowledge of the land (particularly an issue with the pace of climate change), dangerous and unpredictable travel conditions and the impacts of increased ship traffic and other industrial activity, are affecting the emotional and physical well-being of harvesters and their families (Nickels

et al. 2005; Pearce et al. 2010). Feelings of depression or hopelessness can further disable Inuit from participating in harvesting activities.

6.3 Navigation and travel on sea

This section looks at the need for, state of, and capability to undertake charting in the waters of the western and central Canadian Arctic. It is focused primarily on the safety of navigation for shipping. Commercial shipping deals with four factors: (1) the state of seabed survey (e.g. bathymetric hazards); (2) the state of the ice regime (Chapter 2); (3) the amount of storm activity (section 6.4); and (4) availability of search and rescue services.

6.3.1 Seabed surveying: nautical charting and seabed mapping

The maintenance of western and central Canadian Arctic communities and natural resource development both critically depend on transport of supplies from southern destinations. Comparisons of the relative cost per unit weight of cargo via the three common options – air, trucking/barges, and deep-draft vessels (Leyzack 2012) – have clearly shown the economic benefits of the deep-draft ocean-going vessel solution. The seaborne transportation options, however, are limited by a combination of ice-conditions, availability of search and rescue services and the state of nautical charting.

Nautical charting involves ensuring safe shipping corridors along which all hazards to navigation are defined. This does not imply a need for complete charting of the Archipelago however. In order to maintain communities and natural resource development, only sufficient corridors that link these actively visited areas with open water are needed. The commonly quoted estimate that about 10% of the Arctic is charted to modern standards (Narayanan 2011) is open to a variety of interpretations. Do we need to prioritize then, all the other 90%? For areas that are perennially ice covered where surface shipping cannot currently go, or for those



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open areas where shipping traffic is currently not going, those may in fact not be considered a priority. For the actual currently-operational areas, hyperbole aside, “the primary routes are sufficiently well covered to enable safe navigation” (Snider 2005). The question then is how much more than that 10% needs to be covered as a priority in the light of evolving political and climatic changes.

If the predicted retreat and thinning of ice occurs, then more of the newly exposed areas may require new or further charting. Also, if there is a change in areas of vessel activity, such that they start operating in areas which have been previously open but not travelled, then more charting again

may be needed. The aim of this section is to try to assess the state of nautical charting and the need (and capability) for more charting or other seabed mapping in the western and central Canadian Arctic.

Nautical charting is not the only reason to undertake seabed mapping. Other needs include habitat mapping, geohazard assessment and environmental monitoring. All of these have a need that extends well beyond those shipping lanes critical to maintain the communities and industry.

The 2009 press reporting (CBC 2009) can give the impression that there is already a very active federal seabed

mapping program going on in the Arctic today. There is indeed. However, it is important to distinguish those seabed mapping programs dedicated to definition of Canada's juridical continental shelf and those programs dedicated to improved navigation safety. The juridical shelf surveys are in support of Canada's claim to the United Nations Law of the Sea (UNCLOS) which may result in extending Canadian waters out beyond 200 nautical miles (nm) from our shores (MacDougall et al. 2008). The UNCLOS criteria only extend out into international waters and thus surveys are all operating in water depths in excess of 2000 m in the Canada Basin, well outside the CAA. These surveys thus add nothing toward shipping safety within the Archipelago, the focus of this chapter. Nautical charting is performed directly to support maritime shipping safety, ensuring sufficient under keel clearance for surface shipping. This activity is disproportionately focussed on coastal areas where depths within conceivable ships' keel drafts (<50 m) exist, which primarily includes the waters within the CAA.

Because of a deadline for submission in 2013, the UNCLOS program has been very active and correspondingly well funded with, for example, \$51 million CDN allocated in Budget 2004, and a further \$20 million CDN allocated in Budget 2008 (Cote and Dufresne 2008). Most recently in 2014, the CCGS *Louis St. Laurent* received a major refurbishment including the addition of a 12 kHz multibeam echo sounder in order to address further UNCLOS-related deep-water mapping objectives at the North Pole. In contrast, while the federal government has declared that it would be boosting nautical charting surveys in the Arctic (CBC 2009), no corresponding new dedicated funding has been allocated.

Sovereignty issues that lie more inshore, such as bilateral boundary disputes like the US/Canada border in the Beaufort Sea (Chapter 9) or the contention that the North West Passage is an internal waterway, are not constrained by the 2013 UNCLOS deadline. For neither UNCLOS nor bilateral disputes, is it clear that nautical charting contributes to Canada's claim.

The establishment of an Arctic Regional Hydrographic Commission in 2010 (Fisheries and Oceans 2010) commits Canada to increased collaboration and data sharing, but significantly makes no commitment to new data acquisition. Reflecting that omission, this has notably not been followed by any published charting plan for the Canadian Arctic comparable to that put out by the United States (NOAA 2013).

While normal shipping can be maintained within specific corridors, search and rescue (SAR) operations often extend outside those regions. The 2009 Arctic Marine Shipping Assessment highlighted the limitations of existing SAR capabilities across the polar region. Northern community representatives from Gjoa Haven and Ulukhaktok have stated their incapacity to help with accidents incurred by large ships (Stewart et al. 2013). As part of creating an effective Arctic SAR strategy, Russell (2011) identified that limited navigational charts negatively affect search coordination and rescue efforts. Given that the future locations of SAR incidents cannot be predicted, extending nautical charting beyond core shipping corridors would thus be beneficial.

Outside the boundary-centric view of UNCLOS, other approaches to sovereignty follow the view of the Arctic Council nations that the way forward needs to be based on improved environmental stewardship and sustainable development (Crawford et al. 2008). As yet, the term 'environmental stewardship' is not clearly defined. But without a doubt, the first step towards stewardship of the Archipelago marine environment is to adequately understand the bathymetry so that shipping disasters due to poor charting can be averted.

Showing leadership in environmental stewardship would allow Canada to secure its sovereignty claims — "*not only in the courts of law, but in the court of world public opinion, where evidence of exemplary environmental stewardship will be most persuasive*" (Manning 2008).

6.3.2 Historic overview and current state of nautical charting in the western and central Canadian Arctic

Much of the shallower western CAA channels (predominantly within the Kitikmeot region) and the Beaufort Sea have historically had perennial ice cover precluding ship-based hydrographic surveying. As a result, those regions were covered by a helicopter-based through-ice spot sounding campaign starting in 1960, following the decision in 1958 to initiate the Polar Continental Shelf Program (PCSP) (Weber 1983). This program initially focussed primarily on the geology and regional morphology of the deeper Arctic Basin in the North (The LOREX 79 program and CESAR program, Weber 1987), but gradually switched to a Canadian Hydrographic Service (CHS)-led program that worked to get widely spaced through-ice spot soundings in the CAA to support charting. The geophysical requirements of the program were generally met by 6 km grids or sparser. As the surveys switched to a hydrographic focus in the shallower Archipelago channels, specific corridors deemed important for nautical charting were addressed by solutions as tight as 1 km. As a guide, however, critical hydrography in open water shipping areas with depths less than ~100 m are normally conducted by ship lines spacing of no coarser than 300 m. This density of data is rarely met in the Arctic. For example, the northern Amundsen Gulf was covered at 6 km spacing by 1973 and 1974 (PCSP). In more open waters, starting in 1977 to 1978, a 1-2 km line spacing ship base operation was then conducted.

Ship-based nautical charting survey work in the CAA was really only undertaken in a systematic manner after 1958 with the first northern deployment of CSS *Baffin*. Initial operations only covered the Eastern Arctic, but in 1969, when the CCGS *John A. MacDonald* was escorting the SS *Manhattan*, the first “pingo” was discovered in the Beaufort Sea. The expected growth in offshore oil and gas developments and the concern about potential grounding led to a demand for safe shipping lanes to accommodate the deep draft (up to 20 m) oil tankers. This program was

first initiated in 1970 when both the CSS *Hudson* and CSS *Baffin* passed through on their around-America tour. Since then, a 500-1000 m line spacing program was initiated (CSS *Parizeau* 1970, 1971, 1972 and other chartered vessels). From 1981 to 1989, the shipping corridor (Figure 1) was completed using 100 m spacing single beam lines.

In the 1980s, commercial ships were chartered to serve combined hydrographic and geophysical objectives. It was not until 1985 that a vessel capable of undertaking dedicated surveys in the western and central Canadian Arctic was available. That vessel, the CSS *John P. Tully*, undertook extensive surveys of shipping lanes in the Beaufort Sea, Amundsen Gulf and Coronation Gulf from 1985 to 1993. These surveys significantly established safe passages through the Dolphin and Union Strait and Dease Strait bottlenecks.

Dolphin and Union Strait was first systematically surveyed from the CSS *Baffin* in 1977. From 1993 to 1995, the corridor east from there to King William Island was then expanded using three technologies: (1) through-ice spot soundings; (2) through-ice electromagnetic profiling; and (3) conventional launch work. The data density was highly variable, with highest densities just along a designated corridor on the north side of the Coronation Gulf (Figure 2). It was outside this corridor that the 2010 grounding of the MV *Clipper Adventurer* occurred.

As an alternate to the Coronation Gulf-southern North West Passage corridor, a second route was surveyed through Prince of Wales Strait and Viscount Melville Sound. An initial assessment was made using CSS *Baffin* and CSS *Hudson* in 1970 while escorted by the CCGS *John A. Macdonald*. Since the area was not accessible to any of the non-icebreaking platforms at the time, the entire route was then covered using through-ice spot soundings. The deeper (300-500 m) section of Viscount Melville Sound was covered by a 15 nm wide corridor surveyed using 2 km spaced spot soundings in 1977 (outside the corridor there are only 6 km spacing solutions). The central deep section of Prince of Wales Strait is typically about 100 m

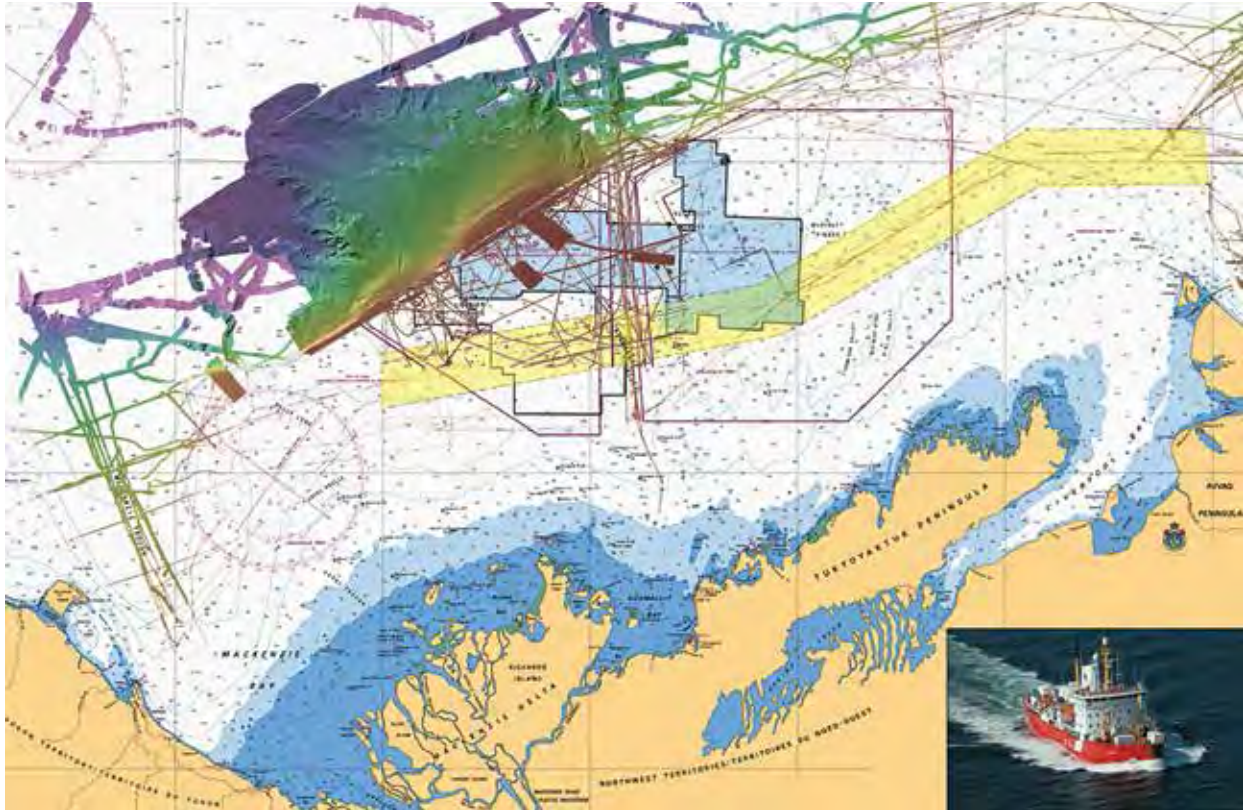
CCGS *Amundsen* Multibeam Coverage – Beaufort Sea

FIGURE 1. Beaufort Sea shipping lane coverage, lease blocks and CCGS *Amundsen* multibeam coverage (particularly 2009-2011 systematic work). The yellow corridor was established between 1981 and 1989 using 100 m line spacing.

deep and was described using ~1000 m spacing through-ice spot soundings in 1982. With the predictions of ameliorating ice conditions, this route may be one that becomes more prioritized.

While the regional CHS charting priorities were to open up the Beaufort Sea to natural resource extraction and to provide transcontinental corridors through the Coronation Gulf and Prince of Wales routes, extra surveys were also done that were more industry-specific, as long as those industries contributed significant financial support towards the charting. An example of this is the charting for the Bathurst Inlet Road and Port Project which was a collaborative project between the CHS, the Kitikmeot Inuit Association, GNWT and a shipping company that

owns ice-class vessels (Ashbury 1997). This involved a 50% contribution (total \$900,000 CDN) from the sponsors which resulted in a dedicated corridor (surveyed in 1997 and 1998 by the CHS) extending south from the main Coronation Gulf corridor into Bathurst Inlet. At this time the Izok Lake lead and zinc property development is on hold, but the charting requirements have mainly been met (the alternate Grays Bay port location may require more work).

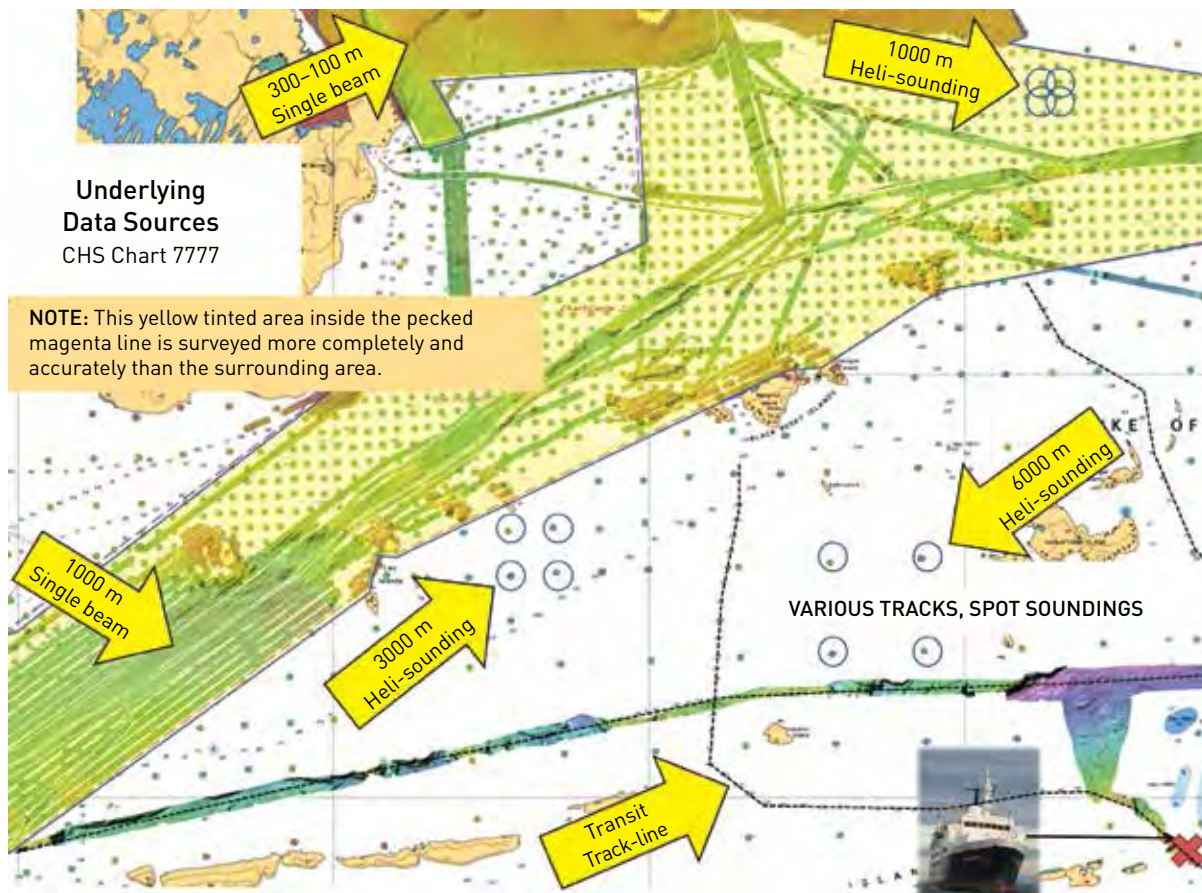


FIGURE 2. Map showing varying data sources and densities in Coronation Gulf, highlighting the designated shipping corridor and the location where the MV *Clipper Adventurer* went aground.

6.3.3 History of hydrographic survey capability and current capability and limitations

As mentioned in the extent of the previous section, the ability to undertake open-water nautical charting surveys in potential shoal areas (generally <50 m) has fallen most extensively on the periods when major (>80 m) launch-carrying dedicated hydrographic survey platforms were available. These included the CSS *Baffin*, CSS *Hudson* and CSS *John P. Tully*.

The CSS *Baffin*'s appearance in 1958 was unique in that she was a dedicated hydrographic vessel carrying six

hydrographic launches. Recognising the complementary nature of the operations, however, her operations were quickly switched to combined geophysical and hydrographic operations. The next vessel, CSS *Hudson*, appearing in 1964, was deliberately built as a multi-purpose platform, capable of carrying up to four hydrographic launches but having the majority of her schedule dedicated to oceanographic or geologic investigations. The CSS *Parizeau* was assigned to Arctic operations from 1970 to 1972 (without launches) but thereafter was withdrawn for other work in the Pacific region. The CSS *John P. Tully* was originally built to support Arctic hydrography with four dedicated launches, but these were removed in 1996, and she has never returned to Arctic operations since.

To supplement these major dedicated platforms, and to perform the less critical deeper areas, chartered vessels have been used, especially in the western Canadian Arctic to conduct surveys.

With the demise of the CSS *Baffin* in 1989, the reallocation of the CSS *Tully* in 1993, and the de-facto shift of focus of the CSS *Hudson* to science only (she last did a dedicated Arctic hydrographic survey in the Rankin Inlet area in 1996), there is no longer any capability to execute the scale of surveys that these platforms used to deliver.

A subset of the shoal work was done in the Inuvialuit Settlement Region (ISR) and the Kitikmeot region on the CCGS *Nahidik*, a 53 m long barge platform capable of carrying one launch, which was based in the Mackenzie Delta from 1974 to 2010. That platform too, however, has been withdrawn from service.

At this time, all CHS open-water operations in the Arctic are restricted to add-on programs on CCG icebreakers during which the hydrographic mission never has first priority. As a result, while surveys are conducted annually in both the eastern and western Archipelago, the foci are opportunistic, making it difficult to add significantly to modern hydrographic data coverage.

The most extensive nautical charting surveys to take place in the Archipelago in the last decade have been driven and funded almost entirely by private industry or other government agency priorities. These include mine access corridors (in the eastern Canadian Arctic most recently) and lease block surveys in the Beaufort Sea.

Since the demise of the CSS *Tully* as a dedicated hydrographic platform, the major shallow water effort in the western and central Canadian Arctic has been in the King William Island chokepoints (James Ross, Rae, Victoria and Simpson Straits). These areas have been addressed using the CCGS *Laurier* on a non-dedicated basis. Notably, the survey priorities have been driven by Parks Canada's interest in finding HMS *Erebus* and HMS *Terror* rather than

the main shipping corridors. Fortunately the current search area (near Requisite Channel) lies not far from the Victoria Strait shipping lanes.

Most recently in 2011 and 2012, a new initiative has been developed utilizing contract hydrographic services that deliver airborne laser bathymetry (known as LiDAR), typically achieving a maximum of 20 m penetration. Open water LiDAR, pioneered by the CHS in the mid-1980s, was discontinued for many years. The recent LiDAR surveys have focused in the shallow King William Island area.

6.3.4 Prioritization criteria for undertaking further charting

The federal government assigns resources to agencies based on a perception of need. The CHS is the agency responsible for the production of nautical charting. As the CHS operate with a limited budget, they cannot address all needs and thus they assign priorities to charting areas based on an internal ranking policy. At this time a definitive prioritization strategy has not yet been finalized. A draft strategy, however, has been proposed that assign ranks to specific areas. That proposed ranking depends on seven factors with different weighting (CHS 2013). These would include:

Chart wellness (weight 20): relates to how modern the cartographic framework is (modern datum, modern units, number of updates, notices to mariners) - Scale of 0 (excellent) to 20 (archaic)

Maritime transportation (weight 5): maximum weight assigned for a high risk chart and high volume traffic

Sovereignty (weight 3): to support the establishment of jurisdictional boundaries (i.e. UNCLOS, Orders in Council) or which has crown interest for CHS litigation or clear support for DND, RCMP, etc.

Ocean and freshwater mapping (weight 1): to support DFO programs such as Safe and Secure Waters, Sustainable

Aquatic Ecosystems, and Economically Prosperous Maritime Sectors and Fisheries; and at least one other government department

Coastal natural hazards (weight 1): where the under-keel clearance available for navigation is critical and where it's used in near real time for safe transit

Client feedback (weight 3.5): commercial, government and recreational user groups have approached CHS

Economic prosperity, political (weight 10): a survey/product required in support of significant marine infrastructure development of a high national economic value or has been specifically requested by the Crown

With a 43.5 point maximum score, it is illuminating to see which proposed criteria would be the most influential. “Chart wellness” is a significant issue in the Arctic as many of the charts are off-datum and in fathoms. However, this is a cartographic factor, requiring reprojection, not necessarily resulting in new charting. To qualify as a high volume of shipping requires meeting a three million metric tonne criteria comparable to the St. Lawrence Seaway. The Frobisher Bay corridor is probably currently the highest volume in the Arctic yet only qualifies as low volume. Notably, however, the projected volume and risk for the Baffinland project involving Milne Inlet and Foxe Basin receive the maximum score in this criterion. The Sovereignty criterion was invoked for the *Clipper Adventurer* site (“CHS litigation”). UNCLOS criteria are not influenced by bathymetry within the Archipelago. The Economic Prosperity criterion is potentially the most influential in the Arctic and has been invoked for the North West Passage choke points (e.g. Victoria Strait).

In terms of allocation of effort, without considering the strategic component, the extremely low population density and shipping density (compared to southern waters) would probably not warrant a high charting priority for any region in the Archipelago. Strategically, however, it has been deemed important to maintain a visible presence in the

Archipelago and this has driven much of the community shipping-access programs. Much emphasis has also been placed on the predictions that the North West Passage could open up and thus become a major shipping lane. However, despite these predictions, none of the major shipping line companies consider the North West Passage as a viable corridor (see Chapter 9, section 9.3.2).

Underlying all this prioritization however, is the limited financial and logistical resources currently available to the CHS. Without expanding their operating budget in support of a dedicated charting campaign for the Arctic, there is little opportunity to significantly address new charting anyway.

In October 2014, the requirement for a prioritization based on needs was again emphasized in the recommendations from the Report of the Commissioner of the Environment and Sustainable Development (Auditor General 2014). The report also recommended the development of a long-term implementation plan based on that prioritization. The report included a response from DFO indicating that such a prioritization plan would indeed be implemented, with a target date of “September 2016 and ongoing” and that a multi-year operational plan would be in place in 2018.

6.3.5 Parallel programs that benefit from systematic seabed surveying

While nautical charting has been one of the driving forces behind seabed surveying in the CAA, the data derived from the newer multibeam sonar systems can also serve other programs that are interested in the submerged morphology of the Beaufort Sea and the Arctic Island channels. The two main interests are seabed habitat, including particularly the potential environmental effect on them as a result of resource development, and geohazards to submarine resource development.

Seabed habitat assessment

Now that multibeam systems provide a measure of seabed roughness (sometimes referred to as rugosity) and seabed acoustic backscatter strength (strongly correlated with bottom physical properties like sand, gravel or mud), they have the potential to measure the characteristics of the substrate that are important to benthic (living on and in the seabed) and demersal (living in the water column close to the seabed) species. Benthic habitat mapping programs (Pickrill and Kostylev 2007) are an integral part of national seafloor mapping strategies.

Habitat definition is important to assess the potential environmental impact of human activities such as pipeline installations and oil spills. As part of this, at the Beaufort Sea Habitat Mapping Workshop in 2002 (Quadra 2002), seabed/benthic mapping was identified as a major theme. Specifically this included ice scour, sources of granular material, sediment type, depth, slope, and bathymetry.

The Beaufort Regional Environmental Assessment (BREA) program, currently funded from 2011 to 2015, has a specific project on this aspect: ‘Impacts of Development in the Beaufort Sea on Fish, their Habitats and Ecosystems,’ the description of which is:

“... a four-year (2011-2015) study that will include a fishing survey in deeper waters of the outer continental shelf as well as slope areas of the Beaufort Sea. ... Increased understanding of the ecosystems on which fish species depend will support environmental assessments and sound decision making regarding fish habitat and offshore oil and gas activities.” (Quadra 2002)

An integral part of understanding the “ecosystem on which the fish species depend” is delineating the surficial substrate using multibeam sonar, as is currently done by the CCGS *Amundsen* ArcticNet program.



The CCGS *Amundsen*

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Submarine geohazard assessment

The proposed development of the hydrocarbon lease blocks in the Beaufort Sea will require an assessment of the risk involved, including dangers due to unstable seabeds (geohazards, see Chapter 9, section 9.2.2). An additional project funded under the new BREA program is ‘Deep Water Seabed Geohazards’, the description of which is:

“Oil and gas exploration in the deep waters of the Beaufort Sea requires knowledge of seabed stability conditions to ensure safe drilling practices. Under this initiative, the Geological Survey of Canada will conduct a regional assessment of seabed instability conditions, such as mud volcanoes, gas vents and faults, subsea permafrost and the severity of these geohazards. Seabed geohazard research provides baseline knowledge in support of spill prevention and contributes to the preservation of the marine ecosystem and protection of renewable resources. Research findings from this regional assessment will be essential for environmental impact assessments and will support informed decision making in the development of an effective regulatory regime.” (AANDC 2012)

Discovery and definition of geohazards, ice scouring, mud volcanoes, gas vents and shallow subsurface geology is primarily achieved through systematic seabed mapping programs using multibeam sonar and sub-bottom profilers. This is exactly the approach using the CCGS *Amundsen*, undertaken through the ArcticNet program in collaboration with the oil and gas industry.

While the Beaufort Sea is considered reasonably charted for the purpose of shipping traffic, the data (principally single beam soundings in the 1970 to 1996 period) used to obtain these charts do not significantly contribute to habitat or geohazard assessment. Thus, resurvey of large areas will be necessary to obtain the information important to assess the environmental impact of proposed offshore natural resource developments.

6.3.6 Contribution of the ArcticNet seabed mapping program

The ArcticNet program was built around the refurbished 1200 class icebreaker, now renamed CCGS *Amundsen*. As part of the program, there was a need to define and better understand the geology, biology and chemistry of the sediment water interface. It was recognized that such a study, which would include a survey of the seafloor, could contribute towards the state of charting in the North. Today, the ArcticNet seabed mapping program has provided a wealth of information (Beaudoin et al. 2008), both from the CCGS *Amundsen* herself and from her associated inshore mapping platforms.

The mapping acquired by the CCGS *Amundsen* has been of three main types:

- (1) Underway transit corridors – a network of confidently navigated conduits (Figure 3 and Beaudoin et al. 2008) has been developed and is available online at <http://www.omg.unb.ca/Projects/Arctic/google/>
- (2) Site surveys – for periods of up to 12 hours at a time, surveys have been conducted of areas of specific scientific

interest. In addition, one SAR 48 hour window of systematic survey was undertaken.

- (3) Systematic mapping – partnerships with the oil and gas industry (2009-2011) have led to the most significant mapping consisting of ~ 90 days of dedicated work on the outer Beaufort Shelf and Slope (Figure 1).

Unlike previous solitary single beam tracks that had questionable horizontal control (Figure 4) often up to several hundred metres, the CCGS *Amundsen* tracks are navigated to within 2 m and represent a clear and finite width corridor (typically 3x the water depth). By having a swath rather than just a 2D profile, one can establish from which side the seafloor is shoaling. They are thus reliable and safe passages that could be utilized by shipping operating outside the assigned corridors.

ArcticNet – small platform seabed mapping

As has been well established through CHS charting activity over the past 40 years, shoal-draft, launch-based systems are essential to operate in uncharted coastal shoal waters. The second mapping initiative of ArcticNet was to provide inshore launch or other shoal-draft vessel operations that could more directly address both the scientific interests in shallower waters and the nautical charting need.

CSL *Heron*: Starting in 2006, the CSL *Heron* (10 m long) was deployed from davits on the CCGS *Amundsen* with multibeam survey equipment from the University of New Brunswick (UNB). It undertook both science and charting surveys and these have been directly incorporated into charts. For the 2008 season, the CSL *Heron* was moved on to the CCGS *Henry Larsen* to partner with the CHS on both science and charting surveys. Again these surveys (notably those at Nanisivik mine dock, Arctic Bay, Resolute, NU) have made it directly onto charts. In order to proceed into uncharted regions, the CSL *Heron* was used to go ahead of the CCGS *Henry Larsen* in Adams Sound and again in Southern Admiralty Inlet, thereby defining new safe shipping corridors.



FIGURE 3. Coverage plot of all ArcticNet data acquired in the western and central Canadian Arctic.

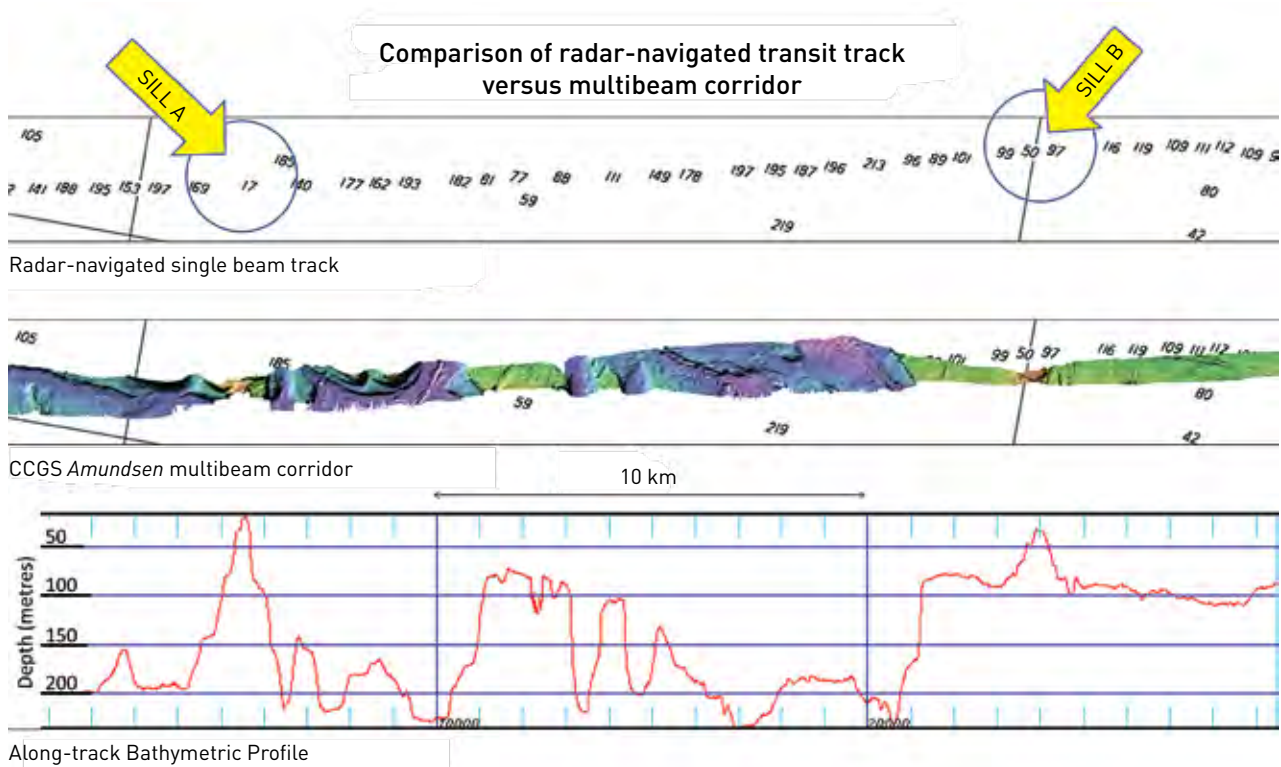


FIGURE 4. Illustrating the problem of navigation using existing lines of soundings on charts. How a well navigated multibeam corridor guarantees both a corridor and defines trends on either side. The lower bathymetric profile along the same corridor illustrates two abrupt, shallow “choke points” (Sill A and B, charted at 17 and 20 m, respectively) that restrict navigation.

BOX 1. *The Clipper Adventurer*

Within the last 16 years, there have been three major vessel groundings in the western and central Canadian Arctic. These include the MV *Hanseatic* in 1996, and the MV *Clipper Adventurer* and MV *Nanny* in 2010.

For the case of the MV *Clipper Adventurer*, referred to in TSBC report M10H006 (2012), the issue was primarily of deliberately operating in an area known to be insufficiently charted. Chart 7777 clearly states that the area is outside the designated shipping lane and in a region with only spot and track soundings. The MV *Clipper*



PIERRE-LOUIS TËTU

The *Sea Adventurer* (formerly *Clipper Adventurer*)

Adventurer issue was compounded by a lack of clarity about the means by which non-CHS reported shoals are used for chart updating. That issue is however secondary to the fact that the vessel was attempting to follow a single line of imperfectly navigated soundings (see Figure 4). Even without omissions in the plotted depth, uncertainty in the true position of the previous track knowingly results in exposure to risk.

The MV *Clipper Adventurer* was operating along a corridor that does not have a high priority in the CHS charting scheme. No regular traffic goes to or from Port Epworth and there is no community there. The corridor has now been surveyed better as part of the response, but would not have been prioritized had not the grounding occurred.

The SAR response of the CCGS *Amundsen* to the grounding highlights an effective model of operating in such sparsely charted waters. She approached along her own pre-existing (2005) well-navigated multibeam track, expanding that corridor as she went. Where she was required to cross shallow uncharted sill crests (similar geologically to that on which the MV *Clipper Adventurer* had lain), she utilized her launch-based mapping system to expand these choke points. In the final approach to the MV *Clipper Adventurer*, a full new corridor was pre-surveyed by the launch-based multibeam system including the entire area around the stricken vessel.

Russell (2011) notes that SAR capability outside the designated shipping lanes is significantly hampered by lack of sufficient charting. For example, in one case a helicopter response over 100 nautical miles from the mother vessel was required as the vessel had no available route to the distress call location as it was not charted (pers. comm. Captain of CCGS *Henry Larsen*, 2008).

This approach, of having a dedicated hull mounted multibeam system on SAR platforms in the North, together with a launch or barge-based system to allow advance in shoal strewn waters, is one of this report's main recommendations.

CCGS *Nahidik*: In 2009, the same UNB multibeam system was moved onto the CCGS *Nahidik* to support collaboratively-funded (Imperial Oil, CHS, NRCan and ArcticNet) surveys on the outer Beaufort Shelf. Previously the CCGS *Nahidik* had carried only a CHS multibeam launch. The addition of a pole-mounted multibeam on the CCGS *Nahidik* herself allowed for the first time 24 hour per day acquisition. With her shoal draft, at 53 m in length, the CCGS *Nahidik* is fully autonomous and thus would be an ideal inshore platform for sustained charting surveys. As previously stated, however, she was unfortunately withdrawn from CCG service in 2010.

CCGS *Amundsen* barge: In 2010 and 2011, the same mapping system was again moved onto the CCGS *Amundsen* landing craft. This meant that there was no longer competition for the limited davit space on the *Amundsen*. In this case the platform was increasingly used in support of safety of navigation for the CCGS *Amundsen* herself. Specific shoals were examined (Iqaluit harbour), chokepoints (Coronation Gulf sill crossings, 2006), potential cable corridors mapped (Cambridge Bay, 2011) and uncharted passages investigated (Le Goulet). Most significantly, in 2010 the barge-based system was essential to allow the CCGS *Amundsen* to approach the stricken MV *Clipper Adventurer* in the Coronation Gulf (see Box 1).

MV *Nuliajuk*: Most recently in early 2012 the UNB inshore multibeam system has been moved onto the Nunavut Government's new fisheries research vessel MV *Nuliajuk*. She has now completed three full seasons of seabed mapping and charting in the Nunatsiavut and SE Baffin Island region. Even though only 19 m long, she is fully autonomous, and thus with only a 3.5 m draft she is a far more cost effective mapping solution than a 1200 class icebreaker for those coastal waters (Brucker et al. 2013).

In summary, the ArcticNet contribution to the state of knowledge of the bathymetry of the Archipelago seaways has been extremely significant. With the loss of a dedicated major federal mapping platform in the CAA since 1993, the CCGS *Amundsen* has represented the most efficient

mapping platform for the past 11 years. With the improved technology onboard, and the commitment to 24 hour a day mapping for period of typically 120 days per year, her seabed mapping database, available online, is now the single largest holding of bathymetric data for the Canadian Arctic.

Alone the *Amundsen* cannot address the deficiencies in current charting coverage, especially in the shallowest regions, but she has actively maintained the growth of our knowledge and acts as a particularly low cost model of data acquisition that could be adopted by all other major CCG icebreaker assets in the CAA. As of the 2014 field season, two CCG icebreakers have now undergone installation of multibeam survey systems. The CCGS *Laurier* has received a pole-mounted shallow water multibeam optimally suited for undertaking shallow water (<200 m) nautical charting surveys, and the CCGS *Louis St. Laurent* has received a low-frequency multibeam which, while primarily designed for deep water UNCLOS surveys, will contribute towards charting in the deeper (>200 m) sections of the CAA.



The MV *Nuliajuk*

TRAVIS HAMILTON/UNB

6.3.7 Impact of climate change on the need for further nautical charting

Climate change predictions to 2050 outlined in Chapter 2 indicate the maximum average temperature increase of +3.8°C occurring in the Beaufort Sea with more reduced effects (+2.4°C) within the Archipelago itself. This should ameliorate sea-ice conditions, the major barrier to marine navigation.

When examined seasonally, the maximum seasonal air temperature increase occurs in the autumn period (up to +7°C in October, November and December), potentially extending the open water navigation season. As this is again most intensified in the Beaufort Sea region, this would particularly benefit the oil and gas extraction industry. In contrast the major seasonal change in the northern route is predicted to occur with an earlier start of the season (before July). Despite receding ice in many places, there are no imminent plans from shipping companies to use the North West Passage for transcontinental traffic anyway (Chapter 9, section 9.3.2). While the North West Passage transit of the commercial bulk carrier *Nordic Orion* made headlines in September 2013, plans to repeat that in 2014 (Waldie 2014) were not in fact implemented. Indeed as a by-product of the climate change predictions there is a likelihood of increased variability in the ice season (Griffiths 2003), which is actually providing even less incentive for transcontinental shipping. Even with a longer shipping season, the variability in ice coverage will still preclude the guarantee of an ice-free corridor so that the insurance costs for non-reinforced vessels will remain prohibitive. The only likely increase is in the natural resource extraction, community supply and tourism industries.

In contrast to the transcontinental shipping community, the natural resource industry is able to address corridor charting deficiencies themselves should it be a perceived risk. This model was demonstrated during the Bathurst Inlet surveys in support of the Izok Lake project, and with the recent CCGS *Amundsen* operations on the outer Beaufort Shelf in support of the lease block allocations there (Figure 1).

The decision to go ahead with resource extraction is mainly economic rather than a result of ameliorating climatic conditions.

The community resupply requirements are already seen as the current priority of the CHS within their limited resources. Given Canada's commitment to maintain viable communities in the Archipelago, the economic benefit of being able to use deeper draft vessels to lower the cost per unit weight has been demonstrated (Leyzack 2012).

The tourism industry is already active and would welcome a longer ice-free season, even if tempered with variability. However, that industry is unlikely to support addressing charting deficiencies other than by using more caution. Whether Canada should support an expanded tourism industry by increased investment in mapping is not clear. Another option would be to legislate vessels keep within the currently charted lanes. Most of the economic benefits of delivering tourists to remote (usually uninhabited) locations probably goes to the vessel operator (normally foreign) rather than the nation or, more significantly, the communities.

6.4 Storms

6.4.1 Introduction

Some of the dominant climate change issues in the Arctic are related to decreasing sea ice, particularly in recent years. The ice extent has decreased at a rate of about 10% per decade and reached a minimum in 2007 at 4.1×10^6 km², 37% less than the climatological average (Comiso et al. 2008; Comiso 2012). The rate of ice melt is accelerated because the increased open water is a positive feedback, because of significant reductions in the surface albedo of sea water compared to sea ice (Zhang et al. 2008). The summer Arctic Ocean is expected to become essentially ice free within a few decades, at the current rate of decline (Holland et al. 2006; Zhang and Walsh 2006; Stroeve et al. 2007; Wang and Overland 2009; Lindsay et al. 2009; Zhang 2010).



DOUG BARBER/ARCTICNET

Declining summer sea ice has opened large areas of open water, from Siberia to the Northwest Territories, and influenced changes in weather and climate. Changes are occurring in the storms, and in associated extreme winds and waves. Larger waves can impact coastal infrastructure, transportation, tourism, resource development and ecosystems; with changing sea ice, change is occurring in winds and waves, even without change to the storm climate.

As ice declines and storms become larger and more intense (Simmonds and Keay 2009), stronger waves, currents, and storm surges are generated that can damage fragile low-lying Arctic coasts, made vulnerable because of diminishing permafrost and land-fast ice and longer summers. An example of a severe storm is the so-called Millennium Storm of 1999, with large waves and storm surge (Small et al. 2011) impacting the Mackenzie Delta ecosystem

(Pisarcic et al. 2011). The Great Arctic Cyclone (2012), described by Simmonds and Rudeva (2012), had high winds and waves that pummeled a mammoth zone of thin, fragmented ice.

Previous IPY (2007-2008) projects studied the impacts of declining sea ice on waves, the upper ocean and the Arctic storm climate, using coupled models, with atmospheric, ocean, waves and ice components, focusing on the southern Beaufort Sea and Arctic Ocean (Long and Perrie 2012, 2013; Melling et al. 2012; Xu et al. 2013). With decreasing sea ice and larger, more intense storms (Simmonds et al. 2008), synoptic weather patterns have been shown to be identifiable as being favourable to storm surge formation in Mackenzie Delta waters, potentially influenced by warm heat fluxes from the waters of the Mackenzie River plume (Small et al. 2011; Perrie et al. 2012).

We need capacity to understand and simulate the storms, waves, storm surge, currents, sediment transport, and ice, both for individual critical storm events on time-scales of days, as well as from the viewpoint of climate change on multi-decadal time-scales. There are gaps in our knowledge related to critical physical processes, atmosphere-ocean-ice feedbacks, and the effects of diminishing ice. Ongoing studies need to more accurately estimate the present climate, and climate change, identifying the factors affecting the spatial or temporal variability, for marine storms, winds, waves and storm surge in the Arctic marginal ice zone and coastal areas.

6.4.2 Safety concerns for marine traffic and ports

The continued reduction of sea ice may bring an increase in northern shipping, as well as changes to local transportation. Thus, there will be a need to develop plans for coastal and port infrastructure to allow supplies and resources to be moved safely, efficiently and cost-effectively (Ruffilli 2011) with consideration to weather-driven events such as ocean waves, long-distance swell, and storm surge (Atkinson et al. 2011; Pisaric et al. 2011) (see Chapter 7).

Swell waves are long-period waves generated by distant marine storms, whereas wind-generated waves are generated by local storms. Because, in decades past, the summer Arctic was mostly ice-covered, swell was not a concern; however, as summer sea ice retreats, swell increases. Swell can be a challenge for shipping operations, for coastal infrastructure, and for ecotourism activities, for example, if the wavelength of swell waves is similar to the inherent frequency of the larger vessels, such as sea-lift barges, bulk carriers (e.g. handymax class), or cruise ships. In this case, swell waves can generate just the right resonance conditions to produce dangerous movements of these boats. For coastal infrastructure, storm waves (including wind waves and swell) can damage port and coastal infrastructure as well as smaller craft, which are often simply pulled up on the beach for storage and used for community activities.

Presently, port infrastructure in most northern communities usually does not include docks and cranes for transferring goods, with cargo often directly delivered to the beach after being offloaded onto barges in the summer. Thus, these operations may involve a certain level of danger in high seas (Ruffilli 2011). For example, Ulukhaktok exclusively uses marine transport for the supply of most non-perishable goods, fuel, equipment, and materials during the short summer season. Tuktoyaktuk is presently a regional marine service and supply centre for resource development, shipping, fisheries and ecotourism, and a candidate for expanding regional capacity for the Mackenzie and Beaufort Sea area. Should Tuktoyaktuk expand its capacity as a marine centre, the community, marine transportation managers, policy makers, and other stakeholders should be mindful of the impacts of severe weather and swell on associated infrastructure and operations (Ruffilli 2011).

6.4.3 Past events/trends and impacts

Of all the Arctic coastal regions, Canada Basin has a relatively high frequency of summer storms (Serreze and Barry 1988; Serreze and Barrett 2008; Simmonds et al. 2008). On average, there are about 14 storms per storm season (June-November) in this area, with the highest storm frequency occurring in October, and the least in July (Hudak and Young 2002). Most storms move into this region primarily from Siberia, tend to linger over the Beaufort Sea, and then dissipate in the central Arctic Ocean (Serreze and Barry 1988; Serreze and Barrett 2008).

In terms of environmental impacts, Arctic storms have an important role in the loss of sea ice (Zhang et al. 2004; Simmonds et al. 2008; Soterbert and Walsh 2008; Higgins and Cassano 2009; Screen et al. 2011). While increased open water provides favorable conditions for air-sea interactions, storm-generated winds enhance the exchanges of momentum, heat and moisture between the atmosphere and the ocean surface and can increase the strength and size of Arctic storms (Simmonds and Keay 2009). Previous studies have shown that Arctic storms are responsible for a large proportion of

moisture transport into the Arctic Ocean and have significant impacts on the generation of clouds and precipitation (Groves and Francis 2002; Sorteberg and Walsh 2008; Jakobson and Vihma 2010). Moreover, Screen and Simmonds (2010) and Deser et al. (2010) suggest that although the atmospheric warming associated with the decline of sea ice is mainly confined to the atmospheric boundary layer, this warming is the cause for most of the atmospheric responses (seasonal, spatial, and vertical structure).

Long and Perrie (2012, 2013) used a coupled atmosphere-ocean-ice model system to simulate a storm that moved into the Beaufort Sea in 2008. They focused on the role of air-sea interactions on the life cycle of the storm and the impacts of open water on storm intensity, development, and the surface fields. This simulated storm originated in northern Siberia and moved slowly to open water areas of the Chukchi and Beaufort seas. Although the atmospheric dynamics were shown to dominate the storm's strengthening and weakening processes, the extent of the open water in the Chukchi and Beaufort seas affected the storm intensity as it passed over this region, whereas no significant impact could be seen if the storm moved over more ice-covered waters off Siberia. In terms of the maximum wind associated with the storm, the loss of Arctic sea ice was shown to cause an increase by about 4 m s^{-1} , compared to conditions when this area was largely ice-covered (typical of possible ice conditions in past decades), mostly due to the enhanced momentum exchange between the atmospheric boundary layer and the troposphere (Figure 5). Due to the declining Beaufort Sea ice cover, the air temperature over the sea ice increased by as much as 8°C compared to ice-covered conditions of several decades ago (Figure 6). However, the atmospheric warming mainly occurred in the boundary layer with no essential warming in the mid- and upper troposphere. Warmer lower troposphere temperatures increased the atmospheric boundary turbulence and downward transport of atmospheric kinetic energy because of reduced stability. Thus, storm-generated surface winds were enhanced by as much as $\sim 4 \text{ m s}^{-1}$.

6.5 Conclusions, gaps, and recommendations

6.5.1 Travel on land

Recommendations for advancing adaptation planning for climate change in the ISR and elsewhere in the Canadian Arctic with respect to land-based travel and subsistence activities have been identified by Pearce et al. (2011a) and Ford et al. (2010):

- (1) Support the teaching and transmission of environmental knowledge and land skills among Inuit;
- (2) Enhance and review emergency management capability (e.g. search and rescue);
- (3) Ensure the flexibility of resource management regimes (e.g. timing of hunts and quotas);
- (4) Provide economic support to facilitate adaptation for groups with limited household income;
- (5) Increase research effort to identify short and long term risk factors and adaptive response options;
- (6) Protect key infrastructure; and
- (7) Promote awareness of climate change impacts and adaptation among policy makers.

6.5.2 Surveying, nautical charting and seabed mapping

The existing state of charting and other seabed mapping in the CAA remains incomplete. The charts required to maintain essential transportation services to coastal communities in the Kitikmeot region are adequate for existing draft vessels during the open water season. However, in order to provide flexibility in routing during the partially ice-covered periods, to allow improved SAR access and to support deeper draft vessels, significant improvements are required.

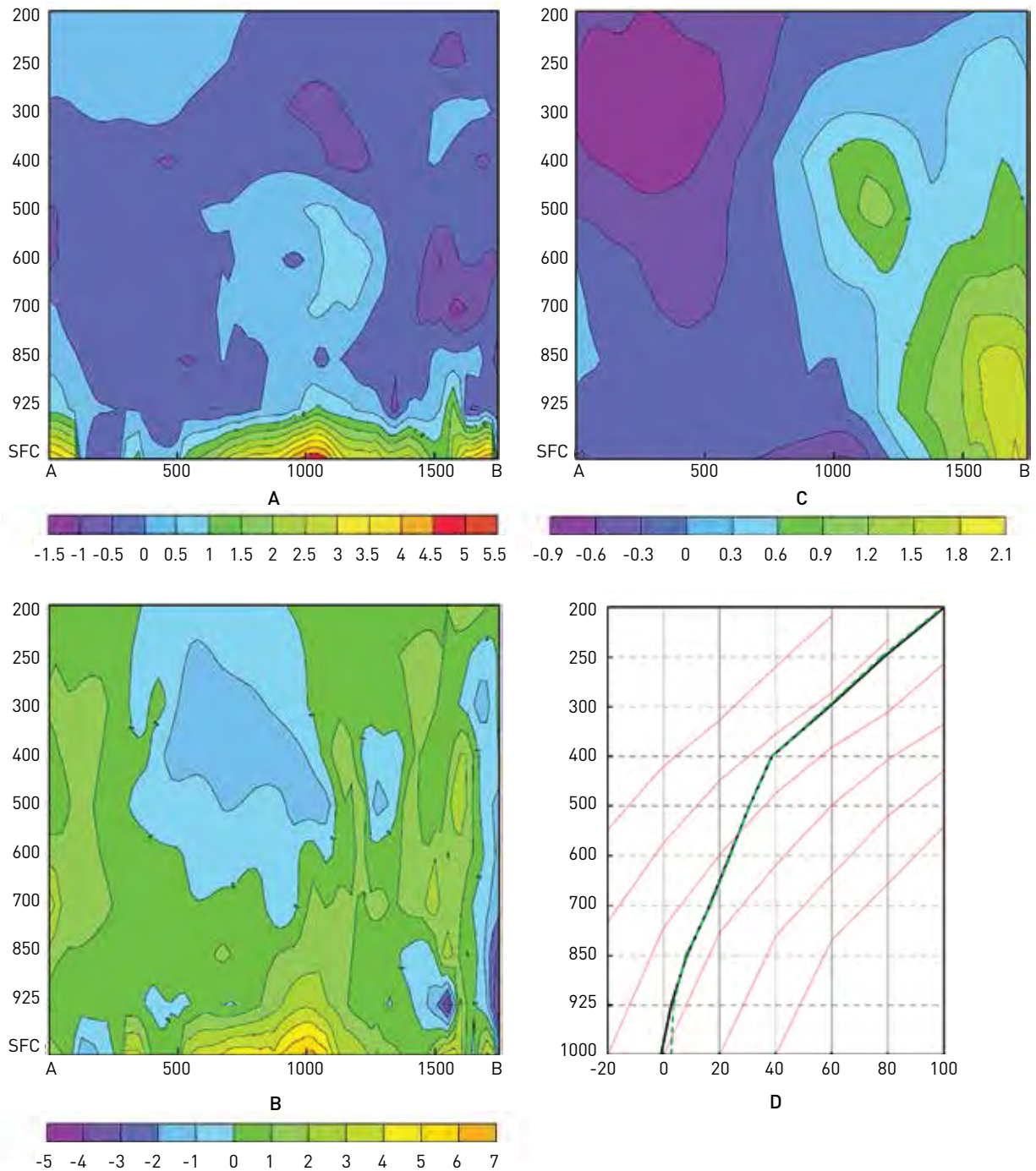


FIGURE 5. Vertical profiles along the black line in Figure 6(b) for the differences between EP2 (model in which sea ice is predicted by a coupled ice-ocean model) minus EP1 (model in which sea-ice cover is predicted by its climatology) for (a) temperature (°C), (b) wind speed (m s⁻¹), and (c) geopotential height (10 m), at 0:00 July 31. The graph in (d) shows the vertical profile of air potential temperature at the black dot (storm centre) shown in Figure 6(b), where the green dashed line is EP2, and black line is EP1; thin black, red and broken straight lines represent potential temperature, temperature and pressure respectively. Units are hPa and °C for Y and X coordinates in (d). Adapted from Long and Perrie (2012).

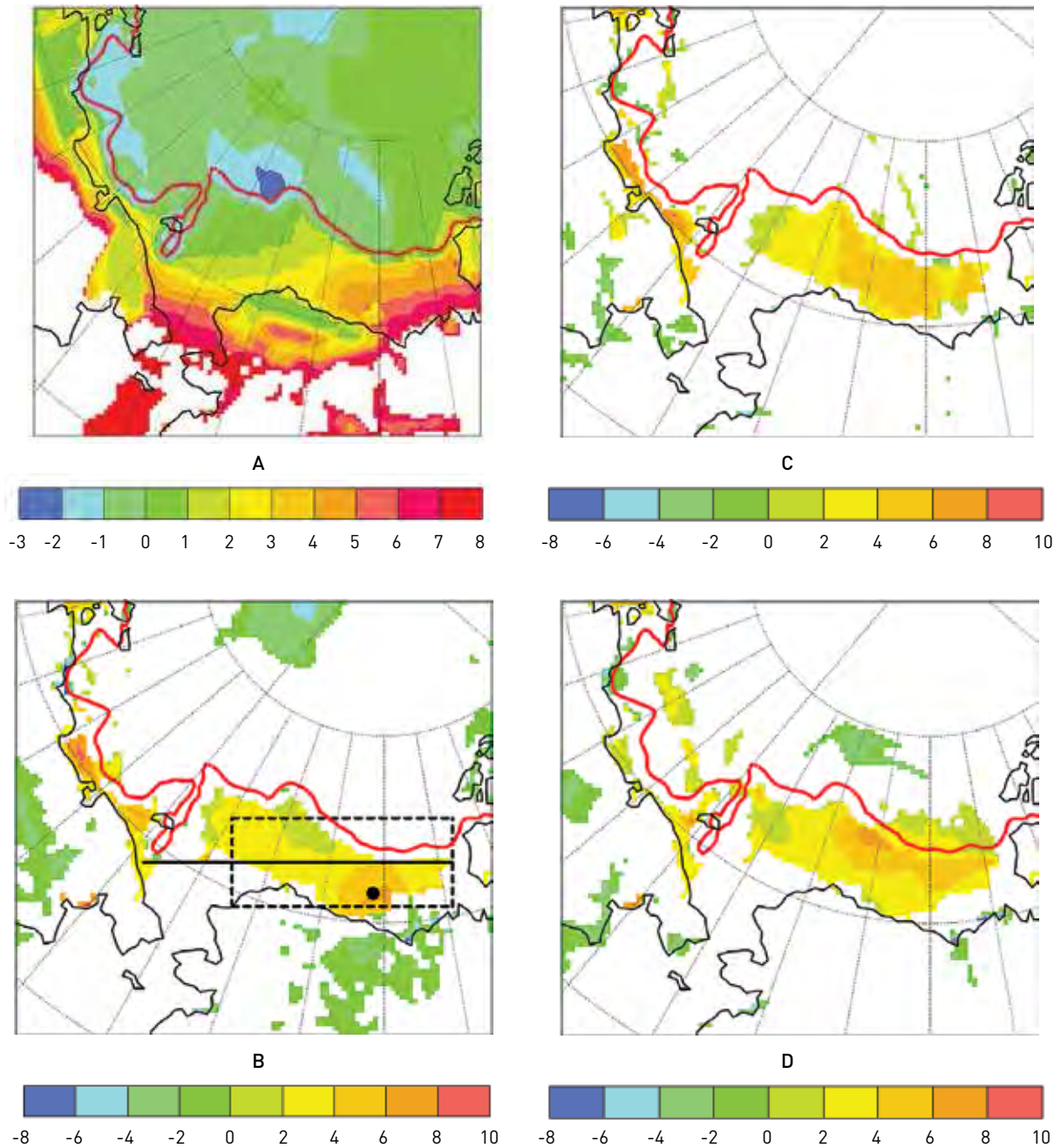


FIGURE 6. Surface air temperature [°C] for (a) EP2 and its differences between EP2 minus EP1 for (b) 0:00 UTC 30 July, (c) 0:00 UTC 31 July, and (d) 0:00 UTC 1 August. The box indicated by the thick dashed line in (b) is the area where the variables are averaged to show their daily variations for the Beaufort Sea area, and the thick line shown is the vertical profile in Figure 5. The red lines show the simulated ice edge. In (a), only the values smaller than 8°C are shown. Adapted from Long and Perrie (2012).

There is currently no government-funded mapping program in the North that can significantly change the state of charting over the next decade. Existing initiatives are piecemeal and limited by access to surplus coastguard icebreaker time. Given these limitations, the CHS priorities appear to be to continue expanding these corridors and particularly improving the approaches and anchorage areas in the vicinities of those communities that justify the effort. The prioritization of effort will continue to be based on balancing relative perceived importance of shipping activity, both large and small, against available resources (CHS 2013). However, both the clients (Wright 2012) and the surveyors themselves (Leyzack 2012) have clearly outlined the short term improvements needed.

Active natural resource exploration is currently underway in the western and central Canadian Arctic, primarily hydrocarbon exploration in the outer Beaufort Shelf and upper slope. Within the lease blocks, oil companies have been undertaking their own seabed mapping activities in collaboration with ArcticNet to support their needs. As natural resource extraction is driven by global demand and energy, given sufficient clarity in environmental legislation, it would proceed irrespective of predictions of climate change.

Tourism activities continue to undertake transits through the lesser charted areas. There is, as of yet, no requirement to seek approval for proposed transits, only reporting those transits to NORDREG (Northern Canada Vessel Traffic Services). Unless legislation is introduced to prohibit vessels from navigating along track soundings or in unsurveyed waters, these activities will continue. Some operators report routinely deploying sounder-equipped inflatable craft in advance of the main platform to mitigate this risk.

Given that the funding climate is unlikely to change, initiatives to improve the state of charting have to utilize existing platforms. The CCGS *Amundsen* model of acquiring underway high quality multibeam corridors has been shown to be particularly effective. All the 1200 class icebreakers, and potentially the CCGS *Fox* and CCGS *Laurier*, could all benefit from this retrofit installation of a basic swath

mapping capability. The reallocation of two berths on board is all that is required to ensure 24 hour acquisition. When the CCGS *Diefenbaker* does arrive (originally scheduled for 2017, currently delayed until at least 2020), she is currently designed to be capable of carrying several survey launches and have her own hull mounted mapping system.

To address deficiencies in the extent and density of nautical charting and other seabed mapping programs in the western and central Canadian Arctic, the following recommendations are put forward:

- (1) Retrofit existing 1200 and 1100 class icebreakers with survey capability to maintain transit corridor and SAR response capability;
- (2) Allocate a significant dedicated subset of the currently available icebreaker time to launch-based charting operations;
- (3) Potentially allocate specific periods of CCGS *Amundsen* time to systematic seabed mapping operations;
- (4) Consider legislation to restrict tourism cruises to specific charted corridors;
- (5) Charting Priorities: if the above are implemented, use the CHS prioritization scheme to assign these expanded capabilities; and
- (6) Habitat and geohazard assessment knowledge gaps, as recommended by BREA program results.

6.5.3 Storms

High-resolution studies are needed to simulate trends and climate change projections for waves, storm surge, and sea ice in an integrated manner following IPCC (2007-2008) climate change scenarios over the period 1970-2100, as well as estimates of extremes and return periods. It would furthermore be important to undertake selected studies for

communities (e.g. Tuktoyaktuk, Ulukhaktok) with respect to their fragile shorelines and associated infrastructure.

The southern Beaufort Sea is shallow and highly stratified. State-of-the-art studies should use modern high-resolution grid ocean models for coastal and near-shore applications, coupled to state-of-the-art models for sea ice and waves and storm surge. In addition to studies related to specific severe storm cases, reliable long-time climate-scale simulations need to estimate future climate change scenario conditions, in comparison to the present climate conditions. Wave-ice scattering can be incorporated by construction of new operational modules, building on previous work, particularly for studies of the marginal ice zone (Perrie and Hu 1996; Bennetts and Squire 2012a, b; Doble and Bidlot 2013; Shen et al. 2014).

For ocean and wave impacts, we would use regional climate model estimates as driving fields at high-resolution in order to estimate impacts of climate change scenarios of the Beaufort-Chukchi region and Arctic Ocean. Thus, storm climate results can be estimated; dynamically downscaled atmospheric fields and marine winds can be used as drivers for ocean and wave model estimates. Results of this work will provide improved ocean circulation results and wave estimates of present and future physical parameters related to ecosystem dynamics and marine infrastructure.

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Chapter 7. The Impact of Climate Change on Infrastructure in the Western and Central Canadian Arctic

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ABSTRACT

The stability and safety of infrastructure in the Inuvialuit Settlement Region (Yukon North Slope and Northwest Territories) and the Kitikmeot region (Nunavut) are of central concern to residents, governments, and industry. Infrastructure sensitivity occurs through climate-induced change in three key areas: permafrost, hydrology and coastal conditions. Permafrost (ground at or below 0°C for two years or more) is especially susceptible to changing climate, particularly where near-surface excess ice occurs. Melting of ice and associated thaw subsidence may induce instability of various infrastructure components. Additionally, land-use changes may alter drainage patterns, with effects on infrastructure that can range from expensive repairs to failure. Hydrological changes will alter seasonal flow peaks and stress drainage infrastructure. In the coastal sector, decreased sea ice has already resulted in increased wave activity. Rising temperatures and storm waves influence coastal retreat, particularly where erosion exposes massive ground ice and the combined effects of thermal and mechanical erosion occur. Projected changes in relative sea level (RSL) in the western part of the region may increase the impact of wave erosion and thermal abrasion on coastal retreat and infrastructure. Sea level is already rising in most Inuvialuit communities and a switch from falling to rising RSL in the Kitikmeot region may increase coastal hazards there. Rising sea levels lead to higher storm-surge flooding, more frequent exceedance of historical flood levels, inundation of low-lying land, and higher wave action on eroding shores. Accelerated coastal retreat has been documented on parts of the Alaska North Slope and the emerging evidence points to some areas of acceleration in the Canadian Beaufort region. Knowledge about the presence of ground ice and thaw-sensitive terrain, hydrological trends, sea-level rise, and coastal processes and hazards will provide the means to design appropriate infrastructure and minimize potential risk. New planning and design standards are emerging to help local decision makers improve the resilience of infrastructure, and educational initiatives are seeking to improve community knowledge of risks to infrastructure and other community assets.

7.1 Introduction

Modern northern communities depend on a wide range of infrastructure to support the well-being of residents, public safety, transportation, and economic activity. Additionally, economic development requires substantial infrastructure and is a major policy area for most northern governments. In general terms, infrastructure can be considered the various components associated with buildings, power, water, roads, airports, marine and related development. The extensive coastal regions in the western and central Canadian Arctic and the proximity of communities to the ocean means that both land and coastal processes in a changing climate can have substantial impacts on infrastructure. The provision of safe, economically sound infrastructure requires coordinated efforts of Federal, Territorial and community governments, planners, engineers and companies that construct and maintain various works.

The western and central Canadian Arctic represents a particularly diverse social and economic landscape with similarly diverse infrastructure needs. Unlike many areas of the Canadian North, the Inuvialuit Settlement Region (ISR) is connected to southern Canada by the all-season Dempster Highway that services several communities in the Mackenzie Delta region, directly and via seasonal ice roads, and maintenance of the highway is important for residents and businesses in the region. This road network is expanding with the construction of an all-season road between Inuvik and Tuktoyaktuk, and other roads are under consideration for resource development initiatives elsewhere in the region. In addition, all communities have local networks of roads that service homes, public buildings and related public works. Trail systems surrounding communities are also developed and maintained for resident access. Transportation in all communities is dependent on scheduled and charter air service and the availability of airport facilities is a critical infrastructure element, particularly in the northern and eastern ISR and the Kitikmeot region where no other means but marine transport is available. Communities without road links are supplied by sealift, either via the Mackenzie River

and Tuktoyaktuk, or by larger vessels from Vancouver or Montreal.

In communities, infrastructure ranges from public buildings like schools, medical centres, arenas and civic buildings, to energy production and distribution networks. ISR and Kitikmeot communities are isolated from wider electrical power distribution grids and depend on local diesel power generation and distribution. Additionally, nearby natural gas wells supply the Town of Inuvik with heating fuel.

Resource development in the region has focused on mineral and petroleum exploration (Chapter 9). In the Kitikmeot region, the exploration focus has been on minerals, with a number of discoveries resulting in proposals for port development in Coronation Gulf (Grays Bay, Roberts Bay) and Bathurst Inlet (Couture et al. 2014). The discovery of large reserves of natural gas in the Mackenzie Delta and oil and gas in the adjacent Beaufort Sea has resulted in proposals for the construction of a pipeline to deliver hydrocarbons to southern markets. The Mackenzie Gas Project (MGP), a consortium of oil and aboriginal companies, has been in discussion and evaluation for over a decade, but as approval was delayed, costs rose, and new shale gas reserves were brought on-line, the project was put on hold. Meanwhile, the sale of offshore leases near the shelf-edge in the Beaufort Sea has shifted attention seaward. The most probable transportation option for any discoveries there would be marine shipping.

The earliest development likely to come on stream is the Amauligak field, still the largest oil and gas discovery in the region, located 75 km northwest of Tuktoyaktuk. Offshore development will require onshore ports, shore-based facilities, and transportation infrastructure. A synthesis of coastal geoscience knowledge to address these issues in the Beaufort Sea region and in the context of climate change is currently being completed under the Beaufort Regional Environmental Assessment program (e.g. Fraser et al. 2013; Forbes et al. 2014).



This wide range of infrastructure needs represents a key challenge for residents and governments in the region. Planning and building safe, affordable, and durable infrastructure is of paramount importance to residents in their daily lives and to sustain and grow the economy of the region. Similarly, infrastructure development needs to reflect both physical constraints of the region and climate, but also to be planned to minimize socio-cultural and environmental impacts. Projected climate change will have a variety of potential impacts on built and planned infrastructure. Thus, in addition to meeting the needs of northerners, infrastructure must be conceived in response to changing environmental conditions which could induce additional maintenance costs, bring about premature replacement, or even negatively impact the surrounding environment.

This chapter presents an overview of the state of knowledge on the sensitivity of infrastructure in the ISR and the Kitikmeot region, with an emphasis on the impact of changes to permafrost, coastal systems and hydrology. There has been a considerable amount of research and engineering work directed at these issues, and this chapter brings this literature together in the context of climate change sensitivity.

7.2 Permafrost scientific background

Permafrost is defined as ground material that maintains a temperature of $\leq 0^{\circ}\text{C}$ for at least two consecutive years (Muller 1943; Brown et al. 2001). While it may be composed of any rock, soil, ice, or organic material, it is ice-rich permafrost that is of particular interest in relation to infrastructure, sensitivity to climate change, and potential for thaw subsidence. In areas of postglacial uplift and falling relative sea level, saline permafrost (not necessarily ice-bonded) can also create engineering challenges. Permafrost is found on land throughout the western and central Canadian Arctic and ranges in thickness from <100 m in the southern limits and parts of the Mackenzie Delta to more than 700 m in areas with long exposure to cold climate (Dallimore et al. 1988). Additionally, due to lower sea levels during the last glaciation, many areas of the shallow continental shelf developed permafrost that remains despite the subsequent submersion by the ocean.

The presence of permafrost is related to the cold climate and reflects the combination of limited energy available in summer to warm the ground and winter heat loss from the soil to the atmosphere. Although permafrost is a phenomenon linked to climate, it does not necessarily respond to climate

variability in a given year. On the other hand, the *active layer*; the surface layer above the permafrost that thaws each summer (Ray 1951), is sensitive to short-term (seasonal) temperatures. The maximum depth of thaw reached at the end of each summer depends on the ground composition, vegetation cover, and other local factors such as orientation, slope, and drainage conditions, and typically varies from 0.5 to 2 m depending on the latitude and regional climate (Brown et al. 2000).

The seasonal thaw and re-freezing of the active layer is well understood (Bonnaventure and Lamoureux 2013) and represents one of the most important aspects of climate sensitivity for many types of infrastructure. The depth of thaw increases through the summer over weeks to months (Figure 1), with implications for infrastructure stability, particularly where the upper part of the permafrost is ice-rich (Figure 2). When ice-rich permafrost thaws, the water drains away, leaving empty volume below the surface that is subject to settling. This can lead to a variety of *thermokarst* processes, ranging from localized to widespread subsidence of the land surface (Figure 3), localized slope failures, and changes in drainage as the land subsides. The latter can result in the formation of new ponds and lakes, and in other cases, the rapid drainage of existing ponds and lakes. Due to natural variations in ice content and land surface material composition, thermokarst typically results in irregular subsidence and landscape change, all of which has implications for infrastructure design and stability.

Ice content in the uppermost permafrost (below the active layer) varies considerably across the western and central Canadian Arctic (Figure 4). The composition of surface material is the primary control over ice content, with fine sediments that contain silt and clay most prone to high ice content, and coarser materials like gravel with lower ice content. Peat can also contain a substantial amount of ice, while ice content of rock is negligible.

Anomalously warm temperatures in a given year may result in thaw to depths below the temporal mean thickness of the active layer, releasing water that would otherwise be frozen.

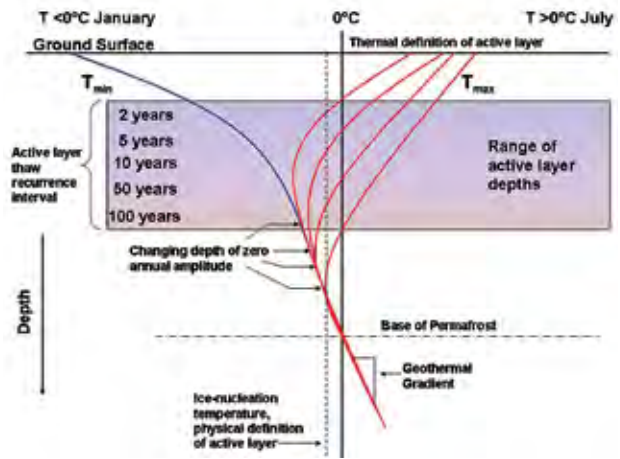


FIGURE 1. Schematic temperature profile of the active layer and uppermost permafrost. The blue line indicates a typical winter temperature profile, while red lines indicate summer profiles. The depth of thaw is dependent on weather conditions, hence, summer thaw and active layer depth varies. Thaw depth can be considered in terms of recurrence, with unusual thaw conditions occurring increasingly less frequently. From Bonnaventure and Lamoureux (2013).

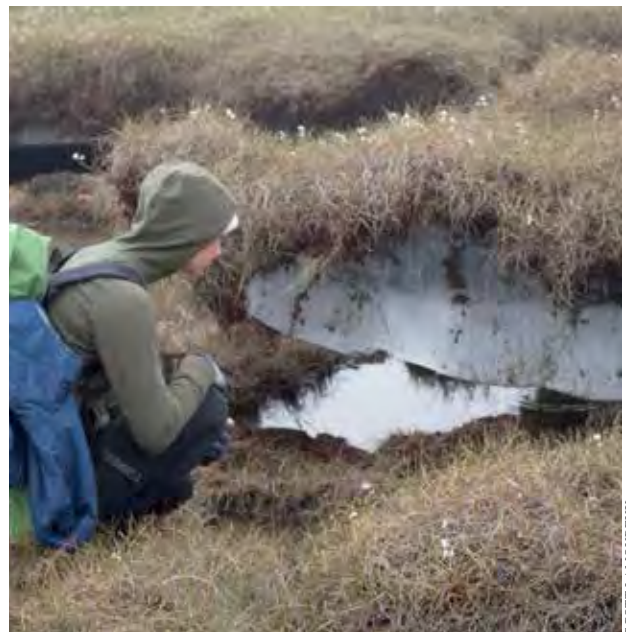


FIGURE 2. An example of ice-rich permafrost just below the seasonal active layer. In this location, the ice has been exposed by disturbance and is now melting rapidly, leading to further surface disturbance.

Year to year variations in weather result in the accumulation of ice below the active layer. This zone, referred to as the *transient layer* (Figure 1) (Shur et al. 2005; Bonnaventure and Lamoureux 2013), is subject to thaw on an infrequent basis and is often ice-rich. If a warming trend continues over a longer period of time, the active layer can thicken and expand into the transient layer and result in thaw subsidence. In some places, layers of nearly-pure ice that can be metres thick occur below the surface (Mackay 1971). This massive ground ice is particularly susceptible to thermokarst or other disturbance (Figure 3). Numerous studies have demonstrated the presence of massive ice in many areas of the region, particularly in the Beaufort Sea region of the Yukon coast, Mackenzie Delta, Tuktoyaktuk Peninsula Cape Bathurst, and Banks Island (Mackay 1959; Rampton 1982, 1988; Heginbottom 2000; Manson et al. 2005b; Forbes and Hansom 2012; Lantuit et al. 2012; Kokelj et al. 2013).

In addition to thermokarst, ice-rich permafrost landscapes are susceptible to other types of disturbance, particularly *active layer detachments* (ALD) and *retrogressive thaw slumps* (RTS) (Figures 5 and 6). These disturbances occur rapidly over hours to days, may remain active for a year or longer, and may be reactivated after a period of inactivity. They represent a major hazard for infrastructure that might be directly impacted, or in cases where they cause rapid erosion, may impact downstream infrastructure. ALD range from 10 m to >1000 m in length and >100 m wide (Figure 5), while RTS can extend for hundreds of metres along coastal slopes with headwalls up to 20 m or more in height and can remove greater amounts of material (Figure 6). ALDs have been investigated on Melville Island (Lamoureux and Lafrenière 2009), while RTS features and processes have received considerable attention in the Beaufort-Mackenzie region (e.g. Harper 1990; Lantz and Kokelj 2008; Kokelj et al. 2009, 2013; Lantuit et al. 2012). Recent research has focused on developing techniques to remotely map these permafrost disturbances and will aid in determining the susceptibility of various landscapes to future disturbance (see Box 1).

Other distinctive forms of coastal erosion in ice-rich terrain include thermal niche undercutting and toppling of tundra polygon blocks defined by exposure and melting ice wedges (Hoque and Pollard 2009; Forbes and Hansom 2012). The impact that these disturbances have on infrastructure can be catastrophic. Conversely, poorly designed or planned infrastructure can trigger these disturbances, resulting in substantial environmental impacts that are beginning to be studied (Lewis et al. 2012; Kokelj et al. 2013). Ecosystem impacts are discussed in Chapter 3.

Collectively, the presence of permafrost and the changing balance between seasonal active layer depth, land stability and climate is of critical concern for the design and

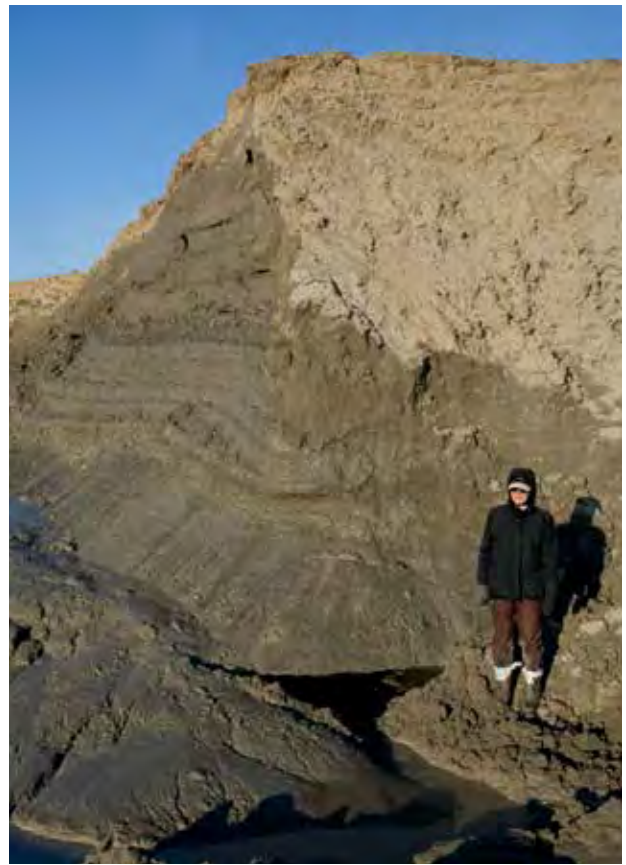


FIGURE 3. An example of massive ground ice exposed by a stream on Melville Island. In this example, the exposed ice is rapidly melting resulting in the collapse of the overlying sediment material, maintaining a steep cliff face.

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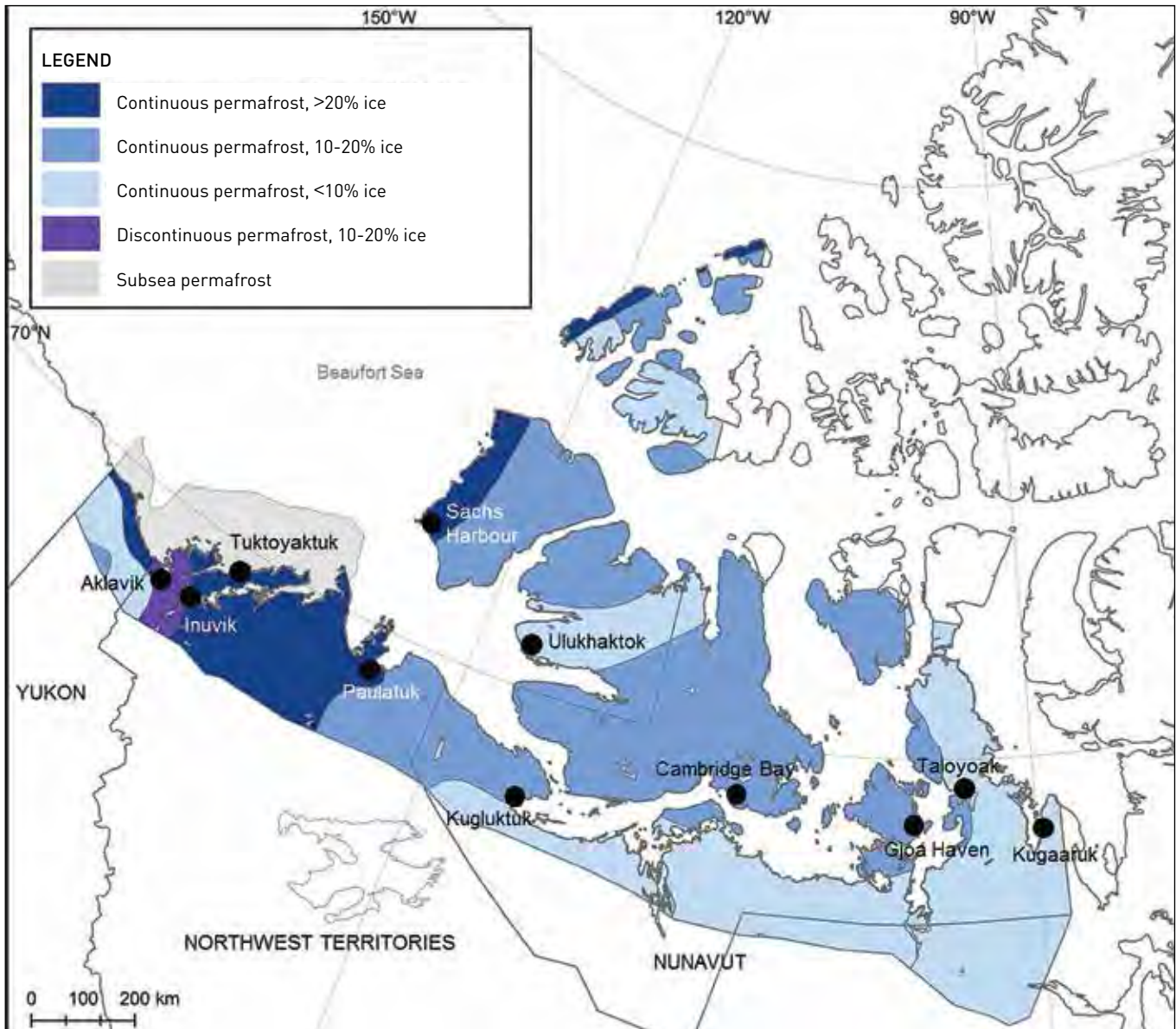
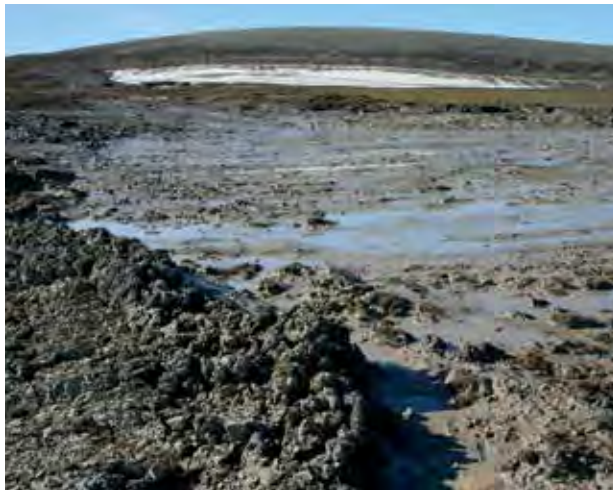


FIGURE 4. Map indicating areas with widespread ice-rich permafrost in the ISR and Kitikmeot region of Nunavut. Ground ice contents are generally >20% (dark blue), 10-20% (medium blue) and <10% (light blue). Permafrost is continuous in all areas with the exception of the Mackenzie Delta (violet), where discontinuous permafrost with 10-20% ground ice occurs. Ground ice contents are highly simplified and can vary substantially over short distances, and may be higher or lower locally. Adapted from the Permafrost Map of Canada (Heginbottom et al. 1995).

maintenance of infrastructure (Couture et al. 2003; Hoeve et al. 2006; Prowse et al. 2009). Recent climate trends and projected climate change in the ISR and the Kitikmeot region indicate both summer and winter warming, particularly in the Mackenzie Delta region (Chapter 2), where an increase in mean annual ground-surface temperature is already apparent (Burn and Kokelj 2009). Air temperatures in all seasons are expected to warm substantially (+1 to +7°C) on an annual basis, with most pronounced warming



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FIGURE 5. Examples of permafrost disturbance on Melville Island. Top: A portion of an active layer detachment (ALD) with soil and plant material removed by shallow sliding of the active layer. Bottom: A retrogressive thaw slump (RTS) with exposed ice and overburden of soil. The thawing of the ice destabilizes the overburden and causes sustained erosion.

in autumn and winter months, especially in the Kitikmeot region and the northern islands (Chapter 2).

Increased autumn and winter temperatures accompanied by increased snowfall and snow cover depth are all conducive to warmer winter soil temperatures. Experiments carried out in the western and central Canadian Arctic show that early enhanced snowpack will result in soil temperatures 8°C warmer (Lafrenière et al. 2013). Warmer soils result from increased insulation by snow cover and reduced heat loss during the winter months, contributing to overall warming of the upper permafrost. In combination with rapid snow loss in the spring due to warmer air temperatures, the soil will begin to warm earlier and increase active layer thaw depth. Thus, the projected climate changes are likely to have substantial impacts on the uppermost permafrost, contributing to warmer winter soils and greater summer melt (Lafrenière et al. 2013). On the other hand, some parts of the region may see less snow. Recent results from the Mackenzie Delta reveal a 32% reduction in late-winter snow depth at Inuvik from 1958 to 2012 (Lesack et al. 2013, 2014).

According to projected climate changes (Chapter 2), further feedbacks are expected as shrub growth expands northward. Shrubs increase the accumulation of snow by trapping, resulting in further thickening of winter snowpack and soil warming (Sturm et al. 2001). Expansion of



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FIGURE 6. Example of a large retrogressive thaw slump on the Peel Plateau, south of the Mackenzie Delta.

shrub cover has been noted in the southern margins of the ISR and Kitikmeot region and elsewhere in Arctic North America (Myers-Smith et al. 2011; Lévesque et al. 2012; Chapter 3).

In summary, the climate warming that is projected for 2050 (Chapter 2) will likely contribute conditions that could enhance the warming of soil, deepening of the active layer, and the thawing of the upper permafrost (Zhang et al. 2008). This is particularly important in the southern margins of the region, where the permafrost is relatively warm and thin (Burn et al. 2009) and changes to ground ice content can be expected to impact infrastructure (Figure 4). Elsewhere, most of the northern region has thick, continuous permafrost and the projected changes are unlikely to eliminate permafrost. Rather, the impact of warming will be as impacts on infrastructure through thaw subsidence and the triggering of disturbance processes such as RTS and ALD. These types of disturbance can rapidly affect infrastructure and represent a major hazard associated with climate change and permafrost.

7.3 Changes in surface and subsurface drainage

Water drainage is another important climate-sensitive phenomenon relevant to infrastructure stability in permafrost landscapes. The hydrology of Arctic regions experiences

high seasonal variability and is dependent on the accumulation of snow during the winter, on the factors affecting the rate of spring melt and runoff, and on the low flow rates during the summer which can increase dramatically following substantial rainfall (see Chapter 3). Subsurface infiltration and drainage in permafrost regions is limited to the shallow active layer where seasonally thawed conditions develop. Hence, climate-driven changes to hydrology contribute to permafrost change, and irregular degradation of permafrost can in turn alter drainage patterns that amplify impacts on infrastructure.

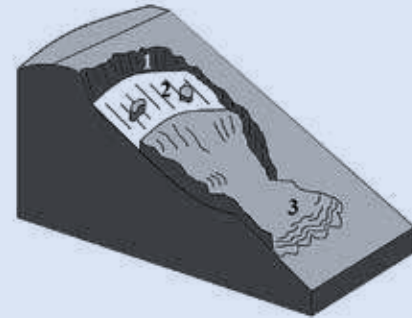
The hydrology of the western and central Canadian Arctic is highly variable and reflects the landscape, vegetation and soil properties, in addition to water storage as snow and ground ice in winter (Chapter 3). To date, few studies have projected changes in hydrology in the region. In one example from the northern islands, Lewis and Lamoureux (2010) noted that spring runoff is expected to be earlier due to warming, and increased snowpack would generate greater total discharge. The runoff period is projected to be longer by 30 days, but the low-flow conditions after snow melt were not assessed (Lewis and Lamoureux 2010) (Figure 7). Hence, little is known about the potential for major summer rainfall events and the potential for flooding. Some work suggests that major rainfall events can generate the highest discharge of the year over a short period of days (Figure 8) (Lewis et al. 2012). However, the broader impact of future summer rainfall remains poorly known for the region.

BOX 1. Mapping permafrost disturbances with satellite remote sensing

Permafrost related hazards are of growing concern in Arctic regions where the effects of climate change are rapidly resulting in unstable landscapes (Nelson et al. 2002; ACIA 2005). Thawing of near-surface ground ice on slopes can lead to instabilities in the substrate, resulting in exposures of ice bodies and/or ice-rich sediments that generate rapid mass movements such as active layer detachments (ALDs) (Lamoureux and Lafrenière 2009). ALDs pose a serious risk for infrastructure and can impact environmental and ecological stability in Arctic regions; thus effective recognition and detection of slope disturbances is critical for future hazard analysis.

BOX 1. (Continued)

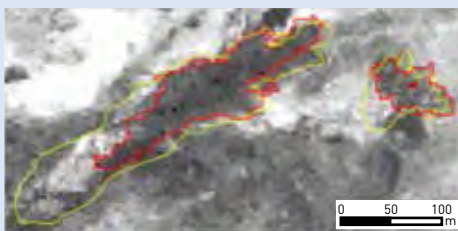
Historically, this has primarily been done through manual image interpretation and field mapping, both of which are cost-intensive. Semi-automatic detection techniques have been successfully applied in more temperate regions to identify slope failures; however, little work has been done to map permafrost disturbances. A new method has been developed to detect and map ALDs using multi-temporal satellite imagery in combination with change detection techniques (Rudy et al. 2013). These methods have been applied to a location with recent and well-documented ALD activity in the Canadian High Arctic where ground-based field mapping of disturbances was conducted, but similar features are widespread in the northern areas of the western and central Canadian Arctic.



A schematic view of an active layer detachment, including the three primary distinguishing features. From Rudy et al. (2013).

The morphology of a typical ALD can be broken into different geomorphic and spectral zones: 1) the scarp; 2) the scar or extension zone; and 3) the toe or compression zone (see schematic). The scarp is the initiation point of the disturbance and is typically evident as a vertical to near-vertical headwall. The scar zone, located at the upper initiation point of the slide, is characterized by bare ground, giving it a bright appearance and distinct spectral signature. Material moving downslope accumulates in the toe zone and is composed of vegetated ridges that are spectrally similar to adjacent undisturbed surfaces. The change in land cover from vegetated to un-vegetated in the scar zone is well captured by remotely sensed data and can be used for the identification of ALDs. Results from this study collectively show promise for the semi-automated detection of slope disturbances in permafrost settings and a cost-effective method to delineate areas for more detailed hazard assessment methods (Rudy et al. 2013).

NDVI 2004



NDVI 2010



LEFT: The removal of vegetation within disturbances results in spectrally different zones visible in satellite imagery (represented here by the normalized difference vegetation index, or NDVI). In NDVI images, areas that are bright represent areas with more vegetation cover or vigour, while areas that are dark grey to black indicate decreased vegetation cover or vigour. Changes in NDVI between dates can be an indication of disturbance. In this example, the 2004 pre-disturbance NDVI is white and indicates that it is well vegetated. In 2010, after disturbance, this same location is darker and depicts a decrease in vegetation cover. This change in vegetation represented by NDVI is a direct result of the formation of an ALD (yellow outline). Change detection methods used in this study were able to detect and classify this change as shown by the red outline. From Rudy et al. (2013).

Increasing discharge in large rivers draining to the Arctic Ocean (Peterson et al. 2002) has been attributed to a climate-driven intensification of the hydrological cycle in circum-Arctic drainage basins (Déry et al. 2009). However, in the Mackenzie River, although the low winter flow has increased, total annual discharge to the delta shows no

statistically significant change and the timing of freshet initiation at the head of the delta is unchanged (Lesack et al. 2013). Thinner late-winter snow cover and local spring warming are driving more rapid breakup and earlier peak flows, with implications for flooding in the delta (Lesack et al. 2014). This may result in lower peak flows on average

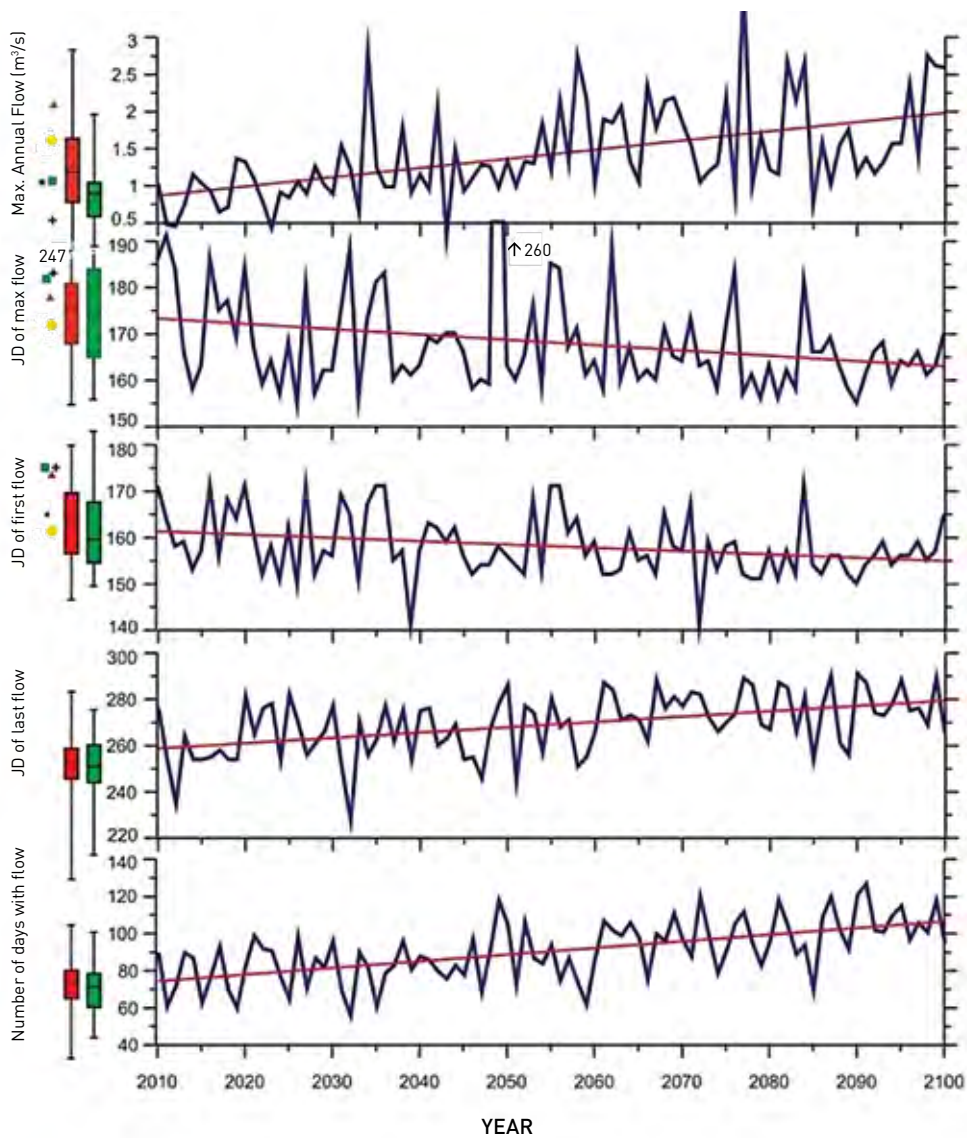


FIGURE 7. Projected runoff from the West River, Cape Bounty, Melville Island in the High Arctic based on IPCC A2 scenario. Dates are in Julian Days (JD), and indicate earlier, increasing flow as the 21st Century progresses. Red and green box and whisker symbols on left axis indicate the range of hydrological response with the model based on 1949-1997 meteorological data from Mould Bay, NT, and 1961-1996 Canadian Climate Model scenario CGCM3-20CM3, respectively. Adapted from Lewis and Lamoureux [2010].

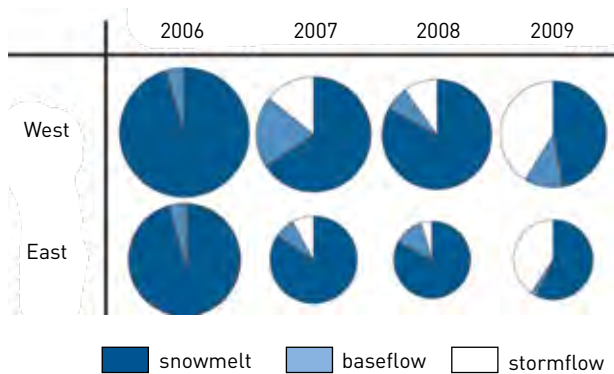


FIGURE 8. Example of changes in runoff for two rivers on Melville Island. Each pie wedge is proportional to the amount of flow from different sources. Two rainfall events in 2009 were responsible for over 40% of river flow for the entire season, while rainfall had little or no influence in other years. Adapted from Lewis et al. (2012).

(reducing the flood threat in Aklavik), though extensive overbank flooding will still occur, while rising sea level and backwater are raising summer low-flow water levels (Lesack and Marsh 2007).

Extreme flows in the western and central Canadian Arctic are normally generated by snowmelt or heavy rainfall (Woo 2012). Flows in rivers and streams can exceed the design capacity of drainage structures such as culverts and bridges, causing damage to infrastructure through flooding and erosion. Extreme flooding can occur rapidly, with little warning, resulting in significant disruption from infrastructure damage. Major examples of flood damage to infrastructure include the washout of a key road bridge in Pangnirtung, Nunavut in June 2008 (Figure 9) and extensive damage to culverts and washouts along the Dempster Highway in the Yukon in the 1980s, shortly after construction. These examples demonstrate the risk to vital infrastructure. The Pangnirtung example also demonstrates the potential disruption a community may face from the failure of critical infrastructure and the challenges of planning for such an event (LeBlanc et al. 2011). Major dissection of streets in Kugluktuk following a 171 mm rainfall event in July



FIGURE 9. Damage to the Duval River bridge in Pangnirtung, NU after a major rainfall flood in June, 2008. The bridge was rendered unusable, which separated important community facilities, and disrupted water and sewage transport until it could be replaced.

2007 caused significant disruption and expense (Figure 8 in Smith 2014).

Flood prediction requires a good knowledge of river flow conditions and historical data. Engineers use this information to estimate the size of floods with different return periods (e.g. 100-year flood). Apart from the Mackenzie River and Delta, the lack of hydrological records in the ISR and the Kitikmeot region (Spence and Burke 2008), particularly on smaller rivers that cross transportation corridors or pass through communities, represents a key limitation to estimating flood size and recurrence. An additional challenge arises from changing climate, which affects the conditions that generate floods and makes predictions based on historical data less likely to be accurate (Lesack et al. 2013). While these shortcomings can be overcome by conservative design practice when planning and building drainage structures like culverts and bridges, overly conservative designs usually add cost to projects that may not be necessary. Hence, the uncertainty of building safe infrastructure for drainage may result in designs that are either inadequate for future flow changes, or may be unnecessarily expensive.



FIGURE 10. Typical road drainage conditions in the ISR and the Kitikmeot region. This example is from Cambridge Bay, NU.

Changes in community drainage represent another dimension of potential impact of climate change on infrastructure. This is especially the case as many communities have developed with minimal or ad hoc drainage plans and infrastructure (Figure 10). Communities or infrastructure built on ice-rich permafrost are susceptible to subsidence when the permafrost degrades, resulting in changing water pathways and ponding. Ponding of water is particularly problematic because standing water can enhance the thaw of underlying permafrost causing further subsidence. These changes can in turn impact infrastructure through either subsidence or higher soil water contents, the latter of which can cause failure of fine grained sediments and disturbance of the soil. Poor drainage can also deliver heat from water to the base of infrastructure, resulting in ground ice melt and irregular subsidence (de Grandpré et al. 2010; Smith 2014). Additionally, subsidence and ponding can affect drainage structures associated with infrastructure (e.g. culverts), further exacerbating drainage issues. Furthermore, ponding in Cambridge Bay, NU has been identified as a public health issue, because it increases otherwise limited breeding habitat for insect vectors of disease (Smith and Forbes 2014).

Finally, construction of infrastructure may alter wind patterns and the accumulation of snow, particularly drifting snow. Drifts can represent a substantial winter nuisance,

but can also impede drainage in the summer and cause ponding and flooding during the snow-melt season. Snow drift patterns can change due to the construction of new or additional infrastructure, or may develop as wind directions change. Predicting the impact of projected climate change on wind directions and local snow drifting conditions is not currently possible, but may become necessary in some situations where accumulation patterns change and require remediation.

Considerable effort is currently underway to develop standards for the design of community drainage infrastructure, as discussed later in this chapter. In particular, community maintenance staff, engineers and planners have sought guidelines to improve the management of drainage in communities to help manage infrastructure.

7.4 Building foundation stability

One of the key sensitivities of infrastructure to permafrost change is through the stability of building foundations which may be highly susceptible to thaw subsidence due to a number of factors (Couture et al. 2003; Hoeve et al. 2006). Firstly, clearing the space for the building may remove insulating vegetation and alter the thermal balance of the underlying permafrost. Secondly, heat from a building in contact with the soil can contribute to warming and thaw of the permafrost. Similarly, the building reduces soil heat loss to the atmosphere in the winter, keeping the soil warmer compared to the surrounding area. Thirdly, the building may alter the drainage or accumulation of snow, resulting in a number of changes to soil moisture and reduced winter heat loss. Collectively, buildings can substantially perturb the thermal balance, leading to the loss of ground ice and thaw subsidence that leads to stress on the structure, potential damage, and in rare cases, failure. These issues are most problematic where permafrost is ice-rich and where the potential for thaw subsidence exists. By contrast, foundations on bedrock or coarse grained soils (gravels) are less susceptible and these effects are often minimal.

Many buildings built before the 1990s are particularly susceptible to foundation subsidence due to inadequate planning to preserve underlying permafrost. This results in increased maintenance and remediation costs (Prowse et al. 2009). Repairs necessary to upgrade deficient building foundations are often expensive. In one comprehensive study, the costs were estimated to approach the assessed value of the buildings in the ISR and the Kitikmeot region and elsewhere in the Canadian Arctic (Hoeve et al. 2006).

Solutions to prevent damage to building foundations differ for retrofitting existing buildings compared to new construction. For new construction, the selection of building sites that avoid ice-rich permafrost is a critical first step. The conventional and often expensive approach to determine ice content includes permafrost coring to recover

samples. Drilling efficiency and economy can be improved by the use of geophysical techniques including capacitive coupled resistivity and ground-penetrating radar. Research has demonstrated the utility of these methods for recognizing ice-rich areas, allowing relatively rapid assessment of conditions prior to validation by excavation or drilling (Figure 11) (De Pascale et al. 2008; Angelopoulos et al. 2013).

In addition to geophysical approaches, considerable benefit for planning infrastructure and recognizing ice-rich terrain can be determined from systematic community mapping of geomorphic landforms, sediments and features. Combined with drilling to sample material, deposits susceptible to disturbance can be recognized. ArcticNet and NRCan researchers have contributed to community mapping in the

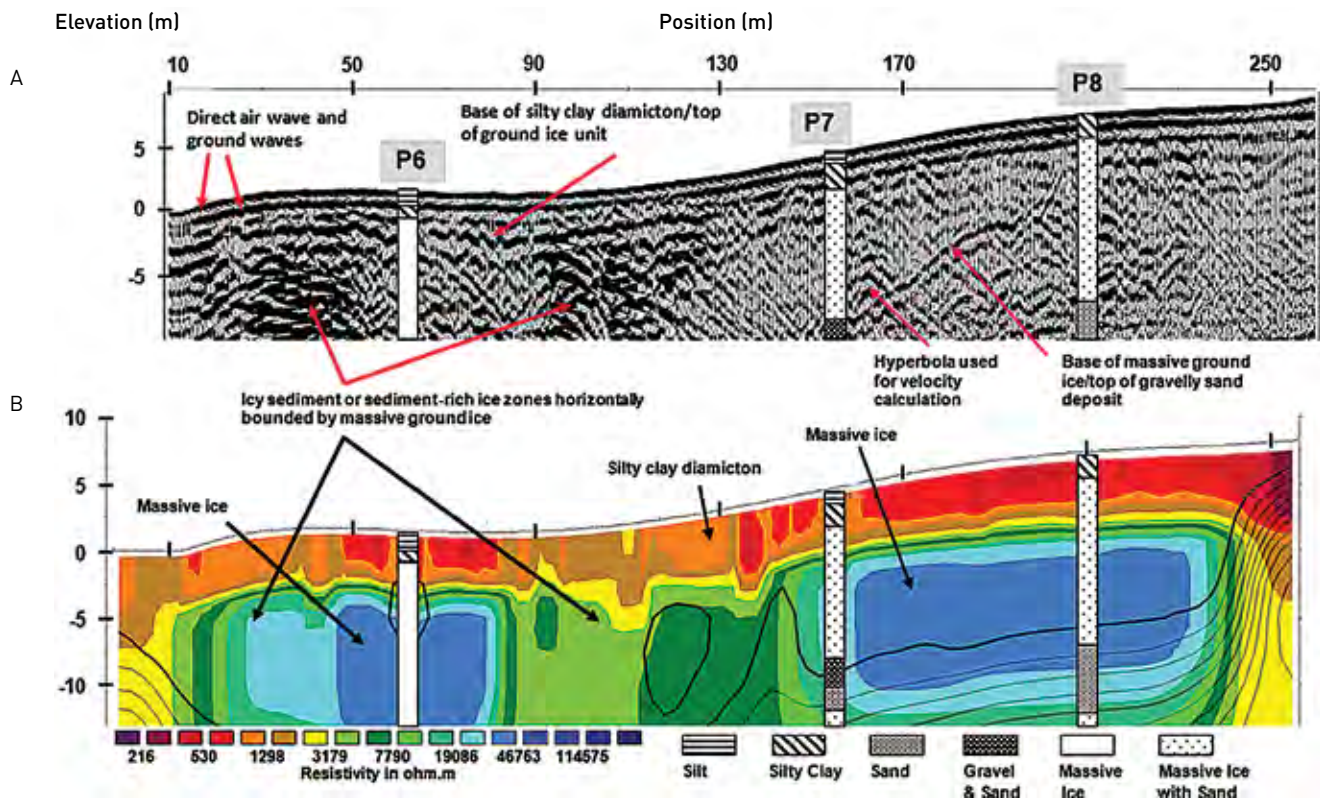


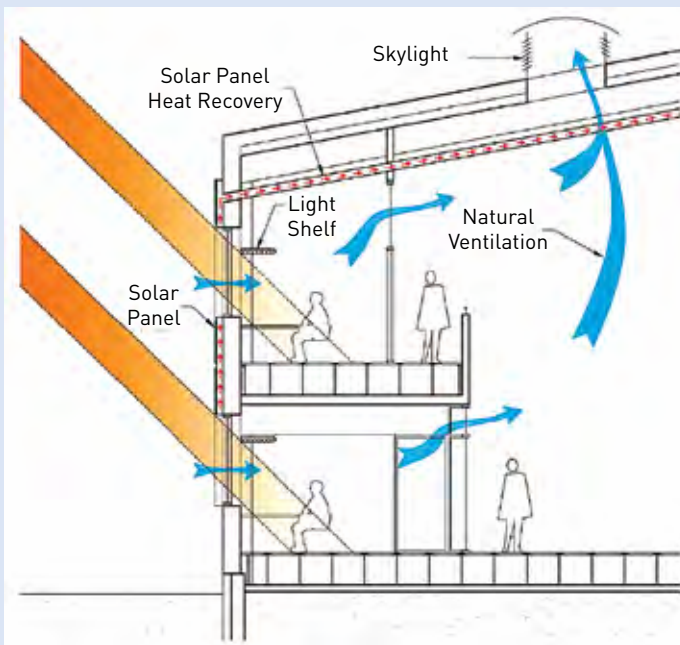
FIGURE 11. Example of ground-penetrating radar (a) and resistivity images (b) from near Parsons Lake, near Tuktoyaktuk, NT. Interpretation of these techniques allows delineation of massive ice and ice-rich zones in the subsurface. Methodological details can be found in the source (Angelopoulos et al. 2013).

ISR and the Kitikmeot regions (e.g. Manson et al. 2005a, b; Smith 2014; Smith and Forbes 2014), supporting community climate-change adaptation assessment and planning (Pearce et al. 2009; Calihoo and Romaine 2010; Johnson and Arnold 2010), although systematic mapping of communities has not been broadly undertaken. Combined with local and traditional knowledge (Catto and Parewick 2008; Forbes et al. 2013), these strategies can be used to create community development plans that incorporate knowledge of areas susceptible to permafrost disturbance.

Preparation of the ground for new buildings is a key first step for minimizing the impact of potential permafrost disturbance. Buildings in northern communities are frequently built on aggregate pads to level the surface and to divert drainage. Once built, the pads will be subject to freeze activity and thus should be composed of coarse aggregate to minimize water retention and encourage convective heat loss, as well as to minimize the transfer of building heat to the ground. However, access to coarse aggregate (gravel) is limited in many northern communities (Borsy 2009), forcing the use of less suitable material.

BOX 2. Canadian High Arctic Research Station – state-of-the-art northern infrastructure

The Canadian High Arctic Research Station (CHARS), currently in the construction phase, will provide a world-class hub for science and technology in Canada’s North that complements and anchors the network of smaller regional facilities across the North. Construction in Cambridge Bay, Nunavut, began in the fall of 2014, and has a planned opening date of 2017. The Station will provide a suite of services of science and technology, including a technology development centre, a knowledge-sharing space, and advanced laboratories, as well as spaces for public use to support integration into the host community.



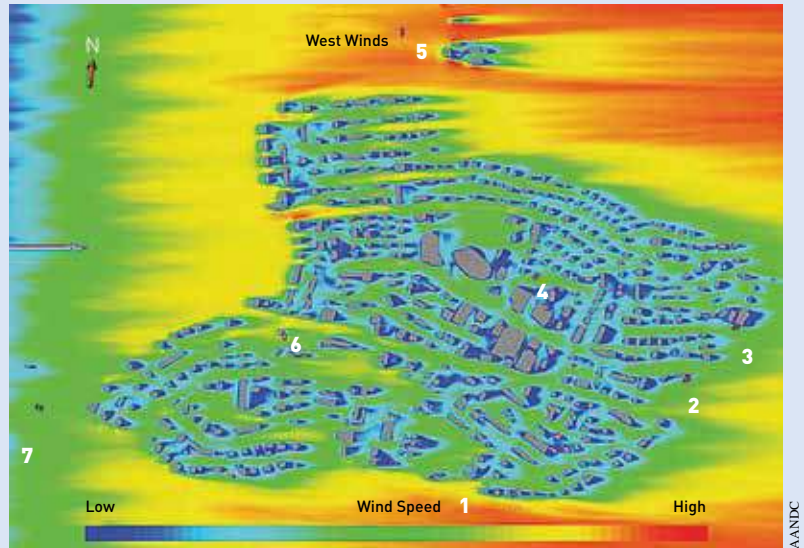
Striving to ensure a sustainable design is of paramount importance at CHARS, given the extreme weather conditions and high costs of operating in the Arctic. This approach relates to the better use of all resources, including energy, water, and materials. Of particular interest are strategies and approaches that could be adapted for use across the North.

The design of CHARS addresses sustainability in a number of ways, including energy consumption, water use, occupant comfort, blowing snow accumulation, and permafrost stability.

Given the high cost of energy and water in the North, it is imperative to reduce consumption wherever possible. Some strategies include

BOX 2. (Continued)

the use of high-efficiency lighting, and high-performance, triple-glazed windows to reduce heat loss. Solar (photovoltaic) panels incorporated into the building façade are being explored as an option to produce electricity and pre-heat incoming ventilation air. The use of composting toilets, low-flow aerating faucets, and water-efficient laboratory equipment are options to dramatically reduce water consumption at the facility.



Occupant comfort is important for worker productivity and satisfaction, and requires special attention in the challenging northern environment. Architectural consideration of daylight in offices and other work areas will ensure sufficient natural light for occupants during the summer months, while “full-spectrum” lighting could reduce the impact of 24-hour darkness during the winter by more closely emulating natural sunlight. Operable windows support natural ventilation, giving occupants greater control over their environment and ensuring adequate fresh air. An “adiabatic humidification system” ensures sufficient humidity is added to the dry Arctic air, while reducing energy consumption associated with conventional humidification approaches.

Blowing snow accumulation is a major problem in the North. During high-speed wind events, snow can accumulate on roads and in entry ways to buildings, posing a health and safety risk and requiring substantial investment in snow removal equipment and operation. These impacts can be mitigated by orienting buildings so that prevailing winds scour snow from doorways. A detailed computer analysis during the conceptual stage helped understand the impact of snow accumulation at the CHARS site (see figure right). As the design develops, mitigation strategies will be confirmed through scale model tests.

Permafrost is another very important consideration in the North. To ensure long-term stability of the underlying permafrost, detailed analyses of ground conditions and the impacts of heat loss from the building to the soil were conducted.

Through consideration of energy and water consumption, occupant comfort, snow accumulation, and permafrost stability, CHARS aims to demonstrate sustainable approaches to building design in Canada’s Arctic. By incorporating proven approaches complemented by studies specific to the Cambridge Bay environment into the design, CHARS will support sustainable operation of a world-class science and technology program that will be on the cutting edge of Arctic issues.



FIGURE 12. Raised building foundation on timber cribs to minimize the impact of the building's heat on underlying permafrost, Taloyoak, NU.

Many early foundations were made of wooden cribs or other simple structures (Figure 12). For new construction, buildings are generally built on engineered pilings or space-frames that provide strong support and isolate the building from the ground, minimizing heat transfer and maximizing ground cooling in winter. Increasingly, foundations composed of concrete slabs on the ground surface are being used, made possible by careful selection of pad aggregate, insulation under the concrete, and the use of thermosyphons. Thermosyphons are devices that utilize a heat transfer fluid, generally ammonia or carbon dioxide, to remove heat from the foundation and release it to the atmosphere from radiators located next to the building (Figure 13). They operate in a passive manner, without pumps or other mechanical action, and depend on the phase change of the fluid: when the fluid warms in the foundation, it vapourizes and moves up to the radiator, and as it releases heat, cools and condenses into a liquid that drains back to the foundation. In this manner, the thermosyphon extracts heat from the base of the building to minimize the risk of permafrost thaw and resulting subsidence. This technology is mature and widely used, however, it is relatively expensive to construct and is generally only used in new construction of larger commercial and public buildings.

Retrofitting foundations to solve permafrost subsidence issues is generally expensive and needs to be assessed on a



FIGURE 13. Example of thermosyphons installed at the Inuvik hospital. This relatively expensive technique minimizes the impact of the building on the underlying permafrost.

building-specific basis (Hoeve et al. 2006). Solutions range from installation of jacks to level the structure, to the use of insulation and thermosyphons. Generally, the costs of these actions are high and are approached on an as-needed basis. Efforts have been undertaken to inventory the scope of potential needs in communities (e.g. Couture et al. 2000; Hoeve et al. 2006) and these indicate high costs to stabilize existing buildings. Notably, a key element for adaptation to permafrost change and building effects is regular inspection of buildings to recognize the need for repairs before the cost becomes prohibitively high (Ford and Pearce 2010). Similarly, simple approaches by building users have been shown to be potentially valuable to minimize the effects of thaw subsidence. One inexpensive method is to remove snow from around the building structure in order to maximize the loss of heat in winter, thereby cooling the soil (Couture et al. 2000).

In summary, building foundations are highly susceptible to thaw subsidence where ice-rich permafrost is found. Construction of buildings may cause permafrost degradation. Projected climate change in the western and central Canadian Arctic is expected to also contribute to degradation of permafrost, adding further challenges to communities for maintaining building use and safety. Prevention of thaw subsidence can be largely avoided, through careful assessment of ground conditions in advance of construction, particularly the location of ice-rich permafrost. Use of appropriate and sufficient aggregate material can minimize formation of ice in building pads, and engineered solutions to foundations ranging from piles to thermosyphons can reduce the risk of structural damage. Existing buildings should be regularly evaluated for signs of thaw subsidence and some situations may benefit from active heat management of the foundation soil through winter snow removal or installation of engineered solutions.

7.5 Road and air strip stability

Roads and air strips in the ISR and the Kitikmeot region are found in all communities and are critical infrastructure for community well-being and the distribution of goods and services. As is the case with building foundations, roads and air strips depend on stability of substrate in a permafrost environment to maintain their design function for safety and operation. Changes to the stability can add substantial cost to regular maintenance and unplanned subsidence can limit use or cause hazards for vehicles (Figure 14).

In general, solar heat penetration into roads and air strips is enhanced by darker road material (typically gravel or asphalt mix) and higher density of the road base (Fortier et al. 2011). Snow clearance further lengthens and enhances heat gain season and typically increases heat loss in spring. Road design can minimize the impact of heat balance changes on underlying permafrost, particularly through the use of thick, coarse aggregate in the road base (Regehr et al. 2013). Additionally, the use of “open graded” embankments where coarse material dominates



FIGURE 14. Severe road heaving on an abandoned portion of the Ingraham Trail, east of Yellowknife, NT. This example shows how quickly roads built on ice-rich permafrost can degrade.

and allows convective heat loss is another means of minimizing the impact of the road on the underlying permafrost (McGregor et al. 2008). Other approaches include sunsheds and snowsheds, air ducts, thermosyphons, insulation and heat drains, but these all vary substantially in cost and viability in isolated communities (TAC 2010). Thermosyphons are expensive and only suitable for severe, localized ground ice problems. Pre-thawing of the ground (removal of ice) prior to construction of the road base is another solution, where time and resources allow (Beaulac et al. 2004; TAC 2010).

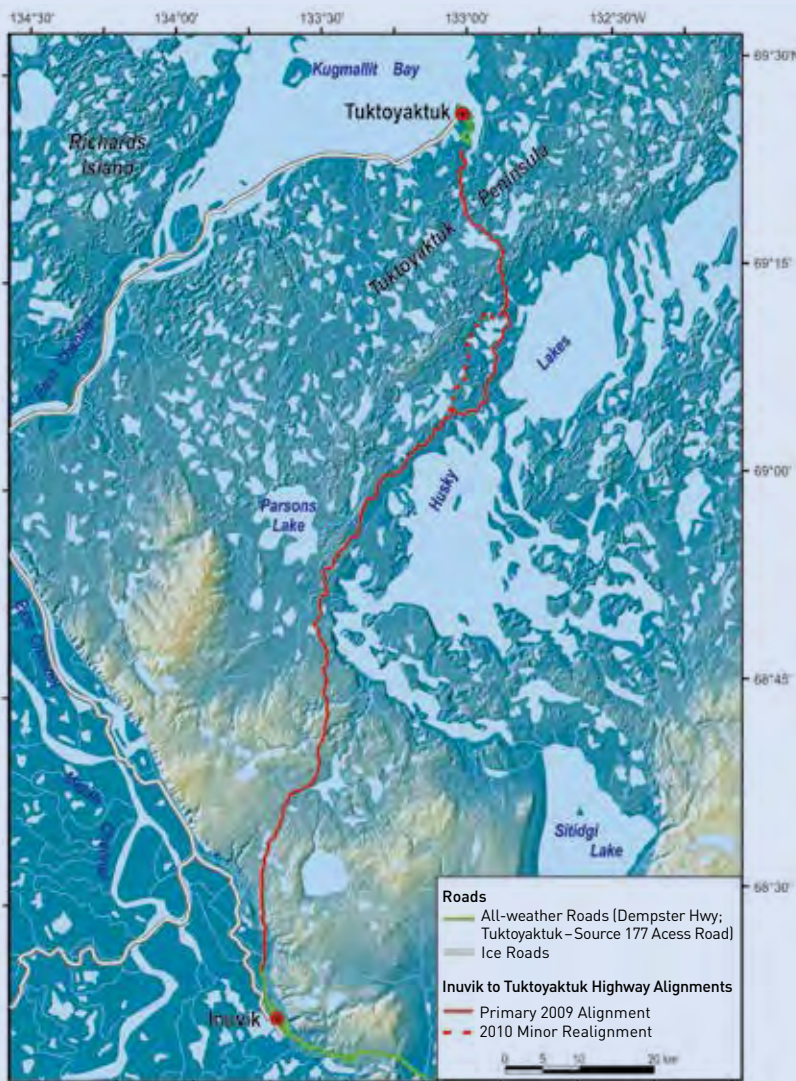
A key consideration in the new construction of roads and air strips is to avoid ice-rich permafrost areas where possible. As was the case with foundations (previous section), a number of methods are available to determine the presence of thaw-sensitive ground and route planning can use this information to reduce risk for the road. Notably, the new highway between Inuvik and Tuktoyaktuk that is currently under construction is routed through areas with known massive ground ice (Kiggiak-EBA Consulting Ltd. 2010). Careful assessment of the conditions resulted in the realignment of the planned route (see Box 3 for more detailed discussion about this highway project).

BOX 3. Construction of the Inuvik – Tuktoyaktuk highway

The \$300 million CAD Inuvik to Tuktoyaktuk all-weather highway received both Federal and Territorial approval in spring 2013 and will be the largest linear infrastructure project undertaken in Canada’s Arctic in decades. The 137 km long highway is currently under construction. Upon completion it will provide a dependable year-round link between Inuvik and Tuktoyaktuk, and significantly, be Canada’s first year-round, overland link to an Arctic port. The highway will utilize an embankment design, wherein 4.8 million m³ of gravel quarried from glacial deposits along

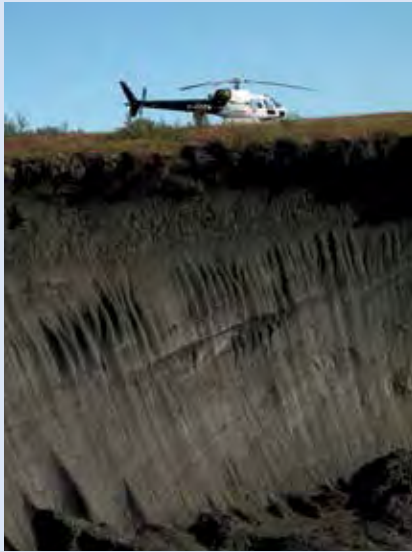
the alignment will be dumped atop a geotextile non-woven fabric that is being placed directly on the undisturbed ground (Kiggiak – EBA Consulting Ltd. 2010). Thicknesses of the embankment will vary from 1.4 to 1.8 m, and this principal design component will ensure protection and insulation of both the active layer and underlying permafrost, significant portions of which are known to be ice-rich.

The route traversed by the highway includes a complex array of sediment types, organic deposits, and chaotic, lake-filled thermo-karst terrain. Of chief concern is the issue of massive ground ice and other ice-rich sediments, which are exposed in widespread retrogressive thaw flow slides (Lantz and Kokelj 2008) and form ice-wedge polygon terrain. Understanding and identifying the nature and distribution of near-surface ice is key to achieving a sustainable highway design and construction. Standard terrain and sediment type – ground ice associations (cf. Heginbottom 2000; TAC 2010) have been used to assess sensitivity and risk. Surficial



Proposed route alignments of the Inuvik to Tuktoyaktuk Highway, and other regional all weather and winter roads, northwest Canada. From Smith and Duong (2012).

BOX 3. (Continued)



S. WOLFE/NRCAN



S. KOKELJ



S. KOKELJ

geology mapping upon which these classifications are based have been undertaken at both reconnaissance scale (e.g. Rampton 1981; 1:250 000) and project development scale (Kavik-Stantec Inc. 2012; 1:10 000), but require detailed ground truthing to ensure their accuracy as thermokarst and periglacial reworking can greatly complicate standard surface geomorphic expression. Additional insights into both the nature of underlying sediments and particularly their ice content can be derived through borehole drilling and near-surface geophysics (e.g. ground-penetrating radar and capacitively-coupled resistivity; cf. Angelopoulos et al. 2013), but these techniques are often spatially limited by issues of cost and access. The lithostratigraphic (i.e. bedrock and sediment layer) records available from abundant seismic shothole drillers' logs which criss-cross the terrain provide an additional information source and have demonstrated that previous surficial geology assessments have overestimated the extents of glaciofluvial and lacustrine sediments, and underestimated till extents (Smith and Duong 2012). These shothole data also provide additional information on the extents and thickness of buried ice and its lithostratigraphic associations (Smith and Duong 2012), challenging previous reconstructions (Heginbottom and Radburn 1992) and refining the scope and location of detailed field assessments required at the advanced construction and design phases. Construction of this highway poses many operational, design, and potential mitigation considerations, all of which may be complicated by future climate change, testing our current understanding of engineering design and construction in a permafrost environment (cf. TAC 2010).



S. KOKELJ

TOP LEFT: Massive ice exposed along a retrogressive thaw slump headwall near Ya-Ya Lake, Richards Island, NT. **MIDDLE LEFT:** Ice rich thermokarst terrain including a drained lake basin along the proposed Highway corridor, approximately 15 km south of Tuktoyaktuk, NT; **BOTTOM LEFT:** Embankment subsidence along the Inuvik-Tuktoyaktuk Highway caused by thaw consolidation of materials used to build the roadbed; **BOTTOM RIGHT:** Ice wedge polygons along the Highway south of Tuktoyaktuk. These ice wedges consist of bodies of pure ice up to 3 m wide, and are encountered immediately below the base of the active layer.

Increasingly, the role of drainage is being recognized as an important issue with respect to permafrost degradation and roads. While drainage considerations are included in all road designs, inadequate drainage provisions can result in movement of water under the roadbed. Research has shown that the movement of water into the roadbed is an effective heat delivery mechanism and can cause unplanned thaw and related subsidence (de Grandpré et al. 2010).

7.6 Pipeline stability

Pipelines are primarily associated with the natural gas and oil extraction industries, particularly in the Mackenzie Delta area of the ISR. Pipelines are found within communities for natural gas delivery (e.g. Inuvik town wells), drinking water distribution, and oil and fuel movements from port facilities to tank farms and onward to power plants, airports and other distribution locations (Smith and Forbes 2014) (Figure 15).

In general, most small pipelines are constructed like the example in Figure 15. In this case the heat from the pipeline and associated alteration of the permafrost during construction can result in localized thaw. Thaw subsidence takes on tremendous significance for pipelines, as the stress of movement can lead to failure and leakage. These issues are of particular importance for buried pipelines, where the heat exchange from the fluid in the pipe can substantially alter the ground thermal regime and result in ground-ice melt, and the potential environmental damage of a leak is heightened by inspection difficulties.

Solutions to pipeline deployment in permafrost regions vary substantially. In general, above ground pipelines have been used, particularly when the contents of the pipe are warm. The Alaska pipeline from the North Slope to Valdez is an early example, where the pipeline was built above ground in permafrost terrain to prevent thaw subsidence and resultant stress on the pipe (Figure 16).



FIGURE 15. Example of oil and fuel distribution pipelines in Iqaluit, NU. These type of pipelines are common in northern communities.



FIGURE 16. Construction approach used on the Alaska Pipeline in central Alaska in permafrost terrain. The pipeline carries oil heated to 49°C to reduce viscosity and allow movement over the length of the route. The pipe is suspended on a pedestal with thermosyphons to minimize ground thaw. Additionally, the pipe is able to move laterally on a sliding block to accommodate thermal contraction and expansion of the pipe during seasonal climate fluctuations.

In the western and central Canadian Arctic, extensive investigations were undertaken in anticipation of the proposed Mackenzie Gas Project (MGP). The MGP and feeder network would collect natural gas from well sites on the Mackenzie River Delta, and the pipeline was planned as a cold gas pipe, where the gas would be transported cold to minimize heat transfer to the surrounding ground. In this manner, it was anticipated that permafrost degradation along the pipeline route would be minimized and the more expensive surface pipe approach used in Alaska could be avoided. However, as with road corridors, pipelines can also be routed to avoid areas with high ground ice content and considerable effort was undertaken to route the MGP away from such areas, although it was not entirely possible to do so, particularly in the Mackenzie Delta (Burn and Kokelj 2009).

7.7 Winter and ice road changes

In some areas of the ISR and the Kitikmeot region, ice roads and winter roads are used to supply communities and resource development projects. These seasonal roads make use of sea ice, frozen lakes and rivers and shrub-cleared land areas to allow the passage of heavy trucks. Due to the intense use, governed by heavy loads and frequent traffic, ice roads require careful planning, design and maintenance during operation to maintain safety and to remain serviceable (LeBouthillier 2005). The Dempster Highway crosses the Peel River at Fort MacPherson and the Mackenzie River at Tsiigehtchic on ice. Ice and winter roads are used extensively in the Mackenzie Delta, connecting Tuktoyaktuk and Aklavik to Inuvik and for petroleum exploration (though this activity has ceased for the time being). The Tibbit (Yellowknife) to Contwoyto Ice Road was opened in 1979 to service the Lupin Mine in the southern Kitikmeot region. It operated approximately two months each year and 8000 truck-trips may operate over the season along the 600 km length (Prowse et al. 2009), but since closure of the Lupin and Jericho mines (2006 and 2008), it no longer extends to Nunavut. Similarly, while exploration was ongoing at

the Hope Bay mine, a 90 km winter haul road was operated for a time by Newmont Mining Corporation across Dease Strait from Cambridge Bay, NU. Since the project was revived last year by TMAC Resources, there is a renewed need for this marine ice road connection and a better understanding of sea-ice growth and stability in the area.

Key constraints for ice road use are linked to climate change through the timing of freeze-up, the thickening of ice on water bodies, and the initiation of melt and degradation of the road in spring. In recent years, warming in autumn and spring (Chapter 2) has notably shortened the duration of use for many ice roads and have increased maintenance requirements. Flooding of the ice surface or spray-ice methods can be used to thicken ice to increase the loading strength (LeBouthillier 2005), but even ice that has high loading strength can be unusable during a thaw event that floods the surface (Prowse et al. 2009). Early winter snow cover can also insulate early ice and slow the thickening, delaying the onset of operations (Prowse et al. 2009).

Winter roads (over land surfaces) similarly require surface soil material to freeze solidly and snowfall to permit grading. Additional challenges for winter roads include late flowing river crossings that may remain as barriers long after the ground surface has frozen. In the Mackenzie Valley, problematic river crossings on winter roads have been spanned by permanent bridges (LeBouthillier 2005).

While all-season roads are under construction to Tuktoyaktuk and contemplated from Bathurst Inlet, seasonal winter and ice roads will likely continue to be an important part of the transportation network in the North, particularly on the mainland. The sensitivity of these seasonal roads to climate conditions during winter coincides with the season of greatest projected climate change in the region.

7.8 Coastal infrastructure

As noted in a number of recent assessments, Arctic coastal infrastructure is exposed to a range of physical forcing, trends, and hazards which are sensitive to climate change (e.g. ACIA 2005; Forbes 2011). These include:

- accelerated global sea-level rise and the implications for local sea-level trends at Arctic communities;
- rising onshore air and ground-surface temperatures, with associated increase in the seasonal depth of thaw;
- rising sea-surface temperatures and their influence on rates of shoreline retreat through thermal abrasion;
- sea-ice interaction with the shore-zone, including ride-up and pile-up;
- thinning and reduction of sea ice, both the landfast ice and the mobile pack;
- associated implications for open-water fetch, storm waves, swell, storm surges, extreme water levels, and shoreline retreat;
- changes in storm climatology with implications for waves, currents, storm surges, ice motion, flooding, erosion, and other hazards in the shore zone.

The coastal infrastructure of the ISR and the Kitikmeot region includes permanent settlements, subsistence camps, seasonal settlements, former settlements, cultural heritage sites, port facilities, dredged channels, navigational aids, environmental monitoring sites, former DEW Line sites and the active North Warning system, many abandoned artificial islands and a large number of exploratory well sites onshore and offshore from the Beaufort-Mackenzie region to Banks and Melville Islands. Navigation infrastructure includes a limited number of navigation aids, towers associated with former navigation systems and automated weather stations (Figure 17), a wide variety of natural



FIGURE 17. Navigation aid tower at Tent Island, YT, 2010 on the west side of Shallow Bay, one of the most rapidly eroding parts of the Mackenzie Delta front. Shoreline retreat here has at times exceeded 20 m year⁻¹. The Decca navigation station at which two lives were lost here in the September 1970 storm would be far out in the water today.

harbours, port facilities at Inuvik, NT, Tuktoyaktuk, NT (Figure 18), Kugluktuk, NU (Figure 19), and Cambridge Bay, NU and minimal wharf or barge-landing facilities at other defence, exploration and community sites. Aviation infrastructure located along the coast includes airstrips at North Warning and former DEW Line sites and community airstrips, some of which (such as Tuktoyaktuk) are at low elevation and extend beyond the shoreline (Figure 18). Hydrocarbon exploration on the Beaufort Shelf and onshore in the coastal zone (notably in the outer Mackenzie Delta) is dependent on transportation and harbour infrastructure, including port facilities, ice roads, all-weather roads, and aviation. Shallow-water and offshore exploration has employed a variety of floating or grounded platforms as well as artificial islands, most of which since abandonment have been reworked by waves, currents, and ice into shallow shoals (see Chapter 9). Ice is an important infrastructure resource, both for subsistence travel to hunting grounds and for winter ice roads as discussed in the preceding section.

Community infrastructure includes dwellings, schools, churches, community centres, community freezers, commercial properties and other components of built heritage, critical facilities such as water supply and sewage lagoons, fuel tanks, power generators, fire halls, health facilities, airports and communications equipment. Cemeteries and

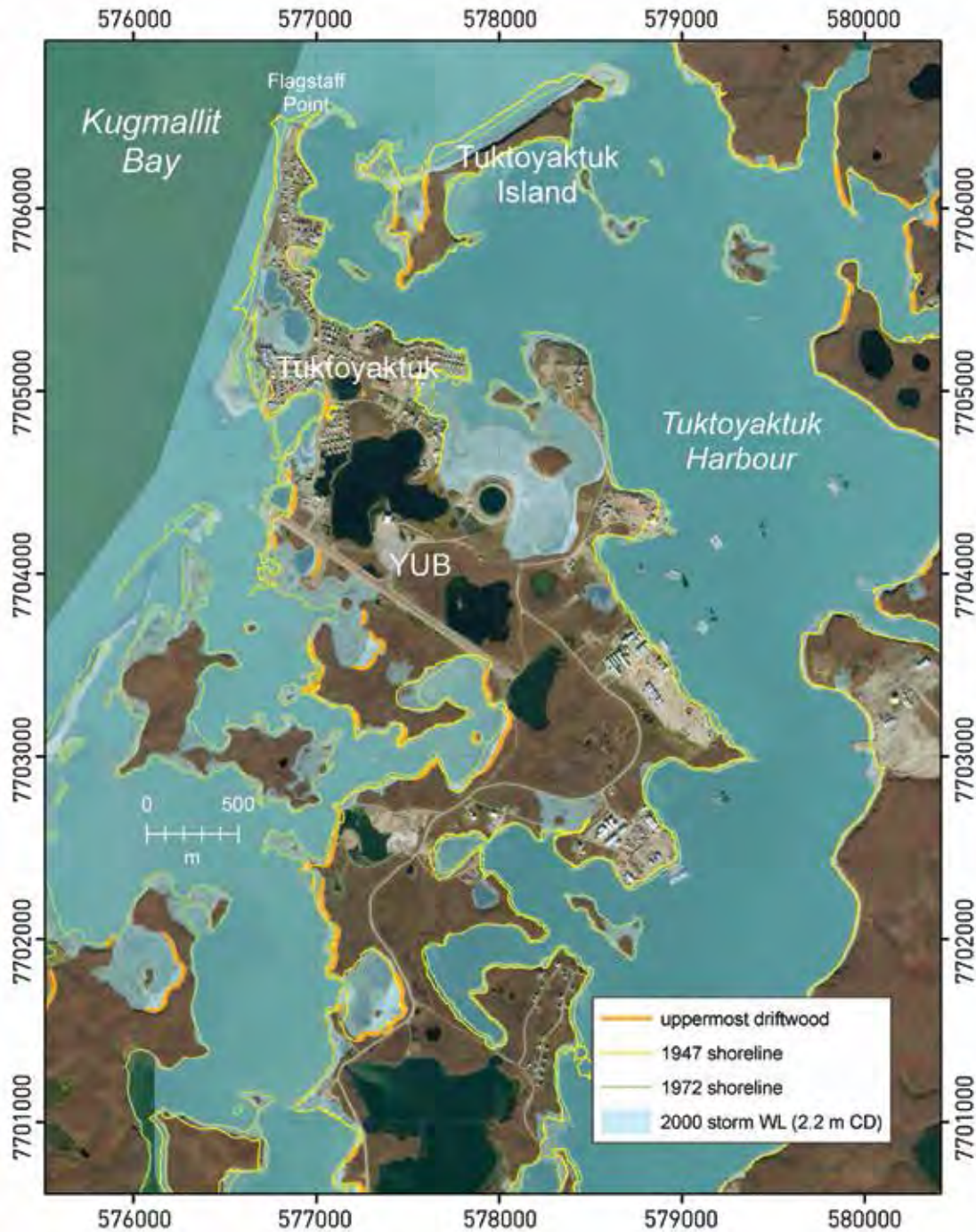


FIGURE 18. Geo-Eye satellite image of Tuktoyaktuk, NT, in 2010, with 1947 (yellow) and 1952 (green) shorelines and the distribution of the highest driftwood (orange), primarily associated with the September 1970 storm. Blue shading shows the extent of flooding in the 2000 storm, when the maximum water level was about 0.2 m lower than the 1970 event. Flood extent was determined by numerically ‘flooding’ a 2004 LiDAR digital elevation model (DEM) in ArcGIS™. Coordinates are UTM zone 8N on a 500 m grid. Adapted from Forbes et al. (2013). Contains material © DigitalGlobe Inc.

other cultural resource sites (particularly historical and archaeological sites) are a particular concern as they are preferentially located on the coast, which in many parts of the region is eroding rapidly (Figure 20). Thus some sites have been lost and others are threatened by erosion. Management of culturally significant sites is limited but includes Parks Canada (notably in Ivvavik National Park on the western Yukon coast and Aulavik National Park on northern Banks Island), territorial parks (e.g. Qikiqtaruk

Territorial Park on Herschel Island, Yukon), oversight by the Inuvialuit Lands Administration (ILA) and the Government of Nunavut, legislated protection in all three territories, and informal community stewardship.

The impacts of climate change on coastal infrastructure are primarily related to flooding, erosion, and ice action in the shore zone. Because of fetch limitation by islands in the Archipelago and by sea ice everywhere, extreme wave hazards known to occur in other regions are negligible. On the other hand, ice interaction in the shore zone can be destructive when it produces shore-zone pile-up ridges and is known to have caused fatalities along the Alaska coast (Forbes and Taylor 1994). Coastal erosion results from a combination of mechanical (waves, currents, gravitational failure) and thermal processes (thawing of ice-bonded sediments and melt-out of excess ice) and is thus sensitive to climate change (Overeem et al. 2011; Forbes and Hansom 2012; Forbes et al. 2014). Flooding may involve permanent inundation (Figure 21), short-term marine flooding associated with storm surges (Figure 18), or (in deltas and estuaries) spring flooding caused by snowmelt freshet discharge and ice breakup (Lesack et al. 2014) with the potential for over-ice flooding and strudel scour (Solomon et al. 2008; Couture et al. 2014).

The stability of coastal infrastructure and its vulnerability to flooding and erosion depend to a large extent on the physical composition and topography of the coast. The coastal geology and geomorphology of the western Arctic



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FIGURE 19. Port facility (wharf and offshore breakwater) at Kugluktuk, NU, 2009 with tug and barge alongside, and pipeline (narrow white line) running up the slope to the fuel tanks (out of view to right). Sea-lift freighter out of Montréal in background. Global Navigation Satellite System (GNSS) antenna in foreground used to measure vertical land motion (Forbes et al. 2004; Couture et al. 2014; James et al. 2014).



DONALD FORBES / GSC

FIGURE 20. Heritage site (1930s cabin) at Nuneluk Spit, Ivvavik National Park, Yukon, 2012. In 1996, the distance from the seaward wall to the top of the cliff was 18.4 m (Forbes 1997); in 2012 it was 0.0 m.



DONALD FORBES / GSC

FIGURE 21. Ice-wedge polygon tundra inundated by rising sea level near Siksik Point, west coast of Banks Island, NT, 2002.

coast has been mapped and classified at a range of scales. The only complete coverage was as a part of Canada-wide mapping of sensitivity to sea-level rise by Shaw et al. (1998a, b), recently revised under the CanCoast initiative (Couture et al. 2014). Circumpolar coastal mapping under the Arctic Coastal Dynamics project included the coast facing onto the Arctic Basin (Beaufort Sea and western Canadian Arctic Archipelago) but excluded other parts of the islands and Arctic channels (Lantuit et al. 2012). More detailed mapping for various parts of the region has been completed within the Coastal Information System of the Geological Survey of Canada, supported by airborne video surveys covering the entire Canadian Beaufort Sea from the Alaska border to Cape Bathurst, and all of Banks Island (Couture et al. 2015). In the past couple of years, the mapping has been extended east to Dease Strait using

archival video (Couture et al. 2014). Physical shore-zone characteristics mapped from video and ground observations in the Coastal Information System can be combined and queried to develop a coastal erosion hazard index (Solomon and Gareau 2003), as displayed in Figure 22.

The western and central Canadian Arctic covers a wide range of coastal geology, topography, exposure, and climate vulnerability for coastal infrastructure. In the Beaufort Sea region of the ISR, there is no exposed bedrock and the coast consists predominantly of ice-bonded sediments with locally high concentrations of excess or massive ice (Harper 1990). There are numerous shallow embayments formed by rising sea levels breaching thaw lakes (Ruz et al. 1992; Hill et al. 1994). Low-lying spits and barrier islands extend across the mouths of lagoons and breached-lake estuaries

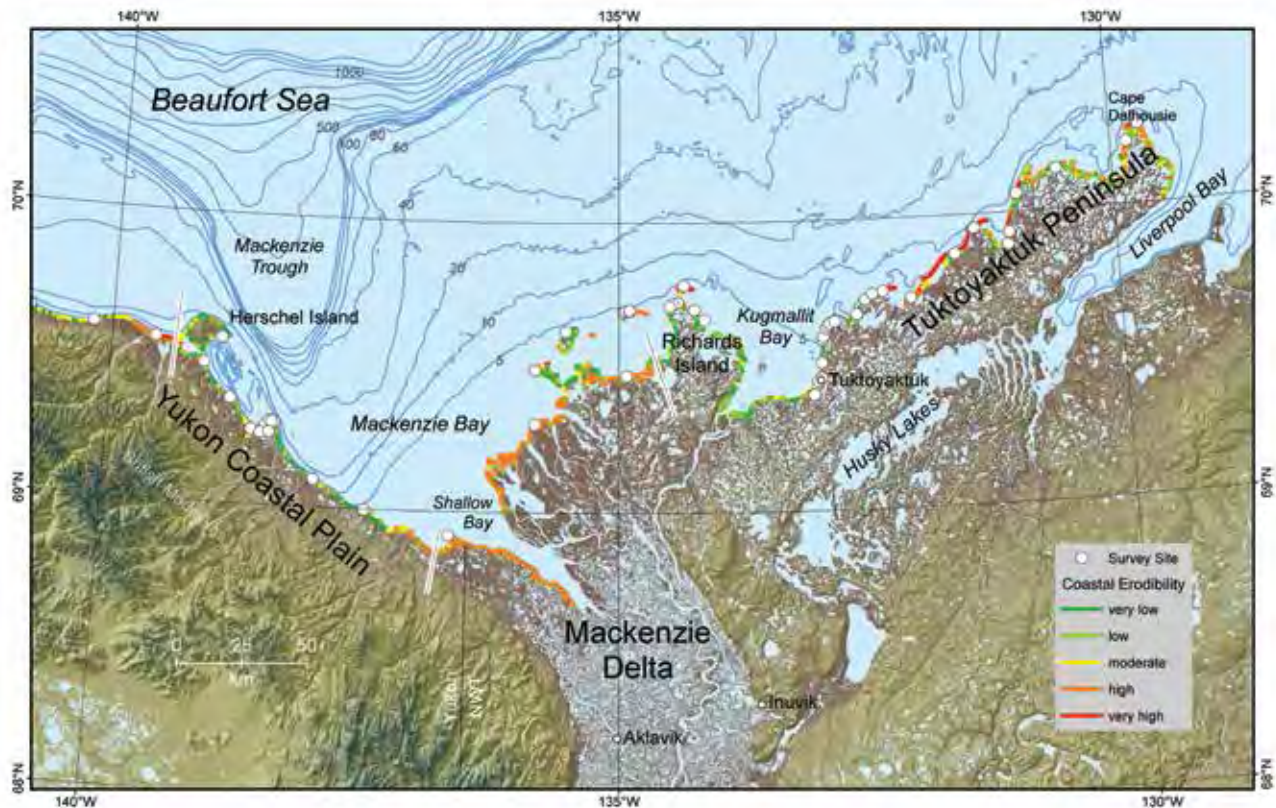


FIGURE 22. Topography and bathymetry of the Canadian Beaufort Sea region with physiographic subdivisions (white bars) after Forbes et al. (2014). Also shown are locations of Geological Survey of Canada coastal erosion monitoring sites and erosion hazard index after Solomon and Gareau (2003).

and are formed by sediments shed from rapidly eroding coastal bluffs (Héquette and Barnes 1990; Dallimore et al. 1996; Hill and Solomon 1999; Forbes et al. 2014). In contrast, the Kitikmeot coast is developed along the more sheltered waters of Arctic island channels, in an area of stable to slowly falling sea level, where shore-zone sediments are predominantly gravel and there is much exposed bedrock (Couture et al. 2014; Hansom et al. 2014).

7.8.1 Sea-level rise

Projected global warming under various emission scenarios or 'Representative Concentration Pathways' (RCPs) is expected to cause an increase in the rate of global mean sea-level (GMSL) rise (IPCC 2013). GMSL has risen at an increasing rate since the mid-19th century (Church and White 2011). The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2013; Church et al. 2013) concludes that the rate of sea-level rise globally this century will exceed the mean rate of rise over the past century. From 1993 to 2010 the mean rate was 3.2 mm year⁻¹ and projected increases in mean sea level as a result of ocean warming and ice mass loss from glaciers and ice sheets for 2081-2100 (relative to 1986-2005) range from 0.26-0.54 m (RCP2.5) to 0.46-0.81 m (RCP8.5).

The scenario that appears to show the closest correspondence to the current global emissions trend in recent years projects a rate of sea level rise in 2081-2100 between 7 and 15 mm year⁻¹ (Church et al. 2013). The AR5 expresses low confidence in higher rates projected using semi-empirical models (e.g. Rahmstorf 2007) but does note the potential for higher rates, possibly in the range of several tenths of a metre, should the collapse of marine-based sectors of the West Antarctic Ice Sheet (WAIS) be initiated before 2100.

The global mean sea-level rise considered above will not occur equally everywhere for a number of reasons. The change in sea level at any one place is affected by vertical land motion (Figure 23) and by other effects such as sea-level fingerprinting (related to gravitational effects

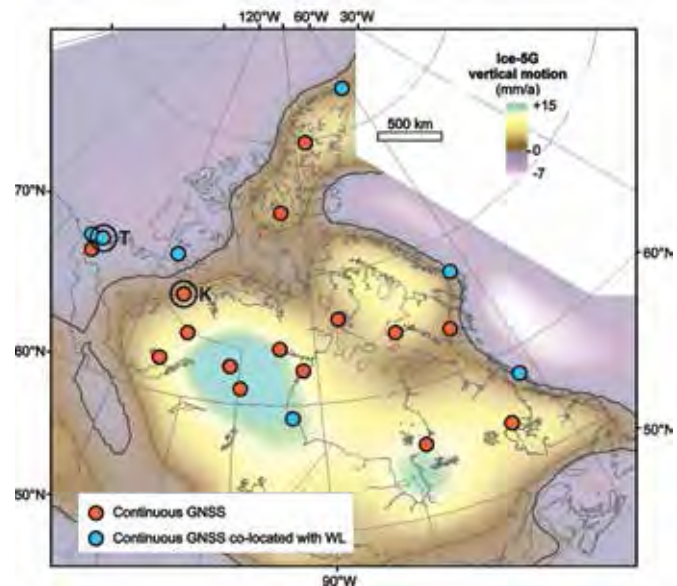


FIGURE 23. Present-day vertical motion in northern Canada from the ICE-5G model. The solid black line denotes zero uplift or subsidence and the broken line denotes uplift of 2 mm year⁻¹, suggesting that some areas between the two lines may already be seeing evidence of a reversal from falling to rising local sea level. Blue symbols are sites of co-located GNSS and tide-gauge stations, and orange symbols are GNSS stations without co-located gauges (northern sites only). Circled symbols with labels indicate the locations of Tuktoyaktuk (T) (Figures 18 and 24) and Kugluktuk (K) (Figures 19 and 24). "mm/a" represents millimetres per annum (year) and "WL" represents water level or tide gauge. ICE-5G 1.2/VM2 data courtesy of W.R. Peltier, University of Toronto.

and elastic crustal response of ice mass loss in the source regions where meltwater is added to the global ocean) and ocean dynamics (Mitrovica et al. 2001; James et al. 2014).

Across the ISR and the Kitikmeot region, vertical land motion is primarily a function of long-term glacial-isostatic adjustment. As represented by output from the ICE-5G model (Peltier 2004), the vertical motion across the study area ranges widely from subsidence in the west to uplift in the east. This is reflected in observations of relative sea-level indicators (e.g. Forbes et al. 2004; Manson et al. 2005b) and direct measurements of vertical motion (James et al. 2013; Couture et al. 2014).

Using the AR5 results, James et al. (2014) have developed projections of relative sea-level change through the century

for 24 locations across northern Canada from Alert, NU, to Moosonee, ON, and from Inuvik, NT, to Goose Bay, NL. These projections account for vertical crustal motion and regional variations in gravitational fingerprinting. In the present study area, projections have been developed for Inuvik, Tuktoyaktuk, Sachs Harbour, Ulukhaktok, NT and Kugluktuk, NU. The absence of projections at other communities, in particular Cambridge Bay, NU and settlements in eastern Kitikmeot, reflects the limited number of GNSS stations on stable monuments in this region.

Figure 24 shows two representative sets of projections – for Tuktoyaktuk, NT, in the ISR and Kugluktuk, NU, in the Kitikmeot region. The contrast between these sites is

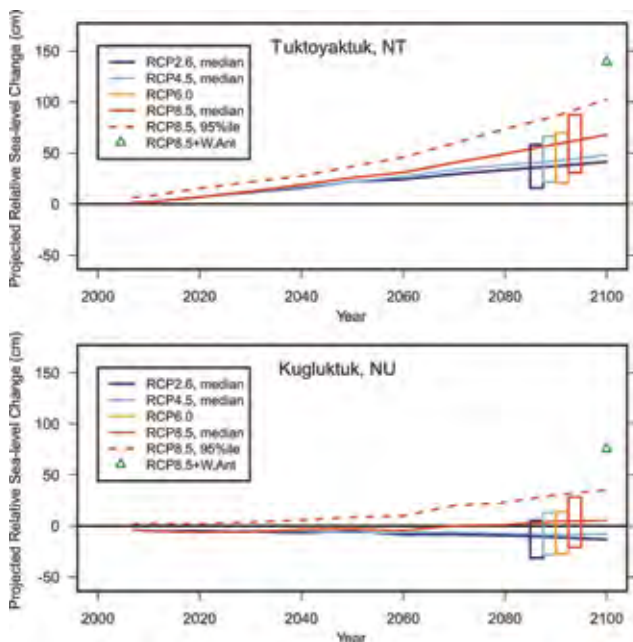


FIGURE 24. Projected relative sea-level change for Representative Concentration Pathway (RCP) scenarios RCP2.6, RCP4.5, and RCP8.5 through the 21st Century (95%ile is 95th percentile). Rectangles also include RCP6.0 and give the 90% confidence range (5% to 95%) of the average over 2081-2100. The rectangles are distributed over a time range for clarity, but their mid-point is 2090. RCP8.5+W.Ant is the median projection of RCP8.5 plus an additional 65 cm contribution to global sea-level rise from West Antarctica. Adapted from James et al. [2014].

primarily a result of differential glacial-isostatic adjustment, although fingerprinting associated with distance to the Greenland Ice Sheet, mountain glaciers and ice caps in northern Canada and the St. Elias Mountains, and proximity to the Mackenzie Delta depocentre and associated crustal loading, may all play a role.

At Tuktoyaktuk (Figure 24, upper panel), with ongoing crustal subsidence, all scenarios show rising local sea levels. For RCP4.5, the rise is more than 0.2 m by 2060 and >0.4 m by 2100. For the upper limit of RCP8.5 ('RCP8.5x' in Figure 25), the sea-level rise is about 0.4 m to 2060 and 0.9 m to 2100. Scenarios involving ice loss from the WAIS raise local sea-level by up to 1.4 m by 2100.

In contrast, at Kugluktuk (Figure 24, lower panel), sea level continues to fall throughout the century for RCP4.5 and until at least 2050 for RCP8.5. For the latter, however, the rise in sea level is projected to overtake the rate of land uplift in the second half of the century. The upper limit of RCP8.5 shows a rise in sea level greater than 0.3 m by 2100 and the WAIS ice-loss scenarios would raise local water levels in excess of 0.7 m. As shore erosion and wave overtopping are already occurring in the vicinity of the sealift wharf at Kugluktuk, the effects of a reversal and significant rise in sea level could have important consequences for coastal infrastructure, the freshwater intake at the head of the delta, cultural heritage sites in the community, and channel and habitat stability in the Coppermine Delta.

7.8.2 Storm surges and extreme water levels

In the IPCC Fifth Assessment Report (AR5), Church et al. (2013) state that a significant increase in the occurrence of extreme sea levels by 2050 and beyond is "very likely". As observed elsewhere, the primary driver of higher and more frequent sea-level extremes (chiefly resulting from storm surges) is the mean sea level on which the surges are superimposed (Hunter 2010, 2012). For any given extreme water level or infrastructure elevation, a modest

rise in mean level can increase the frequency of exceeding that level dramatically. For expected rates of sea-level rise in some regions, such as the southeastern Beaufort Sea, the frequency of flooding at what today are extreme levels (e.g. 2.2 m Chart Datum [CD] at Tuktoyaktuk, NT, Figure 18; Manson and Solomon 2007; Forbes et al. 2014) is likely to increase substantially in coming decades (Figure 25).

The tidal range at Tuktoyaktuk, NT, is very small (0.5 m at spring tides) and meteorological effects dominate the variability in water levels. Storm surges (the difference between observed water level and predicted tide) greater than 1 m were recorded 26 times in the intermittent gauge record from 1961 to 2000 and surges over 1.5 m were recorded 8 times (Manson and Solomon 2007). The maximum surge is unknown, but a surge of 1.85 m accompanied the major storm of October 1963. Because the effects of weather are pervasive, it is reasonable to consider total water level (combined tide and surge) in the analysis of extreme water levels. Unfortunately, the gauge was not

operating during the storm of record in September 1970. The water level for this event (the highest point in Figure 25) has been estimated as 2.4 m Chart Datum (CD) from the elevations of driftwood in and around Tuktoyaktuk (Harper et al. 1988; Forbes et al. 2013). Other major storms in 1963, 1993, and 2000 produced total water levels of 2.2 ± 0.3 m CD (Manson and Solomon 2007) and caused extensive flooding. It is clear from Figure 25 that rising sea levels will make this a more and more common occurrence. Specifically, the return period for a 2.2 m water level is projected to decrease from 40-50 years today to between 10 years (RCP8.5x) and 30 years (RCP4.5) in 2100. At the same time, a 10-year flood event would rise from 1.2 m to 2.2 m in 2100 (RCP8.5x) and to 2.6 m if WAIS ice loss adds another 65 cm to the median projection for RCP8.5 (Figures 24 and 25).

7.8.3 Erosion processes

Studies of coastal erosion in the western Canadian Arctic date back to the 1970s, with early work undertaken or commissioned by the Geological Survey of Canada (McDonald and Lewis 1973; Forbes and Frobel 1985; Harper et al. 1985). These revealed high rates of cliff and shoreline retreat along the Beaufort Sea coast, both in frozen unlithified sediments with high ground-ice content and in areas of thin transgressive barriers migrating landward over low tundra along the Tuktoyaktuk Peninsula (Figure 26) (Forbes and Hansom 2012; Forbes et al. 2014).

Shoreline retreat occurs through a variety of processes, including surface sloughing, active-layer detachment failure, thermo-mechanical niche (undercut) development, ice-wedge meltout, and associated block failure (Figure 27a), and retrogressive thaw slumps failure, often with mudflow transport of fine sediment downslope into the nearshore (Figure 27b) (Harper 1990; Forbes and Hansom 2012). Erosion is driven both by mechanical and thermal effects. The latter are sensitive to climate change (warming ground surface temperatures, inducing deeper summer thaw, and warming sea-surface temperatures, which have a similar

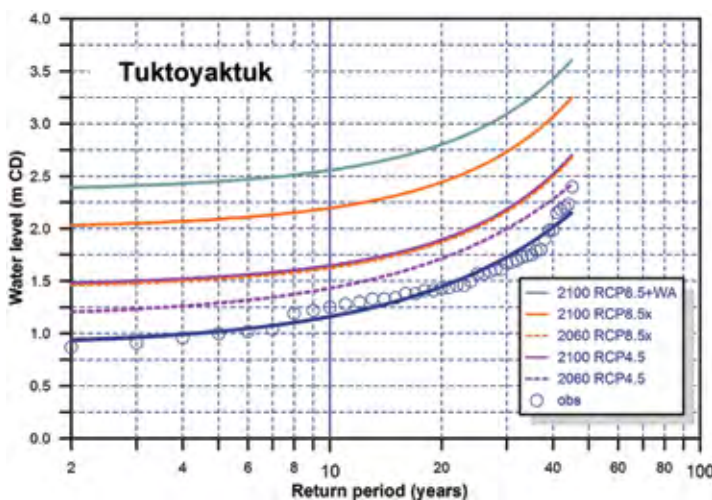


FIGURE 25. Extreme values distribution for annual maximum water levels at Tuktoyaktuk today (blue line fitted to data) and in 2060 and 2100 under various scenarios. A rise in mean sea level raises the extreme values distribution, increasing the potential flood level for any given frequency (inverse of return period) and significantly reducing the return period for a given flood level. 2060 RCP8.5x (dashed orange line) is superimposed on 2100 RCP4.5 (purple solid line). Data are from the Tuktoyaktuk tide gauge (CHS) and Manson and Solomon (2007).



FIGURE 26. Thin transgressive sand and gravel barrier beaches migrating rapidly landward across low-relief, lake-studded, coastal plain with pingos near Tuktoyaktuk, NT, 1992.

effect on ice-bonded sediments in lower cliff, beach, and nearshore parts of the shore profile). The importance of mechanical processes is most evident in the response to major storms, including storm surges and storm waves, during which local retreat of as much as 13 m in a few hours has been observed (Solomon and Covill 1995). During major events such as the August 2000 storm, niche erosion can extend several metres into the cliff base (Forbes et al. 2014).

There is extensive literature on rates of shoreline retreat in the Canadian Beaufort Sea and this shows that they are highly variable both alongshore and in time (Harper 1990; Solomon et al. 1994). Early measurements of retreat rates for the Yukon coast were reported by McDonald and Lewis (1973) and for a much larger area by Harper et al. (1985). However, it was not until the 1990s that digital photogrammetry and GPS survey control were sufficiently advanced to provide confidence in the results from aerial photography. Scattered measurements from repeat surveys at individual survey sites provided local rates (e.g. Lewis and Forbes 1975; Forbes and Frobels 1985; Hill 1990), but these could not be extrapolated alongshore (Héquette and Barnes 1990). Since that time, the network of ground survey sites has been greatly expanded (Figure 22). In an ongoing project under the Beaufort Regional Environmental Assessment (BREA), we are working to assemble and synthesize all available information for the region, but this project is not

yet complete. Nevertheless, a number of recent studies provide reliable information on trends over recent decades.

Konopczak et al. (2014) have recently completed an analysis of shoreline retreat on the western Yukon coast (west of the white bar in Figure 22) using ground surveys and digital photogrammetry. The mean rate of erosion over the time interval 1951-2009 was 1.2 ± 0.4 m year⁻¹ and decreased slightly from 1951-1972 to 1972-2009. Ground surveys revealed a recent increase at the Alaska border site but a decrease further east. Along this 35 km reach of the coast, land loss amounted to 4.5 ha year⁻¹ over the entire study interval. On Herschel Island (Figure 22), Lantuit and Pollard (2008) reported mean rates of coastal retreat decreasing from 0.61 m year⁻¹ to 0.45 m year⁻¹ between 1952-1970 and 1970-2000, based on digital photogrammetric analysis. The highest rates were in the northwest, exposed to storm waves from that direction, also locally at the eastern point and in the area of active RTS activity along the southeast-facing shore (Figure 27b). While rates of shoreline retreat diminished, they reported a 125% increase in the number and a 160% increase in the area of RTS features from 1952 to 2000. Information on rates of coastal retreat elsewhere along the Yukon coast is scattered, but multidecadal mean rates appear to range from 0.1 to 3.1 m year⁻¹ (Couture 2010, Table 5.3).

Solomon (2005) undertook the most comprehensive modern analysis of shoreline retreat in the Beaufort region, covering part of the Mackenzie Delta front, the islands north of the Delta, Richards Island and Kugmallit Bay, including the western half of the Tuktoyaktuk Peninsula (Figure 22). He found a mean retreat rate of 0.94 ± 0.03 m overall from 1972 to 2000 (Solomon 2005, Table 2). Annual rates of shoreline change on the outer Mackenzie Delta front ranged from advance of 6.57 m (1985-2000) to retreat of 16.86 m (1972-1985) with a mean retreat 1972-2000 of 1.77 ± 0.07 m year⁻¹. The highest rates obtained by Solomon (2005) were in the outer islands north of the Delta, where a maximum rate of 22.50 m year⁻¹ was recorded. On the west side, the coast is protected by the outer islands and wide tidal flats; the east coast of Richards Island faces away from

the direction of the strongest waves. However the north end of the island is exposed and cliff retreat at the north end of Richards Island decreased from west to east from 3.7 m year^{-1} to less than 1 m year^{-1} during the 1972-2000 interval (Solomon 2005). The rates in general are higher on the coast of the western Tuktoyaktuk Peninsula, which is exposed to storm waves from the northwest. The overall mean on this coast is $0.75 \pm 0.06 \text{ m year}^{-1}$ with a range from 4.68 m year^{-1} progradation to $10.95 \text{ m year}^{-1}$ retreat.

Overall, this study showed that there was no evidence for widespread acceleration of coastal erosion, but recent surveys on Pelly Island show total retreat of 1.2 km since 1950 and dramatic acceleration since 2000 (unpublished Geological Survey of Canada data, 2014).

We have no data as yet for rates of erosion on the west side of Banks Island, although it is reasonable to assume that they are slightly less than found along the Tuktoyaktuk Peninsula because of the greater persistence of sea ice in that area (at least in the past). On the north coast of Banks Island in the usually ice-clogged M'Clure Strait, the first measurements of shoreline retreat from 2003 to 2009 revealed a retreat rate of 0.7 m year^{-1} on a low bluff shore west of Mercy Bay in Aulavik National Park (Forbes et al. 2011). Detailed work was undertaken at Sachs Harbour (Manson et al. 2005a), where slow erosion of a low bluff just east of the landing beach forced a decision to move the Parks Canada residence to safer ground. Rapid erosion of a low sandy scarp east of the harbour has forced the relocation of a navigation aid in that area. On Pelly Island off the front of the Mackenzie Delta (at the site mentioned earlier), rapid and progressive retreat of an ice-rich bluff by 1.2 km from 1950 to 2014 (averaging $>18 \text{ m year}^{-1}$) has forced the repeated landward relocation of the automated weather station operated by the



FIGURE 27. (a) Block collapse through undercutting (thermal niche development) and ice-wedge melting and failure, Kay Point, Yukon, 2012. Note incoming northeast swell on calm warm day. (b) Polycyclic retrogressive thaw-flow failures in ice-thrust deposits, southeast coast of Herschel Island, Yukon, 2012 (cf. Lantuit and Pollard 2008). Note orange tent in lower right for scale.



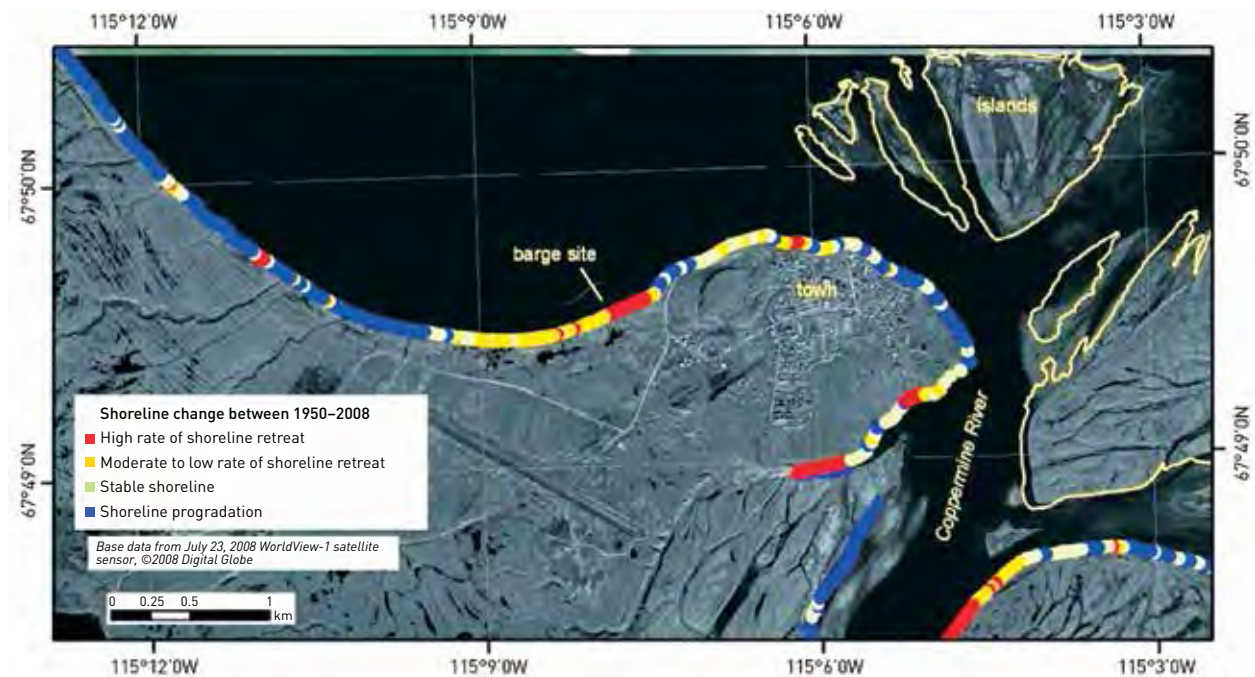


FIGURE 28. Long-term bank and shoreline migration rates in the Coppermine Delta and Kugluktuk, NU waterfront over 58 years, 1950–2008 (from James et al. 2013). High rates of retreat (red) are defined as >3 m year⁻¹. Contains material © DigitalGlobe Inc. (background is a WorldView 1 satellite image).

Meteorological Service of Canada (Environment Canada) (E. Horne, MSC Edmonton, pers. comm. 2011).

Shoreline change rates in most parts of Coronation Gulf are minimal with most examples of retreat being found adjacent to river outlets (James et al. 2013; Couture et al. 2014). The Coppermine Delta at Kugluktuk, NU is the only site in the region where we have found evidence for chronic and potentially hazardous shoreline retreat (Figure 28) (Manson et al. 2005b; James et al. 2013). River banks near the head of the Delta show high rates of change, presumably related to channel migration, and shoreline retreat has been >3 m year⁻¹ in the vicinity of the port (“barge site”) as well. Note that these rates are long-term means over 58 years (James et al. 2013). Moderate erosion rates extend almost 1 km west of the port (Figure 29) and moderate to high rates occur locally in the community (Smith 2014). It is obvious from the view in Figure 29 that erosion is continuing after construction of the port.



FIGURE 29. Shoreline erosion and washover sand west of the port facility at Kugluktuk, NU, 2009, looking east, with tug and barge in port. Offshore breakwater visible at left and high ground in the outer Coppermine Delta just visible in the background.

7.8.4 Coastal infrastructure hazards

The most challenging coastal erosion conditions in the study region affect the community of Tuktoyaktuk, NT (Figure 18), where various shore protection measures have been tried with limited success over the years. Within the past decade, a row of concrete mats was installed on the west side of Flagstaff Point (Figure 30a), and they appear to be working quite effectively. However, monitoring of their stability has shown limited tilting attributable to undercutting. The suspected presence and thermal degradation of excess ice beneath nearshore sediments, if it results in nearshore subsidence, could help to undermine the shore protection mats. As the northern point has lost ground over the past few decades, buildings have had to be moved. The RCMP detachment was obliged to abandon its location at Flagstaff Point and move to a new location. Other examples include the school which formerly overlooked the coast just south of the cemetery, but had to be demolished when it became threatened by coastal erosion. The subsequent construction of the Elders’ home on the same site incorporated a considerable set-back. Other structures have since been built in front, reflecting a dubious confidence in the shore protection measures (Figure 30b). The large rubble blocks which have

been placed along the coast in this area have limited resistance to thaw consolidation and deepening in the nearshore, so that their long-term stability is questionable.

Rapid erosion along the face of Tuktoyaktuk Island is another concern. This has amounted to over 100 m since 1947 and the remaining width of the island in some places is much less than this. The concern is the potential for breaching and opening of a new channel in the middle of the island because this would reduce protection in the harbour and could have other consequences related to sedimentation patterns.

At Kugluktuk, NU, the construction of the port and offshore breakwater in recent years has apparently had little effect to date on the high rates of coastal retreat both east and west of the facility (Figure 29). One advantage in Kugluktuk is that relative sea level appears to be stable at present (Figure 24), but some scenarios including the one that currently seems most plausible (RCP 8.5) will see a change to rising sea level in this community. Smith (2014) identified other issues of shore stability along the community waterfront, where steep banks cut into the alluvial terrace are slumping and exposed to wave attack



FIGURE 30. (a) Concrete mats installed as shore protection at Flagstaff Point, Tuktoyaktuk, NT, 2012, looking south. (b) Backshore peat exposed in beach scarp on South Spit, Tuktoyaktuk, 2012, reflecting landward rollover and migration of the spit (see Figure 18). View looking north to the Elders’ home and other structures built seaward of it on the former school site. Rubble block shore protection can be seen at the point and extends south along the spit, with erosion and spit migration beginning at its southern end in foreground.



FIGURE 31. Small wind waves in Cambridge Bay, NU on a high tide, 2009. Waves have formed the shingle beach in the foreground and conditions leading to beach formation would overtop and flood the low-lying area behind. Note sheds and other equipment stored in the background, with the town in the distance.

in the wide delta outlet channel (Figure 28). In contrast to Kugluktuk, Cambridge Bay, NU, has little in the way of ice-rich deposits along the shore and the beaches are all gravel (Figure 31). The sea-level projections for Cambridge Bay are slightly lower than Kugluktuk (James et al. 2011) and further east sea-level projections feature large amounts of sea-level fall where land uplift rates are larger (e.g. Igloodik; James et al. 2014).

The only infrastructure we noted as exposed to marine hazards in Cambridge Bay, NU (Smith and Forbes 2014) was subsistence-support facilities such as seen in Figure 31 and the dock of a small aviation company near the river mouth. The very protected setting within the bay limits the threat to these sites, but storm flooding on a very high tide is a possibility that may increase with climate change.

Cultural resource sites in many parts of the ISR are threatened by coastal erosion and, in some cases, potential flooding in the event of a major storm surge. Re-surveys of several heritage and archaeological sites in Ivvavik National Park first examined in 1996 (Forbes 1997) have shown that some sites have high vulnerability and indeed some have been lost to the sea. When we returned to the Stokes Point site in 2012, there was no vestige of the graves and the coast had retreated to a position landward of the site (Figure 32).



FIGURE 32. Ice-rich coastal cliffs at west end of the Stokes Point lagoon, 2012, looking west. Note undercutting and overhang. The cliff is 4-5 m high. The archaeological site (graves with memorial artefacts) described in Forbes (1997) no longer exists, as it lay to the right of the cliff in this view.

On the Yukon coast, in addition to the Stokes Point site, the heritage structure at Nunaluk Spit is in grave peril, as its northern wall was directly aligned with the top of the cliff in 2012 (Figure 20). Other sites in the area, including the lower cabin at Niakolik Point on the south side of the Babbage River mouth and historic structures at Herschel Island are on low-lying ground and already face an increasing risk of storm-surge flooding. This suggests the need for a thorough risk analysis for cultural resource sites along the coast throughout the ISR.

Another important class of coastal infrastructure includes cabins and other facilities for use in fishing and hunting activities to acquire food. Although located far from the permanent communities, these facilities can be considered critical community infrastructure as they help to ensure food security in addition to their cultural value. A pilot project has been initiated as a collaboration between the Inuvialuit Land Administration (ILA) and the Geological Survey of Canada to assess the flooding and erosion risks to Inuvialuit subsistence facilities (Figure 33) (Forbes et al. 2013). The figure shows a small area near Topkak Spit (traditional name ‘Tapqaq’) north of Tuktoyaktuk, NT with the locations of cabins or other infrastructure, the line of the highest driftwood (1970 storm level) in some cases landward of the cabins, and an example of traditional knowledge



FIGURE 33. Geo-Eye satellite image from 2010, showing an area near the northern end of Topkak Spit (Tapqaq) on the east side of Kugmallit Bay north of Tuktoyaktuk, NT (Figure 22). Locations of subsistence infrastructure (cabins or sheds) are shown in relation to the 1972 shoreline and the locations of the highest driftwood from the 1970 storm. The quotation is an example of geocoded traditional knowledge from the Inuvialuit Land Administration database. From Forbes et al. (2013).

about this location (courtesy of the ILA). Similar maps have been developed for other sites in the vicinity and were provided in brochure format for ease of use on the land.

It is evident from Figure 33 that some structures are close to being at risk of flooding today. Unfortunately the LiDAR digital elevation model used to map flood extent at Tuktoyaktuk (Figure 18) does not extend to this or other areas of interest for subsistence infrastructure. This precludes an analysis of the further setback required to stay above future higher flood levels that can be expected with rising sea level (Figure 25). A more extensive LiDAR survey in the future would make it possible to do a more complete projection of flood risk.

7.9 Summary: impacts of changing climate on existing and planned infrastructure

Community and regional infrastructure in the ISR and the Kitikmeot region is substantially affected by the presence of permafrost, while other elements of infrastructure such as ice roads and coastal areas are highly sensitive to changing climate conditions. The impacts have a number of implications for the health and welfare of communities, as well as the economic viability of the region. This requires both careful planning and regular inspections and maintenance to minimize risks and costs for repair. Similarly, the design and construction of infrastructure in the region require considerable location-specific knowledge about permafrost, ground ice, soil and drainage conditions. Novel design and engineering solutions exist for many issues related to foundation, road, pipeline and other infrastructure projects, and implementation of these solutions adds cost to projects that requires a good knowledge of the most appropriate needs.

Construction of most infrastructure is overseen by a number of regulatory and standards bodies in the territories and in specific fields such as engineering. Recent compilations for designers of northern infrastructure have been published to increase the awareness of practitioners

to the specific needs for design in these environments. Two notable examples of such efforts include *Infrastructure in Permafrost: A Guideline for Climate Change Adaptation* (2010) published by the Canadian Standards Association and *Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions* (2010) published by the Transportation Association of Canada. These and other efforts have advanced the development of appropriate design for northern regions. Additionally, with support from the Government of Canada, the Canadian Standards Association is currently developing a number of standards for permafrost, thermosyphons, snow loading and community drainage specific for northern communities. These standards are planned to be published in 2014-2015 and represent best practices based on research with the substantial perspective of planners, engineers, and maintenance experts. Efforts to educate the public about permafrost and how to recognize risks to homes and other infrastructure such as *A Homeowners Guide to Permafrost in Nunavut* (Government of Nunavut 2013) have also been developed and bridge the gap between community members and infrastructure professionals.

These efforts are critical for advancing best practices in design and construction of northern infrastructure and for building community understanding of the risks and need for maintenance. However, they depend on vital information about permafrost, sea ice, ground ice content, hydrology, sea-level rise, marine flooding, and coastal sediments and erosion rates, all of which are usually expensive to collect and are often unavailable for a given project. Research has advanced a number of elements to support transferring basic scientific understanding of these factors to users, as well as developing and testing novel approaches to cost effectively map and identify areas of concern. ArcticNet has facilitated a considerable amount of this research and encouraged the transfer of basic and applied knowledge to users in northern communities.

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Chapter 8. Food and Cultural Security

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ABSTRACT

The importance of traditional/country food as a critical resource for the health and well-being of northern populations is well documented. Despite this, shifts in traditional/country food consumption have been taking place over the past 15–20 years related to a variety of changes in northern ecological, social, political and economic systems. Those related to ecological shifts have been primarily associated with food safety due to identified threats from environmental contaminants such as mercury and persistent organic pollutants, and more recently the changes in species availability and accessibility due to shifting climatic conditions. This review will present the current state of knowledge on food and cultural security in the Inuvialuit Settlement Region and the adjacent Kitikmeot region of Nunavut. Adaptation plans and policy have been developed to improve food security in the region. Case studies on some of the adaptation initiatives will be discussed.

8.1 Introduction to food security in the western and central Canadian Arctic

The diet in the Inuvialuit Settlement Region (ISR) and the adjacent Kitikmeot region of Nunavut comprises a mixture of market and country foods. Market foods are those that are transported into the communities either on barges in the summer, by air, or in the case of a few communities in the ISR, via road transport, or in the winter via ice road transport. Due to transportation costs, market foods are generally expensive and often nutritionally lacking. A study conducted on 211 Inuit from 3 communities in Nunavut and 230 Inuvialuit from 3 communities in the Northwest Territories in 2008-2009 found that participants spent the most money (\$2439/year) on non-nutrient-dense foods (including butter, pizza, popcorn, sugar-sweetened juices, ice cream, chocolates) compared to \$748 and \$656 spent

on fruit/vegetables and dairy, respectively (Pakseresht et al. 2014). Country foods include plants, sea-food and animals that are harvested locally, both from domesticated (Box 1) and wild sources. Their contribution to Inuit health and well-being is very important, as harvesting and consumption of country foods is closely tied to Inuit identity. The volume, variety and nutritional contribution of country foods to the diet varies from community to community and individual to individual, depending on personal preferences, food and harvesting costs, and the availability of country food species. Overall, country food consumption is higher in the communities of the ISR and the Kitikmeot region that lack road access, but social, economic and environmental changes are impacting food consumption patterns throughout these regions (Erber et al. 2010). Country foods are particularly important in these communities as monetary access to market food is often more challenging (Egeland et al. 2011b). Climate change is one factor affecting the



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BOX 1. Wrangling reindeer

Previous declines in caribou harvests, caused by changes in herd migration routes, led the Canadian Government to experiment with reindeer husbandry as an alternative source of traditional food and an opportunity for Inuit to enter the wage economy. The first herd was established in 1935 in the Mackenzie Delta and the concept spread around the Canadian Arctic (Conaty and Binder 2003). At one time there were herds in Labrador, Northern Quebec and Nunavut, as well as the ISR (Conaty and Binder 2003). In the ISR the government created the community of Reindeer Station to act as a depot for the management and exploitation of the reindeer herd. With a permafrost freezer, resident wildlife biologists from the South and a substantial Inuit staff, Reindeer Station was for a long time one of the most substantial communities in the ISR (Hart 2001). Meat from the herd was used to supplement dwindling caribou harvests and became a staple in the residential schools and hospitals. It was also the staple meat of the Inuit who were employed as herders and as seasonal labourers to assist in the slaughter. For a variety of reasons, mainly connected to the resurgence in caribou populations and restoration of their original migration routes, most of the government herds disappeared by the 1970s.

However, the survival of the Mackenzie Delta herd offers a possible solution to declining caribou harvests. Although facing both environmental and bureaucratic obstacles, the reindeer still live in the ISR and are now Inuvialuit owned. Furthermore, there is a tradition of reindeer herding and seasonal employment among many Inuvialuit families, and the meat is still regularly consumed.

Although reindeer meat and caribou meat are identified as the same meat (Rincker et al. 2006; Smith 2006), many individuals do not appreciate or identify them as the same as they reputedly differ in flavour. Also, while reindeer meat enters the Inuvialuit food chain as a market food (as it is purchased from the herd owners by either the Community Corporations or the Inuvialuit Regional Corporation), it is then distributed to individual households according to traditional rules of exchange, in effect becoming a traditional food in the process. Thus reindeer have already become part of the solution for Inuvialuit food security.



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traditional food supply (Ford 2009). For instance, the frequency and timing of hunting is affected by the changes in the timing of ice freeze-up or break-up depending on the season (Furgal and Seguin 2006). However, wage employment also affects food consumption, since an income can both facilitate hunting, by providing the means to do so, and create an obstacle to going hunting by taking up potential hunters' time (Searles 2002; Collings 2011). Finally, new technologies such as video games, Internet access, and social media may have an effect on harvesting, although their impact remains poorly understood. Still, the Inuit Health Survey (IHS) found that the preference for 86% of Inuit households was country food and that country food remains a major contributor to Inuit nutrition (Egeland 2010). Cultural and economic adaptability and survival due to changing food supplies is important and needs to be further considered by researchers and policy-makers working with these communities (Collings 2011).

8.2 Accessibility, availability and acceptability of country foods

8.2.1 Food security and country food

Wildlife from land and aquatic environments as well as edible plant life are categorised as country foods. More broadly, country foods may be defined as foods within a particular culture that are available from local, natural resources and that are culturally accepted (Kuhnlein and Receveur 1996). Traditional food is yet another category, one that encompasses country food but also includes some foods derived from market sources, such as bannock, and also has become central to Inuit diet and identity. Both country food and traditional food have socio-cultural meanings, specific acquisition processing techniques, use, composition, and nutritional benefits for the people using the food (Kuhnlein and Receveur 1996).

According to the World Food Summit undertaken by the Food and Agriculture Organisation, the World Health Organisation in 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” (Food and Agriculture Organisation 1996). For the Canadian Arctic to be food secure, sufficient supplies of traditional food must be accessible and available for popular consumption (Duhaime et al. 2008). Even increasing access to healthy market foods is not enough to maintain the health of the population. Traditional foods must also be adequate, thereby requiring them to be both safe to eat (physically acceptable) and nutritionally sufficient (Myers et al. 2004). Traditional food should include culturally acceptable food as well as its adequate distribution, such as sharing within the community (Myers et al. 2004). Food harvested and consumed by Inuit communities needs to be accessible, available, adequate and acceptable if food security is to exist in the ISR and the Kitikmeot region. A comprehensive food security strategy is needed to plan for the supply of affordable healthy market foods and sustainable harvest of country food for the region.

The importance of country food to Inuit is more than just sustenance and physical health, but rather the focus of Inuit identity and well-being (Egeland et al. 2009). Traditional food ensures survival and social cohesion for the communities and hamlets in the Kitikmeot region and the ISR. The relationship between traditional food and Inuit encompasses a connection to emotional, spiritual, social and cultural well-being (Wesche and Chan 2010). Harvesting involves the transfer of cultural knowledge to youth and time spent together out on the land during the acquisition of country foods thereby promoting positive family dynamics (Lambden et al. 2007; Egeland et al. 2009).

The sharing of traditional food and communal participation in the harvest is also deemed important to community health (Van Oostdam et al. 1999; Wesche and Chan 2010). The traditional acquisition of country food promotes a physically active lifestyle that is closely linked to land-based activities (Kuhnlein et al. 2009). As such, a change in dietary patterns from country foods to store bought foods would potentially promote a sedentary lifestyle in Inuit

communities. A sedentary lifestyle combined with poor nutrition may result in an increase in obesity, diabetes and other life threatening diseases (Kuhnlein and Receveur 1996; see Chapter 5).

Traditional food is connected to the physical health of Inuit as it provides the intake of many essential nutrients, vitamins, and minerals (Kuhnlein et al. 2004). Vitamins such as A, D, E, and minerals such as manganese and selenium also provide the necessary nutrition required of a healthy diet (Kuhnlein et al. 2004). Traditional foods are rich in antioxidants, omega-3 fatty acids, monounsaturated fatty acids, protein and micronutrients, and provide essential sources of riboflavin, pyridoxine, iron, zinc, copper, magnesium, potassium, and phosphorus (Berti et al. 1999; Egeland et al. 2009). Results of various dietary studies consistently showed that on days when traditional foods were consumed, the intake of saturated fats, sucrose, and excess carbohydrates that often are found in store-bought alternatives was significantly less in all Inuit regions (Egeland et al. 2009). Affordable store-bought foods that are commonly the only alternative to traditional foods are often high in trans-fats and refined carbohydrates and do not provide sufficient energy. The implications of such a high fat and carbohydrate diet can increase health complications resulting in obesity and other physical illnesses (Kuhnlein and Receveur 1996; Chapter 5).

A food security questionnaire was administered to over 2500 participants by the Inuit Health Survey (IHS) in 2007-2008 (Egeland 2010; Chapter 5). More than half of the households interviewed in the ISR stated that they had enough food to eat (Figure 1). Household food insecurity is defined by the US Department of Agriculture, Food and Nutrition Service (Bickel et al. 2000) as a state of “limited or uncertain availability of nutritionally adequate and safe foods or limited or uncertain ability to acquire acceptable foods in socially acceptable ways.” According to this definition and adopting the same food security questionnaire, the IHS found that 46% of households in the ISR were food insecure. Considering households with children (not represented in Figure 1), 34% were food insecure. Reasons stated

for food insecurity were unemployment, low income and high costs of food. However, while the IHS report revealed that food insecurity has been a problem in the Arctic historically, the situation in the ISR has in fact been improved (Egeland 2010). The reason for such improvement is not known. The Government of Canada provided subsidies from 1986 to 2009 to Canada Post to ship market food to the North via a Food Mail Program. The effectiveness of the program was questioned and it was replaced by a new program in 2010 named “Nutrition North” which targets the subsidies to “healthy food”. The effectiveness of the new program remains to be evaluated. There are also a number of community-based intervention programs. For example, food banks are becoming more popular in the ISR and soup kitchens are also on the rise in Inuvik. A grocery store manager in Sachs Harbour, with the support of the community, reduced the cost of milk by increasing the cost of soft drinks to help families choose healthier products. Because the IHS did not separate the three Inuit regions within Nunavut for data analysis, there are no similar time-trend studies for the Kitikmeot region. See Chapter 5 for a detailed discussion of the health impacts of food security.

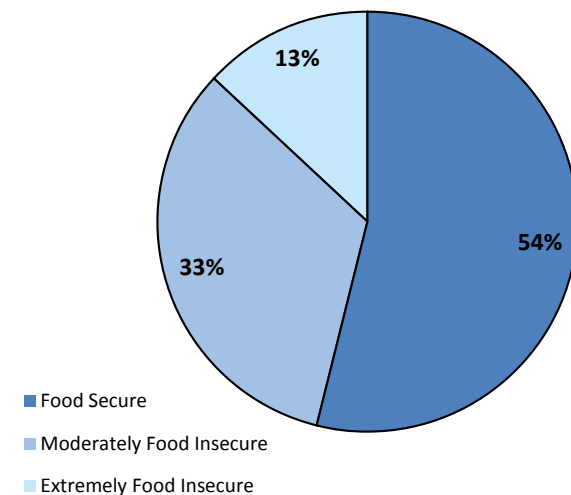


FIGURE 1. Percentage of ISR participants of the Inuit Health Survey on food security as reported from a questionnaire (n=266). Adapted from Egeland (2010).

8.2.2 Contaminants

Another factor affecting food safety/security of country foods is the presence of environmental contaminants. For example, about one half of the ISR homes participating in the IHS indicated that they were concerned about contaminants in country foods (Egeland 2010). A variety of toxic agents have been identified in the Arctic food chain, including heavy metals (e.g. mercury) and persistent organic pollutants (Kuhnlein et al. 2000) (see Chapters 3 & 4). The risks of ingesting these substances must be balanced against the health benefits of country food consumption. For now, the benefits of country food are still thought to outweigh the risks of consumption of contaminants in most cases, but this is an ongoing issue that is monitored by the Northern Contaminants Program under the Aboriginal Affairs and Northern Development Canada (AANDC) department and by the Arctic Monitoring and Assessment Program (AMAP) internationally (AMAP 2003; Donaldson et al. 2010; Laird et al. 2013). Results from the IHS show that contaminant exposure was lower in the ISR compared to Nunavut (Laird et al. 2013). It is important to note that climate change may also increase the amount of contaminants in the Arctic ecosystems, and food safety of country food can become an increasing concern (Armitage et al. 2011).

8.3 Country foods vs. market foods

8.3.1 Country food

The most commonly consumed country foods differ between communities due to differences in local scarcity and abundance.

As part of the IHS, questions to participants asked how much country food had been consumed in the previous twelve months. It was concluded that men ate more country food than women (Chapter 5, Table 4). The results of the food frequency questionnaire conducted by the IHS show the top ten foods listed in Table 1 showing the overall averages for Inuvialuit living in the ISR and therefore do not



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reflect any single community. Caribou is the most important food as 96% of the 362 IHS participants in the ISR reported eating it. The average amount of caribou consumed (meat, dried meat, and heart) was 104 g per day or 39 kg per year. Arctic char was consumed by 70% of the participants and was consumed at 116 g per day or 42 kg per year. Berries, beluga oil and caribou organ meats were also consumed in smaller quantities. In addition, adults older than forty years of age ate more country foods than younger adults (Chapter 5, Table 4).

The questionnaire also asked participants what country foods they had consumed twenty-four hours before the interview. The average proportion of total calories derived from traditional food was higher among older adults, especially males, than younger adults (Chapter 5, Table 4.) Furthermore, it was concluded that traditional food intake had decreased in the past decade (Egeland 2010).

With respect to the participants in the IHS, about 79% and 59% of households in the Kitikmeot region and the ISR, respectively, had an active hunter (Chapter 5, Table 2). Furthermore, the food sharing networks were found to be strong in the communities as 86% and 71% of households in the Kitikmeot region and the ISR, respectively, shared game meat within the larger communities (Chapter 5, Table 2). In the ISR, there are country food distribution programs in Inuvik. Hunters and Trappers Committees (HTCs) and Community Corporations annually deliver reindeer and caribou meat to single families and Elders who need meat and do not have an active hunter in their

TABLE 1. Top ten most consumed country food in the ISR. Data from the Inuit Health Survey conducted in 2007-2008.

COUNTRY FOOD	PERCENT OF INUVIALUIT CONSUMING (%) N=362	AVERAGE GRAMS PER DAY
Caribou meat	96	67
Dried caribou meat	72	30
Caribou heart	54	7
Dried beluga meat	55	16
Beluga oil	56	5
Arctic char	70	116
Whitefish	65	26
Trout	59	22
Geese	65	17
Berries	76	8

household. Country food was most often obtained from hunting and from family members as revealed by the IHS. Friends, community freezers (Box 2) and HTC's were also essential means of sharing country food within communities. Approximately one fourth of the households in the ISR stated that they preferred mainly country food while the remaining households preferred a mix of country food and store bought foods (Egeland 2010).

The availability of country food was also part of the IHS questionnaires. As suggested by previous studies, households are not obtaining enough country foods; most households in the ISR, indeed 86%, preferred to eat more country food than they could get (Egeland 2010). Reasons disclosed for not being able to acquire enough country foods included not having an active hunter in the home, not having a snow machine or boat, and the high cost of supplies and gas to go hunting and fishing. However, when community members ran out of country food, more than two thirds received food from family, friends, the community freezer or the community HTC's. To amend this situation almost 60% bought more store food, and 30% went hunting or fishing and over 25% percent just went without country food (percentages do not total 100 because participants could give more than one answer) (Egeland 2010).

Perceptions of food costs differed within the communities of the ISR. A majority of the households, 61%, stated that they felt country food was cheaper than market food (Egeland 2010). Twenty-five percent stated that country food was as costly as market food, while 14% thought country food was more expensive (Egeland 2010). While there is no available data for estimating the monetary value of country food in the ISR, an estimate conducted in Nunavik found that the replacement of country food by similar market food will cost the household \$3,233 per year; this amount was more than 10% of the annual household income of \$26,000 in 1995 (Duhaime et al 2004).

8.3.2 Market food

Participants in the IHS were also asked about their consumption of store bought foods. As previously stated, many of the market foods available in Inuit communities are of poor nutritional value. High costs of fresh produce, lack of monetary income (see Chapter 5, Table 2), and the poor quality of available fresh produce and unprocessed meats make cheaper and less nutritional foods more popular.

BOX 2. Community freezers: tools for food sharing

Inuit and other Arctic peoples were the first to develop techniques of flash freezing foods to preserve their flavour and texture. Modern industrial food freezing was adapted from Inuit food freezing techniques (air or water freezing) in the 1920s by Clarence Birdseye, an Arctic naturalist who observed Inuit freezing fish and meat. He created the modern frozen food industry by developing mechanical techniques to duplicate the effects of frigid Arctic air and water on foods.

The Inuit froze meat and fish and then stored them in ice houses/ice pits - cavities dug into the permafrost that remained well below freezing throughout the year. These pits acted as a means of storing food for entire communities, especially in the Mackenzie Delta, where large seasonal communities centred on whaling and fishing and were present before European contact. They were an integral part of the Inuit culture of sharing food and resources with each other.

When southern traders arrived, they brought iron implements, which increased the size, capacity and durability of the ice houses that the Inuit (and traders) could construct. Still, an ice house is a major construction project, even with iron tools, but it can last for generations once built. At least one of the ice houses built by Inuit and whalers on Herschel Island remains in seasonal use today (Yukon Government 2006).

Inuit approaches to food sharing meant that food stored in a communal ice house was available to all without restrictions (Searles 2002). With the advent of settlements, the need for a means of food preservation that could serve an entire community became urgent. The Hudson's Bay Company installed ice houses at a number of its posts, as did the government at Reindeer Station, its Mackenzie Delta research station and reindeer herd depot. However, ice houses were major construction projects and were not always physically possible. Hence, in the 1970s governments began installing modern industrial freezer units – entire buildings with several large walk-in freezers – to act as community freezers, and by the 1980s most communities across the Arctic had received community freezers. These freezers were extremely expensive to operate (Chan et al. 2006) but served an important role in traditional food distribution systems (Chabot et al. 2002; Chabot 2003).

Parts had to be flown in from the South, as did technicians to service the new freezer units. Since electricity in most communities is generated from community diesel generators powered by diesel brought in from the South, even basic operating costs were expensive. As a consequence, most freezers were only turned on for use in the spring. Throughout the winter, community members relied on frigid temperatures to keep country food frozen. Still, the expense of operating community freezers has been justified throughout most of the Canadian Arctic by their important role in the Inuit culture of food sharing (Chabot 2003; Ford and Pearce 2010).

In the ISR, beginning in the 1990s, administrative changes in the territorial government led to a decision to cease funding community freezers. The territorial government began providing communities in the ISR with a block grant, along with a one-time offer of shipments of individual chest freezers to each household. This was not very popular in the communities as the block grant covered only one-third to two-thirds the actual cost of operating a community freezer, but most felt that they had no choice but to accept.

Concerns over individual freezers were both cultural and economic. The move to individual chest freezers changed the dynamics of sharing food as individual chest freezers hold a single family's food and not the entire community's. Thus sharing changed from something the entire community participated in, to more of a bilateral exchange – that is, between individuals with freezers filled with food, and other individuals without food. On the economic side, conversely, the operating costs were basically transferred from the government to the individual community members, who had to pay for electricity and upkeep of their new chest freezers. The only community in the ISR to maintain a



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Underground ice house at Tuktoyaktuk, NT.

community ice house is Tuktoyaktuk, where an unassuming white hut hides an impressive underground structure. The Tuktoyaktuk ice house was built in 1963, dug by hand with picks and shovels. The hut contains an insulated hatch that covers the shaft down to the ice house itself. The hut and hatch protect the permafrost from melting and turning to mud, something that has led to the collapse of ice pits and houses before. To reach the ice house, one must first sign a liability waiver and then climb down a shaft dug about 20 feet into the permafrost. Below are three corridors, each opening into a separate storage room.

The Tuktoyaktuk freezer is used to store country food harvested in the summer – it provides a very large storage facility that is used by the entire community. The significance of Tuktoyaktuk retaining a community freezer is not lost on other communities. After the initial construction is completed, ice houses are much more economical and less environmentally damaging than industrial freezer units.

Community freezers also provide a more effective means of preserving food than an individual chest freezer as the ambient temperature is both lower and more uniform, thus avoiding freezer burn to the food stored within them, a noted problem with chest freezers (Chan et al. 2006). More importantly, it allows the community to continue its traditions of food sharing without the inhibitions inherent in having all food stored in individual freezers.

It appears that the lack of community freezers in the ISR is a temporary state of affairs, with pressure to construct new community freezers (Furgal and Seguin 2006) gaining ground as illustrated by the community of Paulatuk, which is developing its own ice house (Inuvialuit Regional Corporation 2011). Although devolution has led the expensive, unreliable industrial freezers to be decommissioned, individual freezers are unsatisfactory enough that the communities are willing to put the labour and money into building ice houses, in effect returning to the freezing technology their ancestors used, to retain the ancestral food sharing culture they still practice. Questions remain about the resiliency of ice houses in the face of climate change, since they are as dependent on the existence of permafrost as the freezers they replace are on imported diesel fuel and technical expertise for their operation.

These “empty calories” are obtained from foods that include bacon, chips, soda pop, sweet drinks and chocolate/candy, which are not healthy to eat on a daily basis (Erber et al. 2010). One of the most commonly consumed market foods was soda pop. Approximately 80% of adults reported drinking soft drinks daily in the month prior to the interview (Chapter 5, Table 4). Surveys in the ISR revealed that one quarter to one third of total calories were consumed from high sugar foods and drinks. These findings have been construed as indicating Canadian Inuit are undergoing the “nutritional transition” from a traditional diet to a less healthy modern diet (Erber et al. 2010; Egeland et al. 2011a; Chapter 5).

8.4 Education and language

8.4.1 Education

Climate change has created particular challenges for both the formal and traditional education systems in the ISR and the Kitikmeot region. Traditional knowledge, also known as Inuit Qaujimagatuqangit, is the accumulated body of knowledge built up by generations of Inuit through their observations and interactions with the world around them. It is spread through personal interaction and provides an intimate knowledge of how individuals can interact with their environment (Jack et al. 2010). Traditional knowledge



of sea ice, for instance, allows Inuit hunters to travel safely over the frozen ocean for seal hunting, while knowledge of ocean conditions and migration routes facilitates whaling and fishing (Krupnik and Jolly 2010). Climate change, by altering the natural environment in unpredictable ways, challenges the viability of traditional knowledge by undermining the empirical foundations of its body of knowledge. In turn, this has serious implications for Inuit food security (Power 2008; Prowse and Furgal 2009). Hunters are now adopting modern technology to plan for hunting trips. For example, the HTC's are now becoming accustomed to viewing satellite images, tracking ice hazards using Global Positioning Systems and sharing knowledge via social media, citizens band (CB) radios, cell phones, etc. This highlights the importance of capacity building in the form of education to improve food security.

Formal education is a recent innovation in Inuit culture. The educational system in the ISR and the Kitikmeot region offers the full range of primary, secondary and post-secondary education, although most post-secondary programs require students to travel to institutions outside the Arctic to complete their education. Seven schools operate in the ISR: one K-12 school in Inuvik and in each of the remaining communities in the ISR with the exception of Sachs Harbour's K-9 school. Aurora College operates community learning centres in each of the communities and has its campus based in Inuvik. Eight schools operate in the Kitikmeot region. Kugaaruk and Taloyoak run one K-12 school each, and Cambridge Bay, Kugluktuk and Gjoa Haven each have a K-6 and a 7-12 school. The Nunavut Arctic College campus is located in Cambridge Bay, and the remaining communities in the Kitikmeot region have community learning centres operated by the college.

Secondary school graduation rates are relatively lower in the ISR and the Kitikmeot region compared to the rest of the country. In 2006 the ISR population aged 15 years and older with a high school education or higher was 55%, down 12% from the Northwest Territories and 21% from the rest of the country (IRC 2013). In the Kitikmeot region, 39% of the population aged 15+ years in 2006 had a high

school education or higher, about the same as the Nunavut territorial percentage but down 36% from the rest of the country (Statistics Canada). Data from the IHS (2007-2008) revealed that approximately 60% of adults from the ISR and the Kitikmeot region did not complete secondary school (Chapter 5, Table 2).

Many communities across the Arctic have developed programs to promote traditional ecological knowledge for priorities such as cultural preservation, health promotion, and adaptive capacity. Such programs range from the purpose-built Piqqusilirvvik Inuit Cultural School in Clyde River, NU to the Junior Canadian Rangers Program funded by the Department of National Defence and the Canadian Forces, to programs created and delivered by community groups. Many programs are also interlinked with and supported by academic research activities. One such program in Ulukhaktok, NT, the Nunamin Illihakvia: Learning from the Land project, has been developed to better understand community members' perspectives on the formalization of knowledge transmission (Stephenson et al. 2013). Dietary and nutritional programs are being implemented by the regional nutritionists in the ISR to inform people of balancing diet and promoting the use of healthier store bought food, such as lentils, etc. These programs are being delivered to cooking circles and other community development programs. Success of these programs will address many determining factors for food security.

With respect to changing environmental conditions, the educational system in the region responds to climate change in two ways. First, educational programs provide residents with the state of research into climate changes and their projected impacts on the Arctic environment. Second, by creating a body of knowledge separate from and complementary to traditional knowledge, formal education increases community resiliency and potentially ameliorates the impacts of climate change upon Inuit food security (Power 2008).

8.4.2 Language

As both food and language are important components of the Inuit culture, efforts to preserve the language have been viewed to be important to sustain food security. However, over the last two to three decades the preservation of traditional languages has either changed little or declined in the ISR and the Kitikmeot region. In 2009, 23% of persons aged 15 years and older in the ISR spoke an Aboriginal language (IRC 2013). From 1996–2006 the retention level of an Inuit language in the Kitikmeot region was the lowest in comparison to the Kivalliq and Qikiqtaaluk regions of Nunavut (KIA Language Network 2011). Part of this trend is attributed to English being spoken in the home and most children speaking only English.

8.5 Housing

The IHS results showed that food insecurity and economic hardship including inadequate housing and the nutrition transition away from traditional food in the context of costly market food represent fundamental public health challenges. Overall, 1 in 4 homes were crowded, 1 in 5 homes provided temporary shelter to homeless visitors, and 2 in 5 homes were in need of major repairs (Minich et al. 2011). In 2009, 32% of residents in the ISR owned households (52.5% in NWT) and 33.8% lived in public housing (15.5% in NWT) (IRC 2013). While about 18% of homes were in need of major repairs, in 2011 about 12% of households were occupied by six people or more (Statistics Canada). With respect to the individual communities in the ISR, the average number of individuals occupying private households fell within the interval of 2.4 to 3.6 (Statistics Canada). Within the Kitikmeot region during 2009–2010, 23% of dwellings were owner-occupied (about the same as in the territory of Nunavut) and 63% of housing was public (14% higher than Nunavut) (Nunavut Bureau of Statistics 2011). With respect to physical housing conditions, the proportion of occupied dwellings that required major repairs was 27%. In 2011 the average number of individuals occupying private households fell within the interval of 2.8 to 5,

and the proportion of dwellings with a household size of six or more was 23.5% (Statistics Canada).

Overcrowded, substandard housing can be considered a product of the same factors leading to food insecurity and is thus a bellwether of existing or impending community food insecurity. By affecting the nutritional burden on a household and reducing the resources available for harvesting, housing may also directly affect food security itself. Poor housing conditions also have the potential to increase community vulnerability to climate change by decreasing this key component of community resiliency. More research on this issue is needed to clarify the network of influences that connect housing, food security and climate change.

8.6 Drinking water

Thawing permafrost, coastal erosion and other effects of climate change have the potential to negatively impact the quality of drinking water and limit water delivery services (Bernier et al. 2005). Drinking water in the ISR and the Kitikmeot region is obtained either by municipal filtered water or via water gathered from the land. In the ISR, water treatment and distribution systems are managed by Municipal and Community Affairs and the communities, and similarly in Nunavut the municipalities and hamlets are responsible for drinking water facilities. Although AANDC manages fresh water resources (e.g. lakes, rivers) in the Northwest Territories and Nunavut, there are separate, territorial agencies that are responsible for source drinking water. For example, the Government of Nunavut Department of Environment manages Nunavut's watersheds and aquifers, and the Department of Health regulates drinking water source protection. However, the territory has no formal source water protection plans (National Collaborating Centre for Environmental Health 2014). The responsibility of protecting drinking water sources in the Northwest Territories falls mainly on the Government of the Northwest Territories Department of Environment and Natural Resources (GNWT 2005) which has implemented a NWT Water Stewardship Project to



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undertake this task (<http://nwtwaterstewardship.enr.gov.nt.ca/?q=swprotection#sw2>). Such efforts will benefit the large part of the Inuit population that continues to practice the traditional activity of obtaining their water from going out on the land (Martin et al. 2007).

Nickels et al. (2006) outlined the issues addressed by community members in the Canadian Arctic with respect to drinking water and water quality. Communities reported that the availability of clean and safe water was poorer in all Inuit regions of Canada due to environmental changes. Residents of the ISR reported that the natural source of drinking water was different and had a worse taste and smell than in the past. Residents also stated their concern about water supplied by the municipality. The water treatment system in Aklavik, NT frequently became clogged due to increased algae and sedimentation linked to low water levels. There was concern in Aklavik that *H. pylori*

contamination of the water supply was having adverse effects on the health of residents, but further study confirmed that drinking water was not the source (Cheung et al. 2008).

It is evident that research into the effects of climate change on water quality and drinking water is required. Arctic fresh water resources are largely confined to surface water, given the ubiquity of permafrost throughout the region. This resource is shared by people, plants, wildlife and industry and is consequently vulnerable to contamination and over-use (White et al. 2007; Evengard et al. 2011). Residents of northern communities have not only voiced their concerns regarding the quality of water but have also observed changes that have already occurred to their fresh water sources. It is expected that climate change will cause changes in precipitation quantity, intensity, frequency and duration (Chapter 2), which will subsequently alter the quality of

drinking water and might increase the risk of waterborne disease. A study conducted in Nunatsiavut compared baseline data on weather, water quality and health and illustrated the need for high quality temporal baseline information to allow for detection of future impacts of climate change on regional Inuit human and environmental health (Harper et al. 2011).

8.7 Conclusions

Climate change impacts on food security are complicated by a host of socioeconomic, technological and political influences in the ISR and the Kitikmeot region. There are potential challenges for both country foods and market foods, as species numbers, migration patterns, transportation networks and storage systems are all vulnerable to disruption. While communities in the South often have multiple redundancies in their food supplies, the Arctic has less resiliency and potential strengths and weaknesses have not yet been explored in detail. However, there are a number of community-level adaptations, including efforts to pool knowledge of traditional food preservation techniques (Berkes and Jolly 2001). The two case studies (Boxes 1 and 2) showcase the success of two adaptation initiatives implemented in the ISR. There are a number of programs, including the Climate Change Adaptation Program funded by AANDC, the Climate Change and Health Adaptation Program funded by Health Canada and the Regional Adaptation Collaboratives Climate Change Program funded by Natural Resources Canada, that work in collaboration to support northern communities to address risks and challenges posed by climate change impacts and to become more resilient. Many of these community-initiated research efforts are attempting to address the impacts of climate change on food security at the local level. More information about the impacts on the communities and the effectiveness of local intervention programs will be available in the coming years.

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Chapter 9. Resource Development

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ABSTRACT

The marine and coastal areas of the Inuvialuit Settlement Region (ISR) and the Kitikmeot region contain known deposits of several metals, oil and gas, and diamonds. The extent to which these deposits are developed, however, depends largely on world commodity prices and improved accessibility to these resources due to a changing climate. Furthermore, development of non-renewable resources in the region is complicated by difficult working conditions (e.g. harsh climate, limited transportation and other infrastructure, isolation, and complex governance). Resource extraction has been a key economic driver in this and other parts of the North for generations; the discovery of oil and gas in the ISR and mineral deposits in the Kitikmeot region has generally led to many positive impacts for the communities, including, in part, improving transportation infrastructure, employment, and the signing of land claims. At the moment, the main activities are exploration; there are no commercial production projects active at this time. Thus while the potential for future resource production is significant, it remains potential rather than actual. Climate changes pose opportunities and challenges for extractive industries based on non-renewable resources and also for traditional Inuit activities based on renewable resources. The main opportunities are associated with changes in marine transportation due to improving sea-ice conditions. The main challenges for non-renewable resource projects are in the stability of structures on land (buildings, roads, storage tanks, ports, pipelines, etc.) due to the deterioration of permafrost. Construction and maintenance of adequate structures including waste-disposal facilities are expensive and add to project costs. With respect to the longer summer marine navigation period associated with climate warming, it was thought that this longer season would result in more trans-Arctic shipping between Europe and Asia because the Arctic route is shorter. However, the Arctic routes pose risks related to dangers of ice, higher capital costs for reinforced ships, higher fuel costs per kilometre for heavier ships, limitations in navigational charts, and high insurance fees. Thus any increases in traffic will be to service Arctic communities and resource projects. We may anticipate an increase in cruise-based tourism with longer ship access, but Arctic communities will have to invest in tourism infrastructure if they want to attract these ships. Climate warming may also impact the prospect for commercial fisheries. Until Arctic fish resources are surveyed adequately to estimate population statistics with confidence, our ability to detect changes in them is compromised. Probably the hallmark of successful resource development projects in these regions will be partnership arrangements between resource owners (the Inuit) and developers such that acceptable risks and benefits accrue to each.

9.1 Introduction

The purpose of this chapter is to consider the effects climate change is having and will continue to have on economic activities associated with renewable and non-renewable natural resources in the marine and coastal areas of the Inuvialuit Settlement Region (ISR) of the Northwest Territories and of the Kitikmeot region of Nunavut. Some of these resources may be found in off-shore waters, and it seems prudent to recall that some regions of the Beaufort Sea lie in territory still subject to boundary negotiations between Canada and USA. With decreased summer ice cover, and a transition from multiyear ice to first-year ice dominating the rest of the season, more of the sea is open to ships and extended resource exploration may well find oil and gas resources in the disputed area.

Warming trends are already observed in the region and model projections suggest that much of the region can expect further warming of 3-5°C by 2050 (Chapter 2). What kinds of effects can we anticipate on the natural resource sector of the economy? Two types of natural resources are usually distinguished, renewable and non-renewable, and these are discussed separately. Much of the economic interest in the North, at least by businesses outside the North, has been focused on non-renewable resources like oil and gas, inorganic minerals, especially gold and other metals and, more recently, diamonds. The people who live in

the region, however, retain their historic ties to traditional renewable resources, especially fish and wildlife. The recent *Circumpolar Inuit Declaration on Resource Development Principles in Inuit Nunaat* noted the long historic relationship Inuit have had with their renewable resources and their intent to preserve those resources (Inuit of Inuit Nunaat 2011). Thus the challenge for regulators is to weigh the benefits for northerners to be derived from non-renewable resource extraction against the risks such developments may pose to the quality or quantity of present and future renewable resources.

With regard to non-renewable resources, climate warming will have little impact on the presence of most resources, but it will have a significant impact upon procedures needed to extract them and to transport them to markets. An exception may be the presence of methane hydrates trapped under land or sea by permafrost, if this is considered a “resource”. As permafrost becomes warmer and more porous, methane trapped by it will escape to the atmosphere where it will drive further warming. Travel and transportation are key components of non-renewable resource development; personnel and equipment must be moved to sites, and products have to be exported. All communities in the ISR and the Kitikmeot region have reported a longer ice-free season (Chapter 1, Table 1) which facilitates the movement of ships but which can impede travel and transport on land because of instability of surfaces. The result is that costs



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of development and production in the region are high. If hydrocarbon or other deposits are exploited successfully, site reclamation will follow after production ceases and new ways of dealing with accumulated wastes are needed. Continued burial of wastes in permafrost pits is unlikely to remain acceptable because so many of these existing structures have leaked (French 1980).

There has been speculation that the longer ice-free season in the Arctic will be followed by increased ship traffic through the Arctic because the distance between Europe and Asia is shorter than through Suez or Panama canals. However, the risks of travel through the Arctic remain high relative to temperate routes and ship owners are averse to additional risk. It seems likely that increased ship traffic will be to and from destinations within the region to service local communities and resource projects. This increased traffic will likely include more military operations, scientific surveys and tourism cruises. Intercontinental traffic has begun to make more use of the northern sea route (NE passage). The over-the-pole route appears to be mostly made up of first-year ice types at this time and will continue this way over the next several decades. The NW passage route, through the ISR and the Kitikmeot region, is projected to be the last of the major intercontinental routes to open due to the presence of remnant sea ice coming in from the Beaufort Sea into the NW passage route (Barber et al. 2012).

Renewable resources are usually thought of as animals and plants used by northerners, but they might also include river flows especially if they can be used to generate electricity. Ice itself may be considered a renewable resource and climate warming has already had a profound impact on it. Any species using ice as habitat can be expected to suffer increasingly stringent limitations. However, warming can have positive impacts on other species by extending the growing season and potentially offering new habitat for range extensions or new migratory routes. Arctic communities have reported numerous species invading the region in recent years (Chapter 1, Table 1) and it remains to be determined what impacts these invasions will have on native species.

9.2 Non-renewable resources

The economic history of northern Canada has been linked inextricably to exploration for and production of non-renewable natural resources, notably gold, iron, nickel, copper, other metals, uranium, oil and gas and diamonds. Numerous exploration projects fall within the geographic boundaries of this report, but no mines are actually operating at this time. Thus the region has significant potential for mineral production, but political and economic conditions will determine the degree to which resource development proceeds. The exploration and extraction of non-renewable resources has profoundly shaped Indigenous/non-Indigenous relations in the Canadian North. As early as 1953 Inuit in Kugluktuk, NU (Coppermine), alarmed at a new round of mineral staking in the region, petitioned the federal government to assert their unceded claim to the land and also to request training in mineral exploration and staking (Kulchyski and Tester 2007). The widespread opposition among Inuit, Dene, and Métis to the first proposed gas pipeline through the Mackenzie Valley in the early 1970s led to the Berger Inquiry, widely regarded as a turning point not only in northern resource development but also in northern land claims and in North-South relations more generally. Indeed, the comprehensive land claims settled over the last thirty years have been significantly oriented around clarifying surface and sub-surface title to the resource-rich lands and seas of the Arctic and subarctic and establishing governance structures to promote meaningful involvement and control over resource development on Inuit, Dene, and Métis lands (McPherson 2003; Nuttall 2008). Tensions remain over the extent to which industrial resource development can be harnessed in the interests of Northerners, and whether its social, cultural, political, economic, and environmental impacts outweigh its benefits. As critical drivers of environmental and social change in the contemporary Arctic, the mineral and energy industries pose major challenges to sustainability and the ability of communities to absorb and adapt to both the short-term impacts of development and its longer-term social and environmental consequences (Warden-Fernandez 2001; Whitmore 2006; Waye et. al. 2009). As a new resource

boom unfolds in the region, many identify a need for comprehensive, accurate, and meaningful assessments of both past and present extractive activities.

9.2.1 Mining

Mining history

The mineral resources of the Kitikmeot region of Nunavut have been of interest to non-Indigenous peoples since at least the late 18th Century (Cameron 2011). Indeed, a central motive of Samuel Hearne's overland journey from Prince of Wales Fort (1769-1772) was to locate the copper riches rumoured to exist along the final reaches of the Coppermine River. Today, a very active exploration program in the region locates new mineral resources every year, and a number of proposed mines are making their way through the Nunavut Impact Review Board's screening and review process. There is also a long history of outside interest in non-renewable resources in the ISR, although in this area the interest has been in oil and gas.

While exploration and staking have shaped the histories of both the Kitikmeot and Inuvialuit regions, only two mines have ever operated within the regions. The Lupin gold mine began operations in 1982 near Contwoyto Lake (in the southerly reaches of what is now the Kitikmeot region of Nunavut, but was then part of the NWT) but has since ceased production, and the Jericho diamond mine operated between 2006-2008, north of the Lupin mine (Figure 1). This is set to change rapidly, however, in the next several years. The Kitikmeot region could see up to eight mines opened in the next five years, including a re-opening of the Lupin mine (George 2011), although projections change rapidly and frequently. Proposals for major road and port infrastructure are also under consideration in the Kitikmeot region. Mineral exploration in the Inuvialuit region has also been steady, although no proposed Inuvialuit-region mines are currently under assessment at the Northwest Territory's Mackenzie Valley Impact Review Board.

Overview of current and proposed mines

While there are currently no operating mines in the Kitikmeot region or the ISR, residents in both regions work at exploration and mine development sites in the regions, as well as at operating mines in the NWT. The mining sector is an increasingly important component of labour, investment, and economic development in both Nunavut and the ISR. An active mineral exploration program in the Kitikmeot region has led to advanced exploration at a number of sites, and there are currently several proposed mines that could be established in the region in the coming years. The Nunavut Impact Review Board is currently reviewing proposals in the Bathurst Inlet region (including the Hope Bay belt), Contwoyto Lake region, and the Back and Hackett River regions (Figure 1).

Gold, base metals (iron, nickel, copper, zinc, etc.) and diamonds are the dominant metals and minerals in the region, but there are also significant showings of lead and various rare earth elements (Nunavut Geoscience 2012). In addition to the mines themselves, a proposal to develop a road linking various proposed mines in the Bathurst Inlet region south to the mines in the NWT and north to Bathurst Inlet (the "Bathurst Inlet Port and Road") has also been partially assessed by the Nunavut Impact Review Board. The proposed port facility, 35 km to the south of the community of Bathurst Inlet, would include the construction of a dock, 18 large fuel storage tanks, a 211 km road to Contwoyto Lake, a 1,200-metre airstrip and two camps for about 200 workers (George 2013). The Government of Nunavut, Nunavut Tunngavik Inc, the Kitikmeot Inuit Association, and a range of Inuit-owned corporations have been active partners in exploration and mine development in the region, but the project remains controversial and concerns have been expressed about cumulative impacts on wildlife (both marine and terrestrial), particularly caribou. Concerns have also been expressed about detrimental social, cultural, economic, and health impacts, terrestrial and marine pollution, erosion, and the impacts of increased shipping through the region.

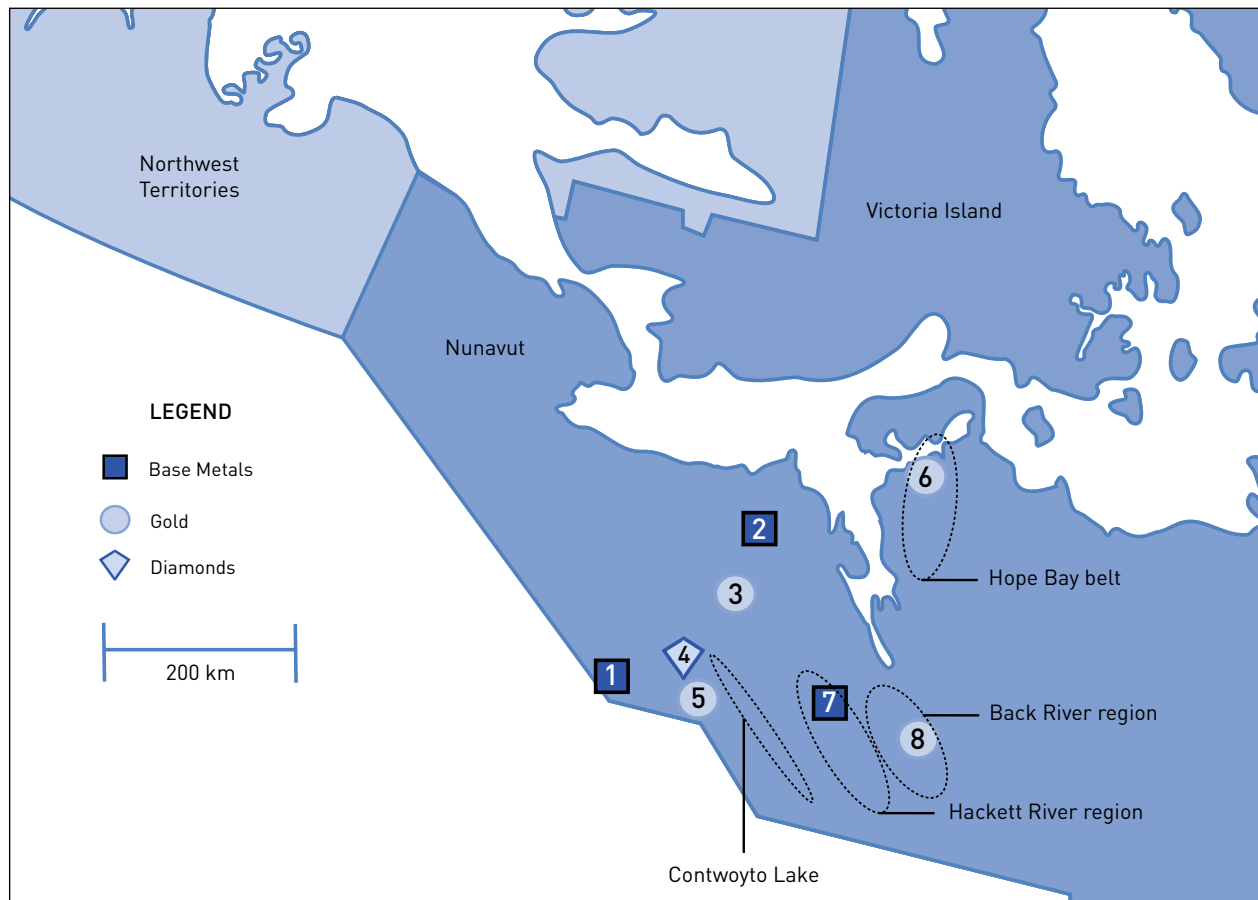


FIGURE 1. Advanced exploration projects in the Kitikmeot region of Nunavut. Mine names: (1) Izok Lake, (2) High Lake, (3) Ulu, (4) Jericho, (5) Lupin Mine, (6) Hope Bay, (7) Hackett River, and (8) Back River. Adapted from the NWT & Nunavut Chamber of Mines website (<http://www.miningnorth.com/exploration>), accessed November 4, 2014.

Mineral development is less dominant in the ISR, where hydrocarbons have been the focus of exploration activities, but significant diamond showings have been identified at the Franklin (on the Parry Peninsula) and Horton sites, as well as at Darnley Bay, a property on Inuvialuit-owned lands near Paulatuk, NT. A gravity anomaly in the Paulatuk region suggests significant mineral deposits in the area. Darnley Bay Resources Ltd. is reporting the potential for at least nickel, copper, platinum and gold throughout the Inuvialuit-owned lands, which has led to a partnership between the company and the Inuvialuit Regional Corporation (Reford 2012).

Concerns have been expressed across Nunavut and the NWT about the rapid development of multiple mines, and their cumulative social, economic, and environmental impacts (e.g. CARC 2003; West Kitikmeot Slave Study Society (WKSSS) 2008; Nunavummiut Makitagunarningit 2010; Bouzane and Mack 2012). These cumulative effects are difficult to assess but are of pressing consideration. The absence of a land use plan in the Kitikmeot region further adds to the challenges of assessing mineral development on a regional scale, although consultation regarding a draft land use plan is currently underway (see Chapter 1, Nunavut Planning Commission).



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It is also important to note the importance of mineral development on lands adjacent to the ISR and Kitikmeot regions. The West Kitikmeot-Slave and Bear geological provinces span the NU/NT border and are among the most mineral-rich regions in the Arctic. Kitikmeot residents have been working at the diamond mines in the NT since their construction (and, before that, at the Lupin mine) and the mines themselves are located within the Coppermine River watershed. Proposals to develop a port and road network in the Bathurst Inlet area are oriented around linking future Kitikmeot mines with existing road and mine infrastructure in the NWT, as well as with an increasingly ice-free shipping route through the Northwest Passage. This shared economic and environmental stake in mineral development in the NWT has been acknowledged through various Impact and Benefit Agreements between Inuit beneficiaries of the Nunavut Land Claim Agreement and the mining companies seeking to develop mines in the region.

Climate change and mining operations

Climate change is a significant consideration for both operating and future mines. Many climate-related changes in northern landscapes have a bearing on mining operations, including a reduction of seasonal and multi-year sea-ice

extent, coastal sea-level rise and erosion, changes in seasonal run-off, changes in permafrost, and changes in plant and wildlife species range and biological productivity (Solomon et al. 2007; AMAP 2012).

For communities in the western and central Canadian Arctic that are anticipating a resource boom in the region, accelerated climate change is of particular concern. In some cases, climate change is acting as a key driver for economic development in the region (Fenge 2009). Should ports be developed in the Canadian Arctic, sea-ice reduction may allow for longer port access by ship, and thus some potential mining operations may become more economically feasible. Climate change also poses serious risks to mineral development, however, particularly with regard to the effects of permafrost warming, coastal erosion, and the stability and maintenance of transportation infrastructure (Instanes et al. 2005). Furgal and Prowse (2008) report that climate change will impact all forms of resource development in the North, including oil and gas, mining and hydroelectric operations, and the subsequent infrastructure and transportation routes of these projects. However, the specific effects of climate change on mining in the North continue to be a major gap in research (Ford et al. 2010). This gap is exacerbated by the inherently high degree of climate variability in the North,

which perpetuates the uncertainty surrounding temperature and precipitation fluctuations. Such uncertainties make it difficult for mining projects to be designed in ways that effectively address necessary adaptations to climate change, although the Nunavut Regional Adaptation Collaborative (RAC) reports (2012a, b) provide important information, discussion, and adaptive strategies to address the impacts of climate change on mining from exploration through to construction, operations, and closure.

Changes to permafrost are perhaps the most significant source of uncertainty for mining operations and infrastructure. IPCC climate scenarios predict that by 2050, permafrost in the northern hemisphere could decrease by 20-35% in various regions of sporadic, discontinuous and continuous permafrost zones (Anisimov et al. 2007). In northern Canada, borehole samples taken during the last 50 years indicate that permafrost temperatures have risen considerably, and since the 1980s, Arctic permafrost temperatures have increased by 3°C (Solomon et al. 2007). These changes have considerable implications for mineral activity as the stability of Arctic surfaces affects roads, airstrips, tailings facilities, buildings, and other mining-related infrastructure.

Indeed, mining operations in the Arctic rely on the predictability of permafrost temperatures for a number of reasons that are mainly related to the structural stability of operational facilities (including tailings ponds) and transportation routes. In the past, mines have been designed with the assumption that climate conditions will be stable (Pearce et al. 2011). As of 2000, there were 160 abandoned mines reported in northern Canada, with almost 70 sites showing physical instability or chemical contamination (Keeling and Sandlos 2009). As permafrost thaws, shifting tailings-containment pits and piles have the potential to collapse and leach toxins into the surrounding environment. Recently, however, projects that require water-retention or tailings-containment structures, large buildings, or pipelines and roads have begun to integrate climate change science into the project designs (Prowse et al. 2009). The Ekati diamond mine in the NWT, for example, considered climate change impacts when designing the mine's tailings dams.

Unfortunately, they were not as prepared for the 2006 ice road closure, demonstrating the necessity for comprehensive climate change preparations and adaptations.

Rising surface temperatures and permafrost thaw increase the structural instability of ice roads in the Arctic, which have provided a method of transportation in the North that is inexpensive and has less environmental impact than all-weather roads. Reliance on a single supply route has proven to be problematic in recent years. A shorter ice road season due to thinning ice in 2006 along the Tibbitt to Contwoyto Winter Road (TCWR), for example, created unanticipated costs for the Ekati and Diavik diamond mines; Diavik had to fly in 15 million liters of fuel once the road closed (Ford et al. 2010). Construction scheduling at the Snap Lake diamond mine was also altered due to the TCWR closure (GNWT 2006). Privately owned and managed, the TCWR is the longest winter road in the NWT and is the main shipping and supply route for the Ekati and Diavik diamond mines, the Snap Lake and Jericho mine developments, as well as the Lupin gold mine, which is currently inactive (Furgal and Prowse 2008). If the Bathurst Inlet Port and Road project proceeds, it will connect mines in the Kitikmeot region to the TCWR, further tying mineral development in the region to the stability and reliability of ice and all-weather roads.

Melting sea ice presents both challenges and opportunities to resource extraction industries. Challenges include increased coastal erosion and collapse, which is already being witnessed along the banks of Tuktoyaktuk and Paulatuk (Wolfe et al. 1998; Instanes et al. 2005; Pearce et al. 2010). Longer ice-free seasons, however, have the potential to attract further exploration and development along the northern shores of the Arctic. As ice melts in the Beaufort Sea, researchers are predicting an increase in water-based transportation for mineral and hydrocarbon extraction (Furgal and Prowse 2008). By 2050, it is predicted that the Northern Sea Route will have 125 days per year with less than 75% sea ice (Instanes et al. 2005), rendering shipping an increasingly attractive component of mineral development plans. However, low-lying coastal

areas will experience an increase in vulnerability to storms and higher waves as sea levels rise and sea-ice regimes shift, which will have impacts on infrastructure in these areas (Walsh et al. 2005).

Alongside shifts in permafrost, increased coastal erosion, and sea level rise, shifts in wind and precipitation patterns and extreme weather events also stand to impact mining operations in the region (Barber et al. 2008; Nunavut RAC 2012a). While climate-related impacts on mining infrastructure and transportation have direct financial implications for mining operations, the broader social, economic, and environmental dimensions of climatic change are also of relevance to assessments of future mining. Climate-related shifts in vegetation, hydrology, and wildlife may alter the migration routes and behaviour of important species of wildlife such as caribou, moose, bears, muskox, wolves, seals, fish, and whales, with associated impacts on traditional harvesting. Most existing mines have wildlife management plans in place that may need to be adjusted in the face of shifting wildlife and harvesting patterns. The short- and long-term environmental impacts of climate-related damage to mining infrastructure, or mine abandonment, remain poorly understood, but pose considerable risks to northern peoples and wildlife. 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 as climate-related sources of vulnerability in the region have not been thoroughly assessed (Cameron 2012). This remains an important focus for future research. According to Lemmen et al. (2008), resource-dependent and Indigenous communities are the most vulnerable to the effects of climate change. Indigenous communities in the North that depend on resource development are especially vulnerable, as many communities shift to livelihoods that are less dependent on subsistence incomes (White 2009). According to Nellie Cournoyea (2009), the CEO of the Inuvialuit Regional Corporation (IRC), proper planning for community and mining infrastructure is essential to the adaptive capacity and sustainability of the Inuvialuit.

Renewable energy and mining operations

It is uncertain how climate change may affect the potential for renewable energy harvestable by northern mining operations. While wind energy has supplemented diesel-generated power at Alaskan mines and the Diavik diamond mine in the Northwest Territories, inconsistent wind conditions have deterred development of a wind farm at the Meadowbank gold mine in the Kivalliq region of Nunavut (Cumberland Resource Ltd. 2005). Although wind is a highly variable climate phenomenon, some work suggests wind speeds may increase during winter months and wind direction may shift clockwise in summer months within the western and central Canadian Arctic (McInnes et al. 2011). With respect to hydropower, there are currently no hydro electric-generating facilities in the ISR or the Kitikmeot region despite considerable potential in the West Kitikmeot (Sexton 2010). The projected increases in seasonal precipitation, snow depth and the onset of earlier snow melt (Chapter 2), however, are likely to impact the flow regimes of the region's rivers.

Outlook for mining

Despite the risks of climate change impacts on the mining industry and its potential environmental, social, and economic implications for northern communities in the western and central Canadian Arctic, the NWT and Nunavut continue to rise in the rankings as regions worth investing in mining (McMahon and Cervantes 2012), presenting social and economic opportunities to the region. However, many Northerners lack the education and skills needed for industrial employment, with jobs going instead to skilled workers from the South (Canadian Polar Commission 2014). Training programs are needed to fill this skills gap and enable increased Inuit participation in this economic sector. Other challenges include boom and bust economic cycles as mines open and close, and increasing interregional connections and mobilities. These changes are likely to interact in complex ways with climate and environmental change in the region, and the cumulative impacts of these changes will test the

resilience of Arctic communities. Mineral development in the North raises challenges for Indigenous communities in particular, due to impacts on food security, health, culture, language, and social and economic life, as well as impacts on political and economic sovereignty (Gibson and Klinck 2005; Angell and Parkins 2011; Nunavummiut Makitagunarningit 2013). Although many Indigenous communities have found avenues for greater participation and control over the economic benefits of mining, such as through Impact and Benefit Agreements, the pace and scope 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 (Caine and Krogman 2010; Bowman 2011). According to Nunavummiut Makitagunarningit (Makita), a non-governmental organization founded in 2009, “decisions about uranium mining are being made [in Nunavut] without respect for the principle of free, prior and informed consent,” (2013, 2) and Makita has raised larger concerns about resource governance in the territory. Future mining activity will not be driven only by economic factors, then, but also by the complex intersection of political, social, cultural, and environmental change in the region.

9.2.2 Oil and gas

Today, non-renewable resource exploration and extraction in the non-renewable hydrocarbon resources of the region are principally deposits of oil and gas in the southern Beaufort Sea and Mackenzie Delta areas and deposits of coal, metals or diamonds scattered widely in the area. The Arctic regional oil and gas industry was reviewed comprehensively recently by the Arctic Monitoring and Assessment Program (AMAP 2010). One of the main environmental issues remains oil spills and how to deal with them. In spite of years of research on how to manage spills, there remain calls for improved abilities to cope with real and potential oil spills in the Canadian Arctic (e.g. Porta and Bankes 2011).

Development in the western and central Canadian Arctic

1970s and 1980s

Although oil was first discovered in Normal Wells, NT in 1919, it wasn't until 1968, when oil and gas was discovered at Prudhoe Bay, Alaska, that exploration efforts began to boom in the western Canadian Arctic, particularly in the coastal, and later offshore, waters (CAPP 2009; Callow 2012). Between 1970 and 1989, fifty-three hydrocarbon discoveries were made in the Mackenzie Delta and Beaufort Sea (SCE WG 2008). In 1982 the government and the hydrocarbon industry had estimated between six to thirty-two billion barrels of recoverable oil from the Beaufort Sea, and it was further predicted that early production could begin in the region by 1986 (EIS 1982)

Despite the significant potential for oil and gas production in the region at this time, the momentum towards reaching these high expectations was short-lived. A notable influence impeding the oil and gas industry in the 1980s was a global drop in demand (and price) for oil, which peaked at \$35/barrel USD in 1980 and dropped to \$10/barrel USD in 1986. Another factor in discouraging hydrocarbon production was the outcome of the Mackenzie Valley Pipeline Inquiry (aka the Berger Inquiry). The discovery of huge gas fields in the early 1970s prompted several proposals for pipelines to be constructed along the Mackenzie Valley and into northern Alberta and British Columbia. In 1977 the Berger Inquiry recommended to the Minister of Indian and Northern Affairs that a pipeline not be approved but rather delayed to provide time to resolve Aboriginal land claims (CAPP 2009). For example, the year of 1984 marked the signing of the Inuvialuit Final Agreement, a comprehensive land claim agreement which provided the Inuvialuit rights and management of the Inuvialuit Settlement Area (an area over 900,000 km², including a portion of the Beaufort Sea; see Chapter 1 for more details). This introduced a new regional-level of governance, specifically advisory and regulatory agencies (i.e. the ISR co-management boards and Hunters

and Trappers Committees, see Chapter 1), which were required to approve any development projects before they started. Additionally, with the harsh climate, ice conditions, permafrost, darkness, lack of infrastructure, sovereignty concerns (see *Maritime jurisdiction in the Beaufort Sea*, this chapter) and remoteness in the Canadian North, plus the concerning repercussions that the 1989 *Exxon Valdez* grounding in Prince William Sound had on hydrocarbon development, the financing and logistics of oil and gas exploration had become economically unfeasible and challenging. The year of 1989 marked the cease of exploration drilling until 2005.

2000s and onwards

After a decade of little to no hydrocarbon activity in the western Canadian Arctic, the increasing prices for oil and gas, as well as a renewed interest for the proposed Mackenzie Gas

Pipeline, reignited the prospects for oil and gas exploration. Exploration rights to land parcels on the Mackenzie Delta and Beaufort Sea were issued by the federal government in the 2000s; by 2007/2008, licenses for the deeper continental shelf had been acquired by hydrocarbon companies (INAC 2010). Between 2010 and 2013 alone, the area licensed by hydrocarbon companies in the Beaufort Sea and Mackenzie Delta grew from over 2 million hectares to over 3 million hectares (INAC 2010; AANDC 2014; Figure 2). As of 2013, Franklin Petroleum Canada Ltd. holds exploration licenses for the largest total area, followed by BP Canada Energy Resources Company (Figure 3).

The potential for hydrocarbon reserves in the western Canadian Arctic today has grown since the early estimates in 1982 (EIS 1982), particularly in the Mackenzie Delta and Slope (Figure 4). Not only is the Mackenzie Delta/Beaufort Sea region estimated to contain between

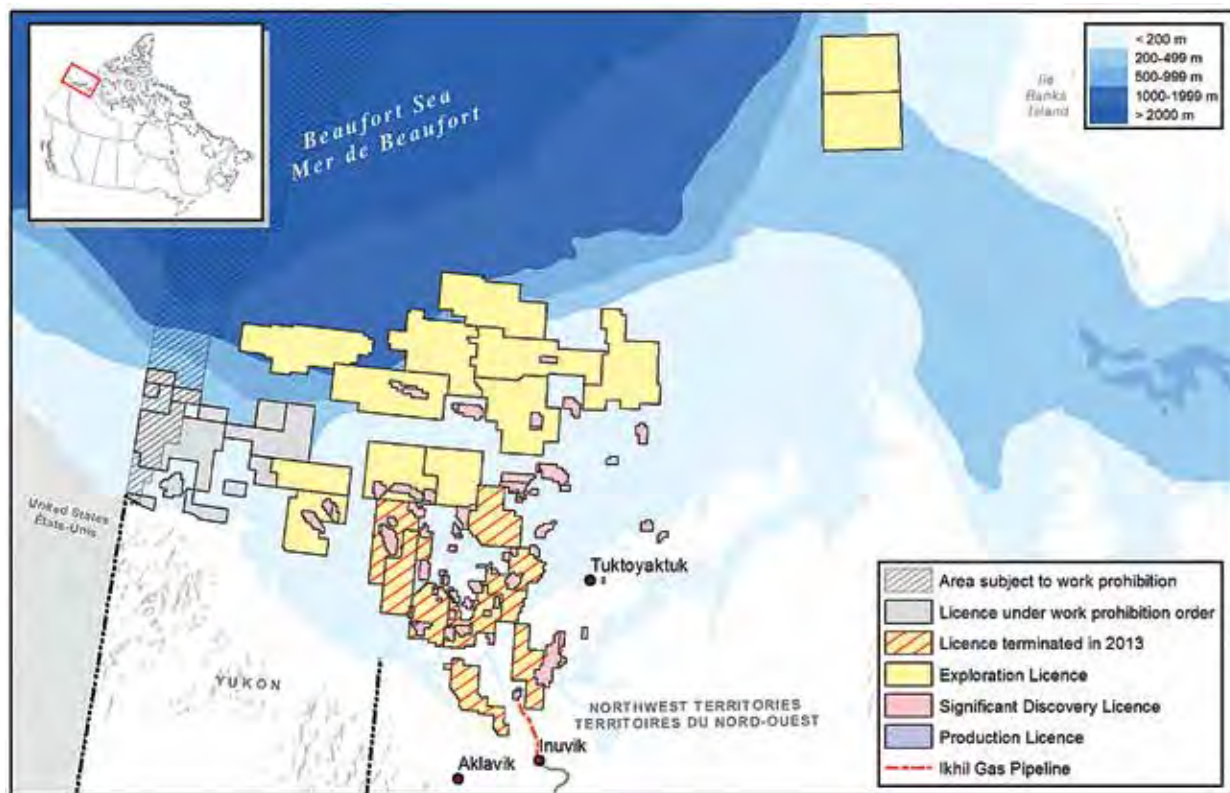


FIGURE 2. Hydrocarbon exploration licenses in the Mackenzie Delta and Beaufort Sea, 2013. From AANDC (2014).

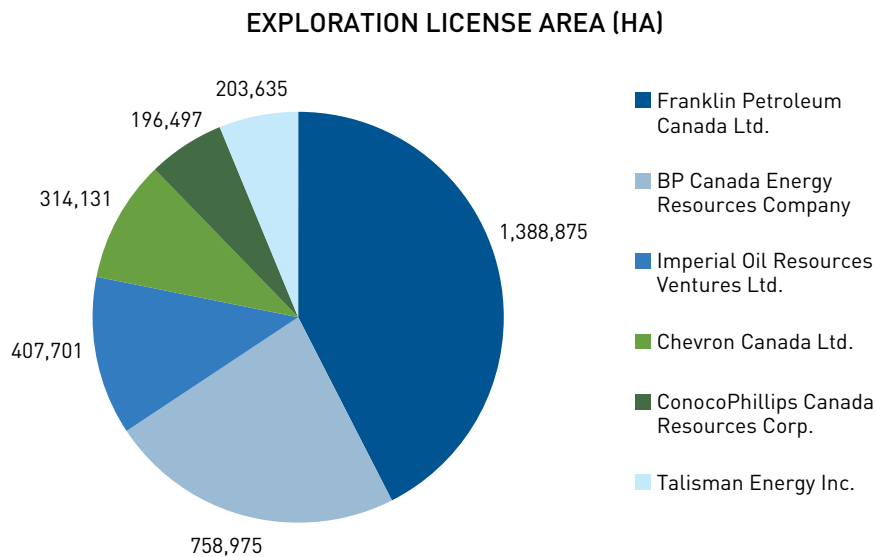


FIGURE 3. Exploration licences (by total area) in the Beaufort Sea and Mackenzie Delta held by petroleum companies, 2013. Data from AANDC (2014).

1-1.2 billion barrels of recoverable oil reserves (Callow 2012), but it is also assessed as having a mean estimate of about eight to nine billion barrels of undiscovered oil and dozens of trillion cubic feet of undiscovered gas (Gauthier et al. 2009; Table 1).

With respect to productive wells, the Ikhil field is the only operational site within the ISR, supplying Inuvik with 7.3 billion cubic feet of natural gas over the course of 14 years of production (AANDC 2013). The next closest site is the Normal Wells field which has produced a total of 269.8 million barrels over the last 22 years, and Cameron Hills which has produced 32.7 billion cubic feet of natural gas and 2.5 million barrels of oil over 11 years of production (AANDC 2013) (Figure 5). Outside of these fields, no other hydrocarbon production is currently underway in the Mackenzie Delta or the Beaufort Sea. Shallow shelf oil production is predicted by 2020 (Callow 2012) while deep offshore production is estimated to occur later (BREA 2013).

Maritime jurisdiction in the Beaufort Sea

For four decades, Canada and the United States have disagreed over the location of their maritime boundary in the Beaufort Sea, an area likely to contain commercially recoverable oil and gas reserves. Both countries assert jurisdiction over a wedge-shaped maritime sector within 200 nautical miles of the coast north of Alaska and the Yukon Territory (Figure 6). Beyond the 200 nautical mile Exclusive Economic Zone (EEZ) here and elsewhere, it is possible for states to claim and exploit the resources on and under the seabed according to the provisions of the United Nations Convention on the Law of the Sea (UNCLOS). Notably, states must demonstrate that beyond 200 nautical miles there lies a “natural prolongation” of the continental shelf, more commonly referred to as an “extended continental shelf”.

Together, Canada and the United States have been collecting evidence of the seabed’s shape and geology in order to establish their entitlements to an extended continental

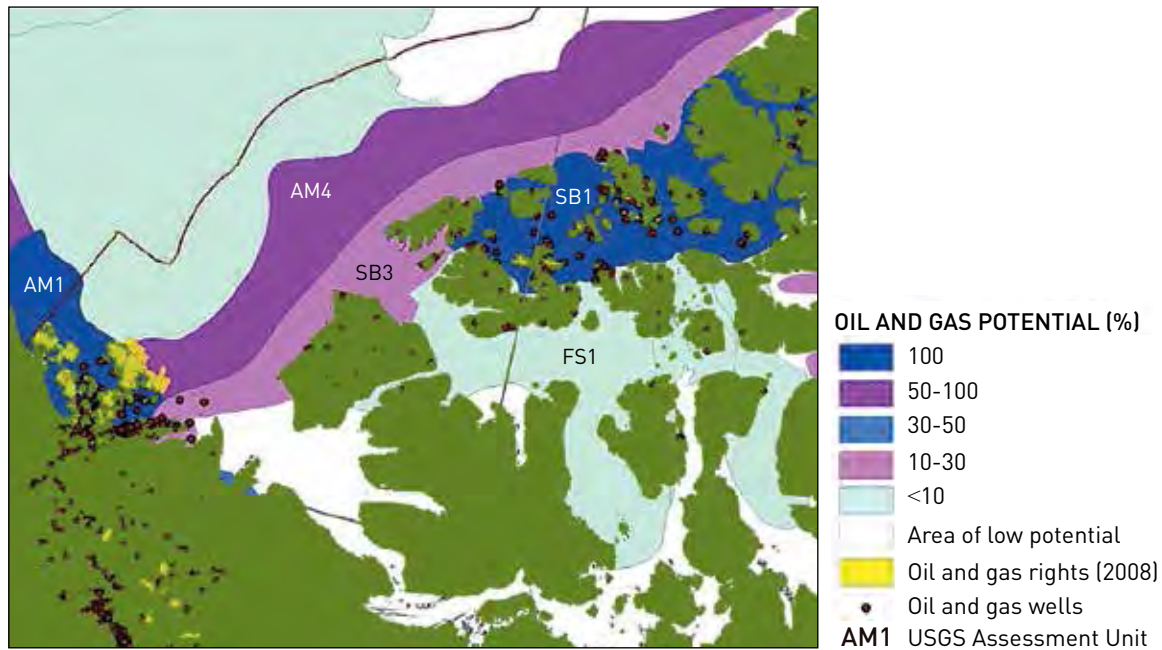


FIGURE 4. Oil and gas potential in the western and central Canadian Arctic. The United States Geological Survey (USGS) Assessment Units are defined as volumes of sedimentary rocks sharing similar geological properties, and were recently assessed for undiscovered hydrocarbon reserves (Gauthier et al. 2009). Adapted from Stephenson and Hartwig (2010), Fisheries and Oceans Canada. This does not constitute an endorsement by Fisheries and Oceans Canada of this product. Original material available online at <http://www.dfo-mpo.gc.ca/Library/341178.pdf>.

TABLE 1. Estimated volumes of undiscovered oil and gas in the assessment units spanning the western and central Canadian Arctic as per the United States Geological Survey (Figure 4). From Gauthier et al. (2009, supplementary information).

USGS Assessment Unit	Probability of hydrocarbon reserves (%)	OIL (UNITS OF BILLIONS OF BARRELS)			TOTAL GAS (UNITS OF TRILLIONS OF CUBIC FEET)		
		Mean	95% probability (95 th fractile)	5% probability (5 th fractile)	Mean	95% probability (95 th fractile)	5% probability (5 th fractile)
AM1	100	6	2.5	12.5	35.9	12.8	75.5
AM4	54	2.3	0	7.7	15	0	52.9
SB3	22	0.4	0	2.7	3.6	0	22.9
SB1	100	0.42	0.06	1.3	4.95	1.2	12.9
FS1	9	n/a	n/a	n/a	n/a	n/a	n/a



FIGURE 5. Operational hydrocarbon production sites in the western Canadian Arctic. From AANDC (2013).

shelf in the Beaufort Sea. Early mapping results suggest the two states may be entitled to exploit seabed resources far beyond their EEZs. Neither country has articulated a legal position on the placement of the boundary beyond 200 nautical miles – probably because they are uncertain that the existing methods used for calculating their declared lines within 200 nautical miles would benefit them beyond this distance from shore. This situation opens up the possibility of a positive-sum outcome as they explore options for resolving the Beaufort Sea maritime boundary dispute.

Oil and gas spill prevention research

Introduction

Offshore hydrocarbon development in the western Arctic is in the early stages of exploration. Exploration drilling structures in shallow waters of the inner Beaufort Shelf employ bottom founded platforms (Figure 7a), while in the deeper



FIGURE 6. Canadian and American claims in the Beaufort Sea.

waters of the mid to outer shelf and upper slope floating platforms are used or proposed (Figure 7b). In either case the platform and/or the drilling systems come in contact with the seabed and subseabed. It is this interaction between drilling facilities and the seabed that needs to be clearly understood to minimize the risk of drilling mishaps and the potential for oil and gas leaks and spills. In addition, subsea pipelines also interact with the seabed and are subject to potential leaks and spills.

By understanding the nature of both the seabed and subseabed, geologists, geotechnical engineers and geophysicists can identify hazardous conditions, known as geohazards, that may adversely affect the integrity and stability of the drilling system and/or pipeline which could lead to structural failure and leaks and spills.

From a northern community perspective these leaks and spills will adversely affect the renewable resources of the

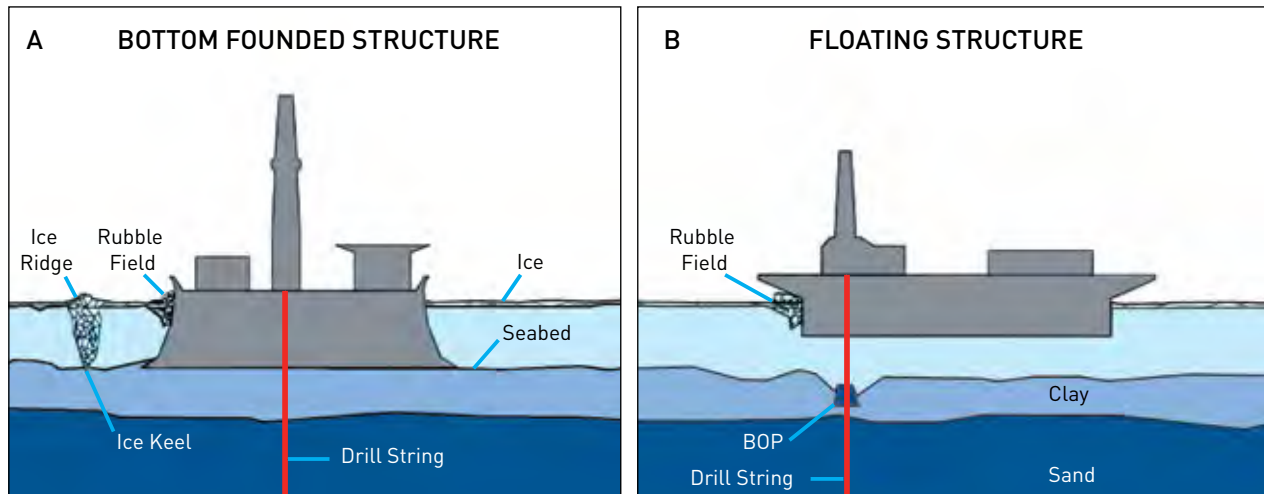


FIGURE 7. Schematic of bottom founded (a) and floating (b) drilling structures illustrating the interaction between drilling systems and the seabed and subseabed.

marine environment, including whales, seals, fish, plankton - in fact the entire marine ecosystem. Adverse impacts on the marine ecosystem can have negative consequences to the sustainable traditional way of life.

By conducting oil and gas spill prevention research the risk to the environment can be significantly reduced. Research in the Beaufort Sea from the early 1970s to present day has led to the identification and investigation of a variety of geohazards both on and below the seabed. By understanding the negative impact of the seabed environment on offshore hydrocarbon development structures such as the drilling systems and pipelines, the knowledge becomes available to support timely and relevant regulatory processes by both government and the Inuvialuit agencies. This knowledge also feeds engineering design strategies for offshore facilities by industry.

Most marine research is focused on the adverse impact of exploration activities *on* the environment, such as the effects of noise on marine mammals. On the other hand, spill prevention research is focused on the opposite point of view, the adverse impact of the environment *on* development activities. This section describes the types of geohazards which may be encountered and their potential negative

impact on engineering structures. It is important to note that this research was initiated in the early 1970s to 1990 on the Beaufort Shelf, followed by a cessation of activity until 2001 when geohazard research was reinitiated on the outer shelf and upper slope.

Offshore geohazards to be investigated were identified by ongoing interaction among the Inuvialuit Game Council, National Energy Board, industry lease holders in the Beaufort Sea and the Geological Survey of Canada (GSC). Data acquisition was conducted by the GSC in collaboration with industry, ArcticNet and the Beaufort Regional Environmental Assessment (BREA) program. Data analyses were conducted independently by industry and the GSC. GSC research was funded by the GSC and the Program on Energy Research and Development. Offshore geohazard research continues today with the same group of collaborators.

Offshore geohazards

Blasco et al. (2013), Rankin et al. (2015), and Woodworth-Lynas et al. (2015) provide a comprehensive technical description of potential seabed and subseabed geohazards that may adversely affect the integrity/stability of offshore

engineering facilities during operations such as drilling and transporting hydrocarbons. Additional references are provided where knowledge goes beyond these three key references.

Figure 8 is a three-dimensional image of the Beaufort seabed illustrating a seafloor saturated by the cross-cutting tracks made by the keels of drifting sea-ice pressure ridges. Pipelines will need to be buried in trenches below the deepest ice scour encountered along route to ensure the safety of the pipe during operation. Current research is focused on determining the depths of extreme ice scours and the factors which may limit these depths (Blasco et al. 2011). Recent evidence shows that even though Arctic sea-ice conditions are becoming thinner overall there are mechanisms which create very thick first-year and remnant multiyear ice types, particularly in the Southern Beaufort Sea (Barber et al. 2014).

During the 1970s and 1980s, 37 artificial islands were constructed on the Beaufort Shelf by dredging sand from the

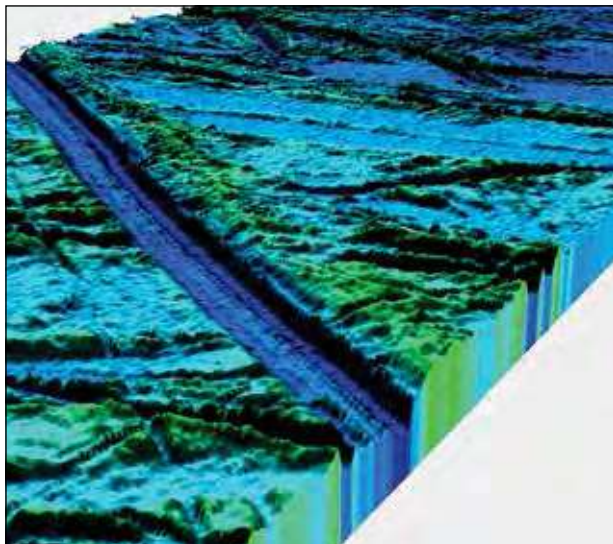


FIGURE 8. Three-dimensional sonar image illustrating the Beaufort seabed saturated by the tracks of ice scours created by the passage of drifting ice keels. Scour depths have been observed to 5 m below seabed in localized areas of the shelf.

seabed. The islands supported exploration drilling platforms (Figure 9a) and were abandoned on completion of the drilling program. Over the last 25 to 35 years these sand islands have been eroded by wave and current action. Seabed mapping of these islands over time has shown the crests are now 2 to 5 m below sea surface (Figure 9b) and are now hazards that could damage the hulls of vessels.

Engineering structures in contact with the seabed or subseabed, such as platforms, drilling systems (Figure 7a, b), or pipelines require sediment of sufficient strength to support the structure for the period of time the structure is operational – be it a few months or a couple of decades. Loss of lateral or vertical support could compromise the stability of the structure. Ongoing research is directed at mapping the regional distribution of sediment properties to identify weak or low strength sediments.

Seabed sediments in water depths greater than 100 m have been observed to have failed to form submarine landslides on the upper slope of the Beaufort (Figure 10). Research is being conducted to map the distribution of these geohazards, determine their age and cause, and hence the negative impact on deep water hydrocarbon development.

Subsea permafrost in the form of ice-bearing sediments (Figure 11) is now known to occur to depths of 700 m below sea surface (Blasco et al. 2012). The heat generated by drilling activities or the production of hot oil and gas from deep reservoirs can result in the melting of the ice within these sediments, softening of the sediments, loss of structure support and failure of the structure. Knowledge of the ice contents and distribution of ice-bearing sediments across the Beaufort provides the basis to develop mitigative measures that minimize the impact of subsea permafrost.

Shallow gas under pressure has also been identified as a geohazard. Petrogenic gas migrating upward from reservoirs at great depth or biogenic gas from decomposing organic matter in shallow sediments can become trapped in the sediment layers to be drilled. By mapping the distribution of potentially hazardous gas charged sediment

A



B

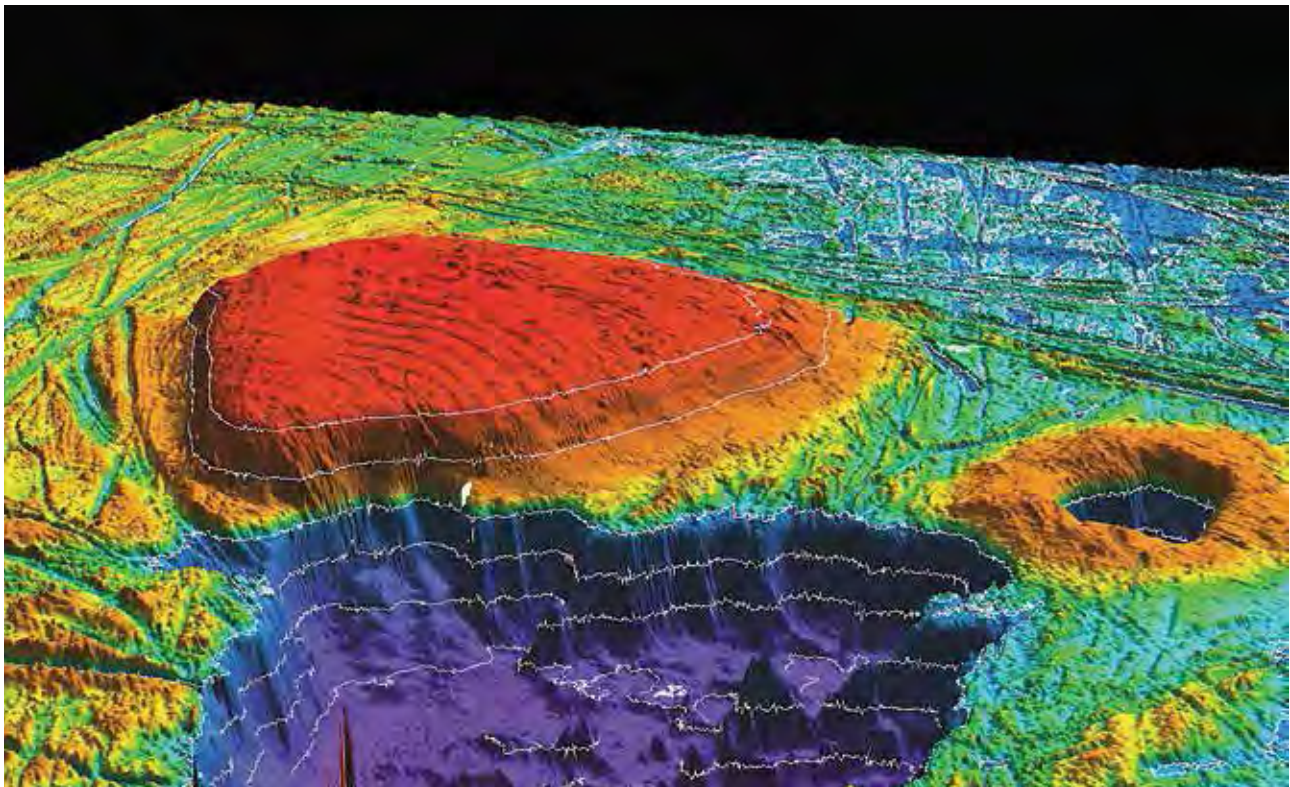


FIGURE 9. Artificial exploration drilling island Issungnak in 1981 (a). Three dimensional sonar image of the island 5 m below sea surface and the dredge pit from which sand was excavated to construct the island (b).

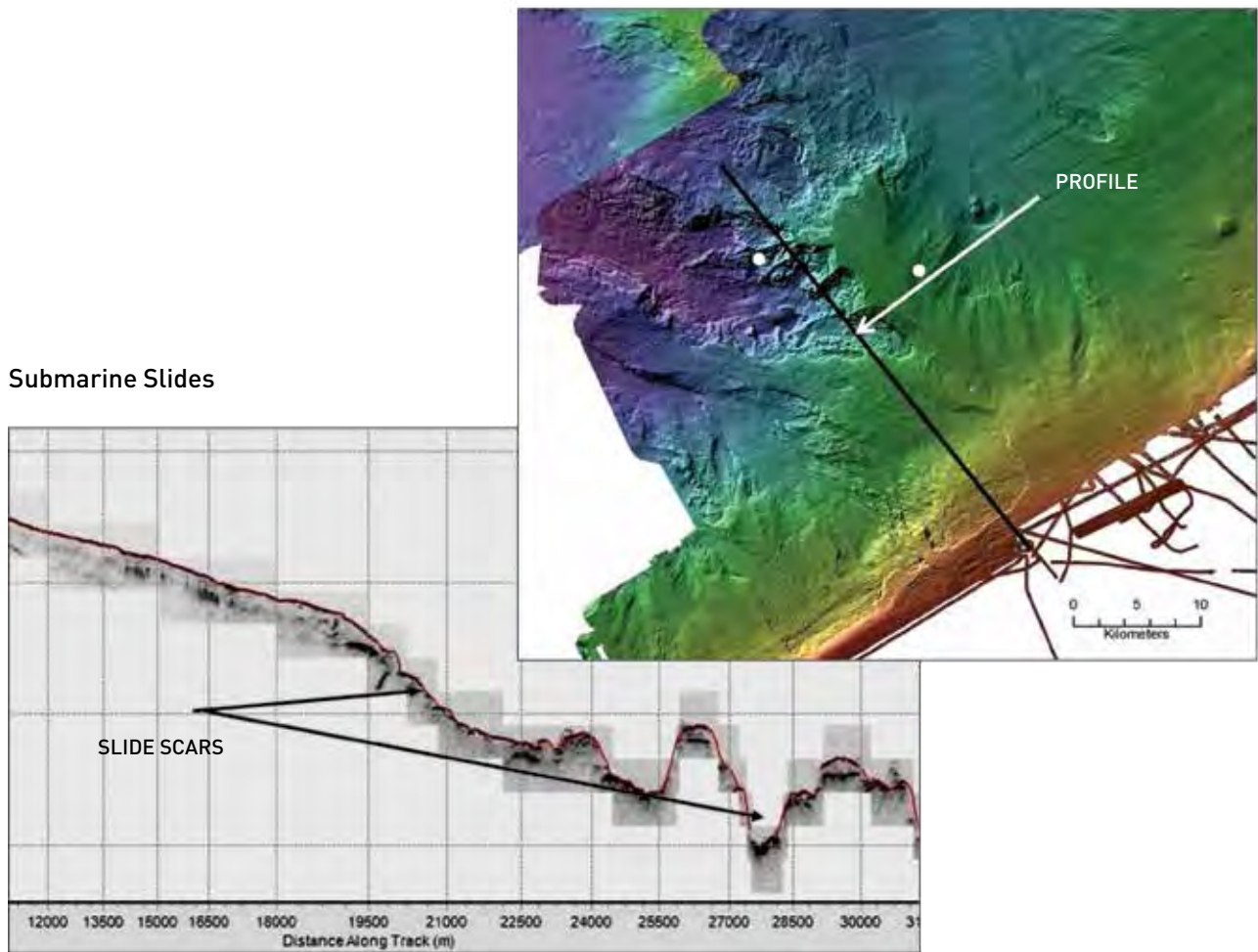


FIGURE 10. Sonar image of a submarine landslide scar shown in map view and cross section. The two images illustrate the significant lateral extent and depth of the landslide.

layers, drilling procedures can be implemented to prevent loss of well control and blowouts.

Evidence of significant gas migration from deep and/or shallow sources below the Beaufort seabed has been demonstrated by the occurrence of several hundred relict and active mud volcanoes on the seabed (Figure 12). Knowledge of the distribution of these instability features means they can be avoided during the selection of exploration drilling sites and defining routes for subsea pipelines.

Gas hydrate, frozen methane gas (similar to dry ice), occurs in subseabed sediments in forms much like the ice within

permafrost (Paull et al. 2012). The negative impact resulting from drilling through hydrate is also similar to that of sub-sea permafrost whereby the hydrate can decompose as temperature rises and/or pressure is decreased. Decomposition leads to instability around the well bore and reduced facility support with potential loss of control. The decomposition of hydrate leads to the generation of large volumes of gas and water and, under natural conditions, may contribute to the shallow gas geohazard and the formation of mud volcanoes on the seabed.

Sediments at depth below seabed can be under pressures greater than the weight of the overlying sediments and water

FIGURE 11. Sediment core taken from the Beaufort seabed showing the distribution of ice in sediments. The ice occurs as veins, lenses, massive ice and invisible pore ice throughout the core.

Ice Veins



column, a condition known as overpressure. Overpressure can be generated by the presence of excess gas and/or fluids that have entered the sediments after deposition (see above shallow gas, hydrates) or be generated by rapid sedimentation rates during deposition. From a geohazard perspective, overpressured sediments need to be identified or predicted so that exploration drilling operations can mitigate the problem with appropriate technologies to contain the excess pressures while drilling.

Other geohazards

Other geohazards such as faults, where the seabed and subseabed sediment layers have vertically and horizontally sheered, have been identified during regional mapping of the seabed. Faults can be associated with unstable and/or overpressured zones that can adversely affect the integrity of wells being drilled. Continued seabed mapping would result in the identification of unknown faults and other instability conditions which may adversely affect hydrocarbon development.

Sea-ice hazards

Marine ice (i.e. sea ice and glacial ice) can create hazards that are challenging for oil and gas related industries to manage (Barber et al. 2014). Arctic climate change would

lead us to believe that sea-ice hazards are decreasing in the Beaufort Sea as we increase the proportion of annual ice and decrease the proportion of perennial ice. Recent results show that, in fact, significant challenges remain in terms of the detection and prediction of motion of sea and glacial ice hazards. Thick ice features identified during field work in the Southern Beaufort Sea (SBS) (Figure 13) were of sufficient size and mass that a drill ship would have to detach to evade them or icebreakers would have to tow or break them up (difficult to impossible depending on mass). The many hazardous glacial and multiyear ice (MYI) features that remain in the SBS are difficult or impossible to distinguish by satellite remote sensing. We expect these hazards to exist for at least the next several decades, because the Beaufort Gyre will continue to carry glacial and MYI southward from along the Canadian Arctic Archipelago (CAA) into hydrocarbon exploration areas and to circulate at least some of this ice back to the MYI-generating NW flank of the CAA (Figure 14), making development of an ice management system for oil and gas development challenging.

Observations of highly variable circulation of small but very thick ice islands and MYI floes illustrate a number of key challenges: 1) we need better remote sensing detection methods to be able to distinguish marine glacial ice entrained in sea ice; 2) we need improved surface wind direction forecasting if we are to describe the average flow field of the ice with useful accuracy; and 3) we need high resolution measurements of near-surface currents since high frequency oscillations and eddies force deviations in sea-ice motion away from the average flow field. We summarize recommendations into three areas required for management of ice hazards:

1. Hazardous ice feature detection: Current active microwave satellite sensors have limited ability to detect hazardous ice features. Future research is required to exploit polarimetry and the higher temporal resolution data that will be available through constellation missions (e.g. Radarsat Constellation and the European Space Agency missions). Given the limitations of current state-of-the-art satellite hazardous ice detection, dedicated aircraft surveillance may

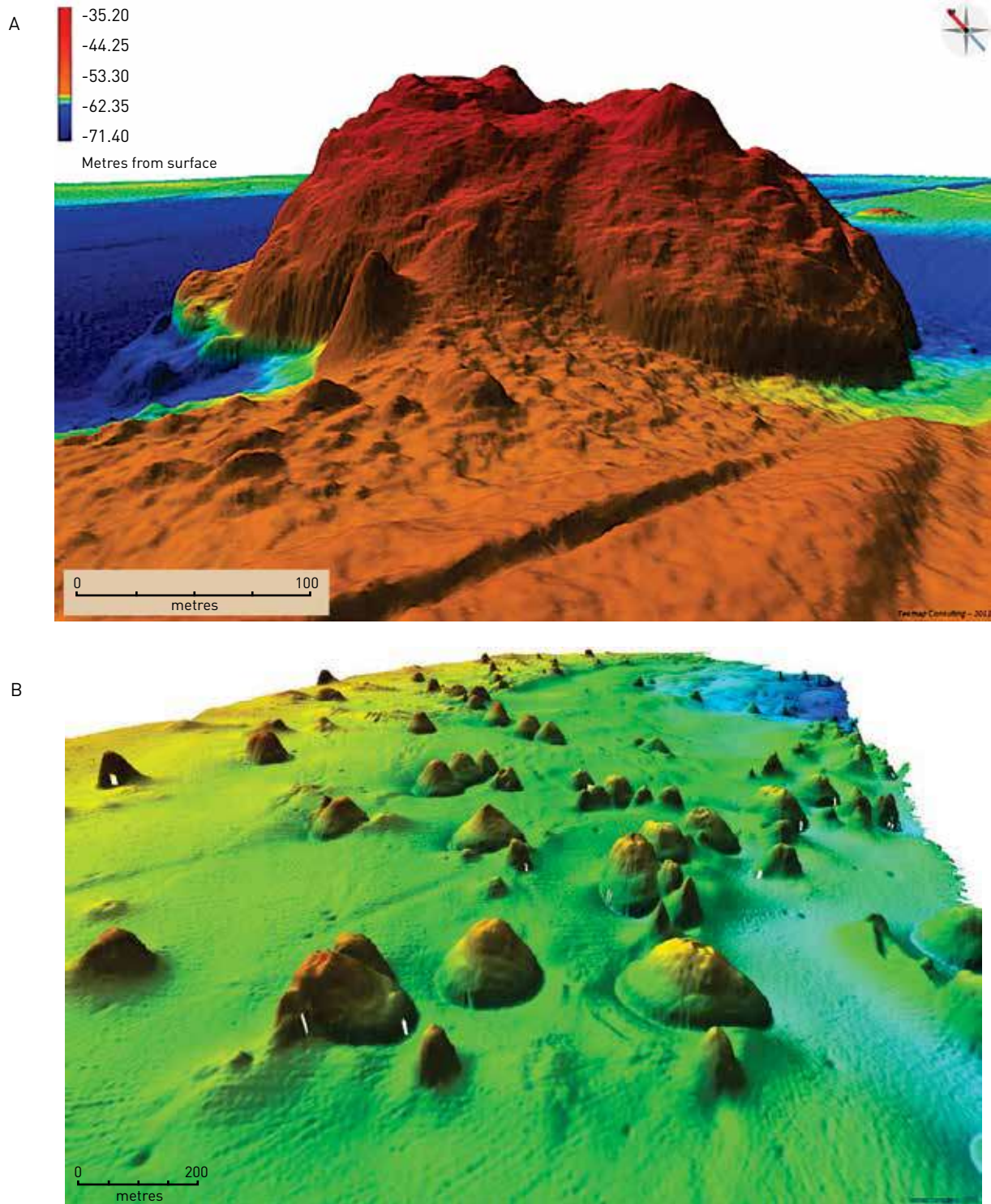


FIGURE 12. Three-dimensional sonar image of a single active mud volcano (a) on the Beaufort Shelf and an array of several hundred relict features (b) along the shelf edge.



FIGURE 13. Photographs of thick multiyear ice (MYI), glacial ice and a map showing the location of industry exploration. Example photographs of: A) thick MYI and B) glacial ice. The southern limb of the Beaufort Gyre advects ice features, such as in A and B, into the lease areas depicted in Figure 2. Adapted from Barber et al. (2014).



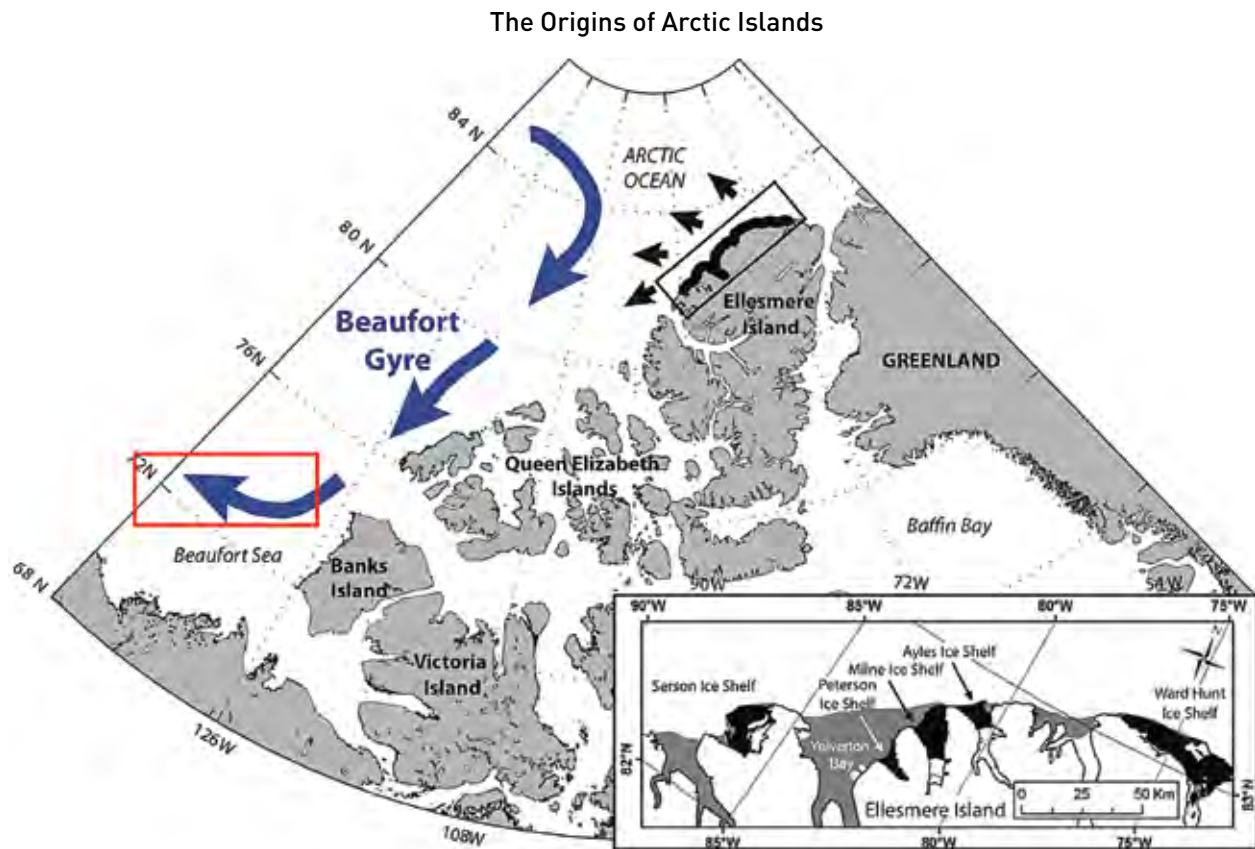


FIGURE 14. Marine ice hazards, sources and pathways. Multiyear sea ice builds up along the NW flank of the CAA. Ice shelves break off and are entrained in the Beaufort Sea Ice Gyre and travel south and west over areas of oil and gas development. Adapted from Jeffries (1987) and Copland (2007).

continue to be necessary for the foreseeable future in ice management systems. Because hazardous ice features may be hidden among manageable floes, the required density of flight surveillance will be higher than, for instance, in the managing for icebergs in the North Atlantic Ocean. However, this solution is inevitably limited by weather conditions. Very high resolution optical satellite data may be used to supplement airborne surveillance, but it is limited to cloud-free days.

2. Wind field observations and forecasting: Local wind estimates from satellite data (e.g. Komarov and Barber 2014) may provide improved forecasting of wind speed; with the advent of the proposed Synthetic Aperture RADAR constellation system by the European and Canadian Space

Agencies, repeat coverage would be reduced to 3 h, making this a good candidate for estimating the local surface wind field. However, further research into the potential for estimating wind direction by Synthetic Aperture RADAR is needed. For now, however, improved forecasting of wind direction will require local wind observations, at the very least including winds recorded at oil or gas extraction support vessels and permanent platforms. One further option may be installation of recoverable or disposable anemometers, with real-time telemetry, on upstream floes, a solution that would require parallel development of modeling routines that self-correct semi-continuously using real-time, local wind data from a distributed (i.e. Lagrangian) network of observatories.



PHILIPPE BOURSEILLER/ARCTICNET

BOX 1. Government and industry cooperate to develop technologies and skills to respond to an oil spill in the Canadian Arctic

Several relatively small oil spills have occurred in Canadian Arctic waters or in nearby waters off Greenland or Alaska (Macdonald et al. 2007):

- Shore tank destruction, Deception Bay, Canada, 1970 (Ramseier et al. 1973)
- Oil tanker *SS Johnathan Harrington*, Elson Lagoon, Alaska, 1944 (Brower 1980)
- USNS *Potomac*, Melville Bay, west coast of Greenland, 1977 (Maurer and Kane 1978)

Large spill events have not occurred in the Canadian Arctic but large spills in other cold waters are instructive:

- Tanker *MV Braer*, Shetland Islands, 1993 (Davies and Topping 1997)
- Tanker, *Exxon Valdez*, Prince William Sound, Alaska, 1989 (Rice et al. 1996; Peterson et al. 2003)

Perhaps even more alarming than sea surface spills have been sub-surface blowouts like those of the *Ixtoc* spills, the Ekofisk Bravo Platform and the recent *Deepwater Horizon* well in the Gulf of Mexico. These and other experiences have illustrated the importance of preventing similar occurrences in the region and of being prepared for them if they should happen. They have brought under scrutiny the processes used in Canada to regulate oil and gas exploration and production. The state of understanding was described recently in the Environmental Studies Research Funds (ESRF) report 177 (SL Ross Environmental Research Ltd. et al. 2010).

Recently the Pew Environmental Group (Porta and Bankes 2011) has argued that Canada and other northern governments and businesses are inadequately prepared for an oil spill in Canadian Arctic waters both from a regulatory viewpoint and from a spill recovery viewpoint. The perception that Canada is unprepared applies in spite of many years of efforts to develop the technologies and skills needed to respond to such an event. For decades, the need for adequate preparedness has been recognized with the result that government and industry have cooperated in a range of programs to prepare for an oil spill. Until a spill happens, however, the state of Canada's preparedness will remain untested. The oil and gas AMAP report (2007) listed the primary and secondary methods of oil spill response for seven northern countries; Canada, like USA, Greenland, Iceland, Faroe Islands, Norway and the Russian Federation, relies primarily on mechanical containment and recovery of surface oil and secondarily on dispersants and in-situ burning and, in some circumstances, bioremediation (Crandall and Thurston 2010, p. 2-217).

Arctic Marine Oilspill Program (AMOP)

The Arctic and Marine Oilspill Program (AMOP) was started as a five-year effort by Environment Canada to develop/adapt oil spill countermeasures suitable for Arctic waters. Results were reported yearly at the AMOP technical seminar from 1978 to 2007. The seminar proved popular with participants from governments and industry and gradually the scope was expanded to include international studies of oil spills, not just of those in the Arctic. In 1983 a parallel seminar on chemical spills was added to consider spills of other chemicals (1983-2007). Then the scope was extended further in 1999 to include approaches to remediation of sites affected by spills. This led to a third type of seminar, "Biological Solutions for Site Remediation, Restoration, and Rehabilitation" again held in conjunction with AMOP. Finally, in 2008, all three seminars were combined as the "AMOP Technical Seminar on Environmental Contamination and Response." Over the years since 1978 hundreds of scientific and technical studies have been reported at AMOP seminars and these have been published in the annual Proceedings volumes; bibliographies of these papers are available from Environment Canada by email (222 pages) from SpillSeminars@ec.gc.ca or by telephone (613) 998-9622.

Environmental Studies Research Funds (ESRF)

The Environmental Studies Research Funds (ESRF) program has sponsored environmental and social research in an effort to improve decision-making capabilities regarding oil and gas exploration and development in frontier areas of Canada. The ESRF program, initiated in 1983, is funded by levies paid on frontier lands by oil and gas companies. The project is managed by a small board representing the departments of the federal government, the governments of Newfoundland and Nova Scotia and public members. The research priorities are established approximately a year ahead and currently include a northern component with "oil spill preparedness, fate and effects" and "regional effects management" as priorities. Many of the reports from ESRF projects are available as PDF files from www.esrfunds.org/pubpub_e.php.

3. Surface current observations: It is possible that High Frequency Coastal Radar (sometimes called CODAR, i.e. Coastal Ocean Dynamics Applications Radar) could be used to measure the surface current field updrift of installations. It can be effective over a range of 30–50 km. However, since it measures only radial components of velocity, multiple stations would be required to characterize current vector fields precisely enough to model high-frequency ice drift velocities (local deviations from the average pack motion) in a field updrift of a drill rig or other structure. An alternative would be an array of upward looking Acoustic Doppler Current Profilers installed as a real-time cable network upstream of any drill ship location. Such a network would need a spatial resolution on the order of 10 km to adequately represent or model the highly variable surface currents observed in the Arctic (Barber et al. 2014). An ice motion forecasting model would also benefit from data on pack compression rates, due to ice-ice and ice-shore interactions, telemetered from stress sensors in the updrift pack. We realize that these recommendations may seem impractical at this time, for to implement them fully would require development of sea-ice-capable observational instruments and of forecast models capable of ingesting moving arrays of real-time observational data. In the long term, developing such a system is possible and the benefits of an accurate forecasting model could outweigh the costs of the system.

Recent results (Barber et al. 2014) illustrate a very complex circulation regime with forcing by both the ocean and the atmosphere combining in ways that make precise prediction of ice motion a significant challenge, yet paramount to avoiding unwanted interactions of ice and industrial operations. We conclude that development of potential oil reserves in the Arctic, particularly in the Beaufort Sea, will require significant investments in technology and modeling capability if a fully functioning operational ice management system is to be developed. The problems reviewed above are also pertinent to the detection, mitigation and impacts of an oil spill in sea ice. To date little is known about how to detect or manage such a spill, nor what the impacts would be on either the physical or biogeochemical systems of the SBS.

Impact of climate change

The impact of climate change on the seabed over the next few decades is not well understood. The stability of the seabed and sub-seabed are affected by changes in the sea-ice regime, sea bottom thermal regime and seafloor currents. As noted in the above section on sea-ice hazards, ameliorating ice conditions will still leave the Beaufort Sea exposed to extreme ice features, albeit possibly less frequently over time. The implication here is that extreme ice scour events that cut into the seabed would still be problematic for sub-sea pipelines. The complex interaction of warming Atlantic, Pacific and Mackenzie River waters will increase the temperature of seabed and sub-seabed sediments which may enhance the degradation of subsea ice-bearing permafrost and gas hydrates. More dynamic Atlantic and Pacific water masses coupled with more extreme wave action (resulting from more storms and open water) will result in increased bottom currents on the shelf and slope. Such accelerated activity could increase bottom sediment mobility and enhanced seabed erosion.

Determining the seabed response to warming and more dynamic bottom waters is dependent on the thermal and physical properties of bottom sediments. The thermal and physical properties of these sediments are dependent on water depth and their geological history (Taylor et. al. 2013) – including exposure to glacial processes, sea level fluctuations, varying rates of sedimentation – all of which are known to vary widely across the shelf and down slope.

Research to date has resulted in the recognition of the multiplicity of factors that need to be assessed to determine the impact of climate change on the stability of the seabed both in the near and long term. However, knowledge of the interrelationships and magnitude of these factors is limited. Ocean/atmosphere models need to be coupled to the seabed to allow for the prediction of climate change impacts on the stability of seabed and sub-seabed sediments. Quantifying the rate of change of the seabed imposed by climate change will determine if there will be a negative impact on hydrocarbon development or not.

Conclusions

Exploration drilling is the current focus of hydrocarbon development in the Beaufort Sea. Exploration drilling is a short-duration activity that takes place over a few months during any single year. Under such conditions the strategy could be to simply avoid geohazards and sea-ice hazards where possible. However, production facilities such as platforms and pipelines will be in place for at least a couple of decades and the negative impact of offshore hazards, such as the recurrence rates of extreme ice scours, degradation of subsea permafrost and gas hydrates, over time must be considered. The inclusion of glacial ice into the Beaufort Sea ice is of significant concern, as is the presence of extremely thick multiyear sea-ice features which are developed along the NW flank of the CAA and travel south and southwestwards over current and near future exploration and development areas along the Mackenzie Shelf break (c.f. Figure 14). Climate change has also affected the speed at which sea-ice hazards move, increasing both their velocity and increasing variability in their trajectory, both aspects complicating the ability of the oil and gas sector to manage these ice hazards.

Over the past few decades of mapping the seabed and sub-seabed, the above described geohazards have been identified and are being investigated in terms of their distribution and extent to which they pose a problem to exploration drilling activity. Offshore geohazards are not ubiquitous across the Beaufort Sea but may be limited in terms of geographic extent, distribution with depth, and severity of impact on development.

Ongoing regional mapping of the seabed and subseabed will expand the knowledge of offshore geohazards and lead to the development of appropriate mitigative measures. Spill prevention research can go a long way towards reducing the potential negative impact of Arctic offshore hydrocarbon development on the renewable resources of the marine environment - not only in the Beaufort Sea where exploration activity is currently focused but in other marine areas of the western Arctic such as the Banks Shelf and Slope. To

date there is little in the way of scientific evidence as to the detection, impacts on the marine ecosystem, or mitigation of an oil spill in sea ice.

9.3 Renewable resources

Rapid warming has reduced the extent of summer ice coverage of the Arctic Ocean and has decreased the thickness of sea ice that still remains (Chapter 2). With less ice the sea is becoming navigable for longer periods in summer, potentially opening the way to increased ship traffic, including cruise tourism. Climate change will also affect animal distributions, ranges and survival among other factors. With respect to harvestable fish species, changes to the ecological productivity and biodiversity may or may not favour the development of commercial fisheries. Large aquatic and terrestrial mammals elicit limited economic interest, but they are valued by local people for other reasons, mainly their cultural importance and for their value as human food. The impacts to subsistence species and implications for food security are covered in Chapters 3, 4 and 8 of this assessment.

9.3.1 History of renewable resource industries

Previous to oil and gas and mining developments, the Inuvialuit were significantly impacted by industrial whaling introduced in the region in the 1890s (Arnold et al. 2011). The whaling community at Herschel Island introduced alcohol, diseases, and a disruption in sustainable wildlife harvesting. It is estimated that in 1865 the Inuvialuit numbered around 2,500 but by 1905, at the end of the whaling boom, the population had declined to 259 (Arnold et al. 2011: 81). Whaling also brought a migration of Inupiat from Alaska into the Inuvialuit region. These migrants blended into the local population and helped to support community numbers.

The whaling boom lasted close to twenty years, ending by 1910. This collapse could have proven to be devastating to



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the people of the Inuvialuit region were it not for the fur trading boom which started after the whaling boom. While the Inuit of the Kitikmeot region were not heavily involved in the whaling boom, they did participate in the trapping boom. The rise in prices of Arctic fox pelts and other furs led many Inuvialuit to move quickly from whaling to trapping. This became the dominant economic activity of the Inuvialuit from the 1910s to the 1950s. It promoted a new dispersion of the people across the region as groups migrated to find new trapping areas. New centres arose around trading posts. In addition to trapping, reindeer herding was introduced to the region by the Canadian government in the 1930s using reindeer brought over from Alaska (Arnold et al. 2011; see Chapter 8, Box 1). Reindeer herding never developed as the government had hoped, and to this day it remains a marginal activity.

9.3.2 Arctic marine shipping

The following section summarizes the results pertinent to the scope of this regional impact assessment from a larger ArcticNet project. Please refer to the IRIS-2 regional impact assessment for further details on this project's findings.

The seasonal melting of sea ice in the Arctic Ocean and the trend towards reduced extent (see Chapter 2) has fuelled speculation about the control of both Canada's natural resources and its sea routes. The savings in distance that can be achieved with the Arctic routes are substantial: for example, a trip between London and Yokohama through the Northwest Passage is 15,700 km and 13,841 km through the Northeast Passage, both significantly shorter than the route through Suez (21,200 km) or Panama (23,300 km). These findings fuel the idea that Arctic routes, because they are shorter, will attract abundant through traffic and consequently will become major political issues.

Many shipping companies have indicated a lack of interest in developing operations in the Arctic for a number of reasons (Lasserre and Pelletier 2011). Extreme cold, poor visibility (due to fog or complete darkness), drifting ice, small icebergs (which are difficult to detect), and inter-annual variability in ice extent (despite the trend in melting) 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) and the near sinking of another one in September 2013 (Staalesen 2013). It can also be costly to upgrade (ice-strengthen) and insure vessels to operate in the Arctic. Finally, along Arctic routes, there is

a scarcity of port facilities and navigation aids (including nautical charts), especially on the Canadian side. Until navigation through the northern routes can be done as safely and as quickly as on longer temperate routes, Arctic routes seem likely to remain uncompetitive. Financial models attest to the same idea: Arctic shipping may be technically feasible, but it remains challenging and costly for many shipping companies (Lasserre 2014). Among shipping companies that do display interest for Arctic shipping, destination traffic is often preferred to transit.

Operators that are currently active in servicing local communities and resource development operations in the Canadian or Russian Arctic have indicated intentions to expand service offerings in the Arctic shipping market (Lasserre and Pelletier 2011). The local shipping services market, particularly the servicing of mining and oil and gas operations, seems attractive to ship owners for several reasons. Firstly, the extension of the relatively navigable season provides local communities with access to shipping consumer goods, a cheaper alternative to air transport. Shipping companies like Desgagnés and Nunavut Eastern Arctic Shipping have already expanded their networks and now service western Arctic communities and compete with Northern Transportation Company Ltd. based in Hay River. Increasing services and competition could help improve the availability (and cost) of goods for local communities. Secondly, the non-renewable resource exploration and development sector is experiencing a boom cycle, both with the prospect of declining ice cover and strong 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 is certain. Not only will resources need to be shipped to final markets but their production sites will also need servicing.

Impacts of shipping on marine mammals and their habitat

Many of the shipping impacts upon marine mammals have been identified here through the Arctic Council's Arctic Marine Shipping Assessment (2009). Clearly there is a need

for further research on these impacts, but in the meantime, marine shipping requires proper management and use of best practices to reduce impacts to natural ecosystems.

Direct interaction: Ships often travel along migration routes and across biological hotspots. In small areas and corridors in use by marine mammals, such as through the Canadian Archipelago, there is a higher chance of interaction with ships. Tourist vessels may also seek aggregations of animals such as haul-out habitats where animals may be more vulnerable to disturbance (Huntington 2009). In both cases ship strikes and general disturbance are particular concerns. In the latter case, Arctic whales have been observed to vacate areas where ships were approaching (e.g. Myrberg 1990). As climate and ice conditions continually change, not only may marine mammal migrations change but, with longer ice-free seasons, ships may traverse the Arctic waters for longer periods also, making interactions with animals more probable (Arctic Council 2009).

Sound: Frequencies travel about four times faster in water than in air, so ship noise reaches animals farther away underwater than above water. When an ice cover is present the sound tends to travel even further, making for a situation of significant noise pollution in ice covered waters. The problem with increased frequencies and occurrences of sounds to aquatic animals is that it has the potential to interfere with their communication, foraging, social interactions, predator avoidance, and can even impact their ability to hear, lead to physiological distress, discourage certain habitat use, and, in extreme cases from a combination of these impacts, result in death (Arctic Council 2009). See Chapter 4 for more details.

Pollution: Cruise ships generate grey water, garbage, contaminants (e.g. cleaning agents), and atmospheric pollutants. Residents of Ulukhaktok, NT and Gjoa Haven, NU have stated their concerns about the effects that water-borne contaminants/pollution may have on marine mammals and the environment in general (Stewart et al. 2013). With respect to atmospheric emissions, black carbon produced from ships in the Arctic is associated with increasing ice

melt in the region, and in light of increased storms and changes in wind direction/magnitude, ships may be prone to higher rates of accidents and spills (WWF 2013).

Introduction of new species: Shipping is the main human pathway by which marine organisms are introduced into new environments (Molnar et al. 2008), either via ballast water and/or ship surfaces (e.g. propellers, rudders) in the case of barnacles or mussels. The risk of transferring foreign, invasive organisms (including animals, plants, and micro-organisms) via ships between ecosystems of similar latitude and conditions, where species can adapt, out-compete and displace other species, may become more serious with increasing ship traffic in the Arctic (Arctic Council 2009). This phenomenon can indirectly affect marine mammals by impacting the underlying food web structure (e.g. Hallanger et al. 2011), introducing predators (e.g. Higdon et al. 2012), or causing physical harm in the case of pathogens and parasites (Bax et al. 2003).

9.3.3 Arctic tourism

The following section summarizes the results pertinent to the scope of this regional impact assessment from a large-scale eastern ArcticNet project. Please refer to the IRIS-2 regional impact assessment for further details on this project's findings.

It has been anticipated that longer summer periods of marine navigation will support increased ship-based tourism. Tourists are attracted by opportunities to see unique Arctic wildlife (birds, bears, whales, etc.) and unique features such as sea ice, 24-hour daylight (or nights), pingos, etc. Parks and other conservation areas (Chapter 1, Figure 11) are attractive destinations for tourists. Businesses of this type can be expected to appear wherever wildlife viewing opportunities exist (e.g. the Mackenzie Delta). The success of these ventures will likely depend largely on the facilities put in place (e.g. accommodations, meals, small boats, etc.) to offer tourists enjoyable experiences.

In addition to tourists, other visitors consist of government, scientific and military personnel and the supporting staff and facilities needed to conduct their operations. Military bases, notably radar stations, have been prominent across the Canadian Arctic and military activities are still important at scattered times and places. With increasing interest in and access to the Arctic by international interests, there will likely be sustained interest within Canada in Arctic military operations to support Canadian sovereignty there. Arctic scientific studies will likely be driven partly by scientific questions and partly by a Canadian desire to have more visible activities taking place in the Arctic.

Expansion of cruise tourism in the Canadian Arctic

Only two out of eleven tour ship operators already present in the western and central Canadian Arctic have expressed their intentions to increase their presence, and three out of an additional 51 operators surveyed intend to increase their presence in the Canadian Arctic (Lasserre and Têtu 2013). The lack of interest is due to several factors. Firstly, Cruise North Expeditions, a company already present in the Canadian Arctic, and Arctic Odyssey, a member of the International Association of Antarctica Tour Operators, underlined the financial crisis and price of oil as main barriers to expansion of their activities. Secondly, the lack of maritime infrastructure in the North, emphasized not only by the shipping industry but also by northern community members (e.g. Stewart et al. 2013), is a major constraint. Thirdly, some operators drew attention to the somewhat prohibitive Canadian legislation that regulates navigation. For example, the *Coasting Trade Act* (1992, ch.31), according to Silversea Cruise (pers. comm. 2012), prohibits vessels from leaving Canada if they wish to embark from and return to a Canadian port the same day such as the case with a one-day cruise. From an economic perspective, such a law discourages companies from visiting certain communities.

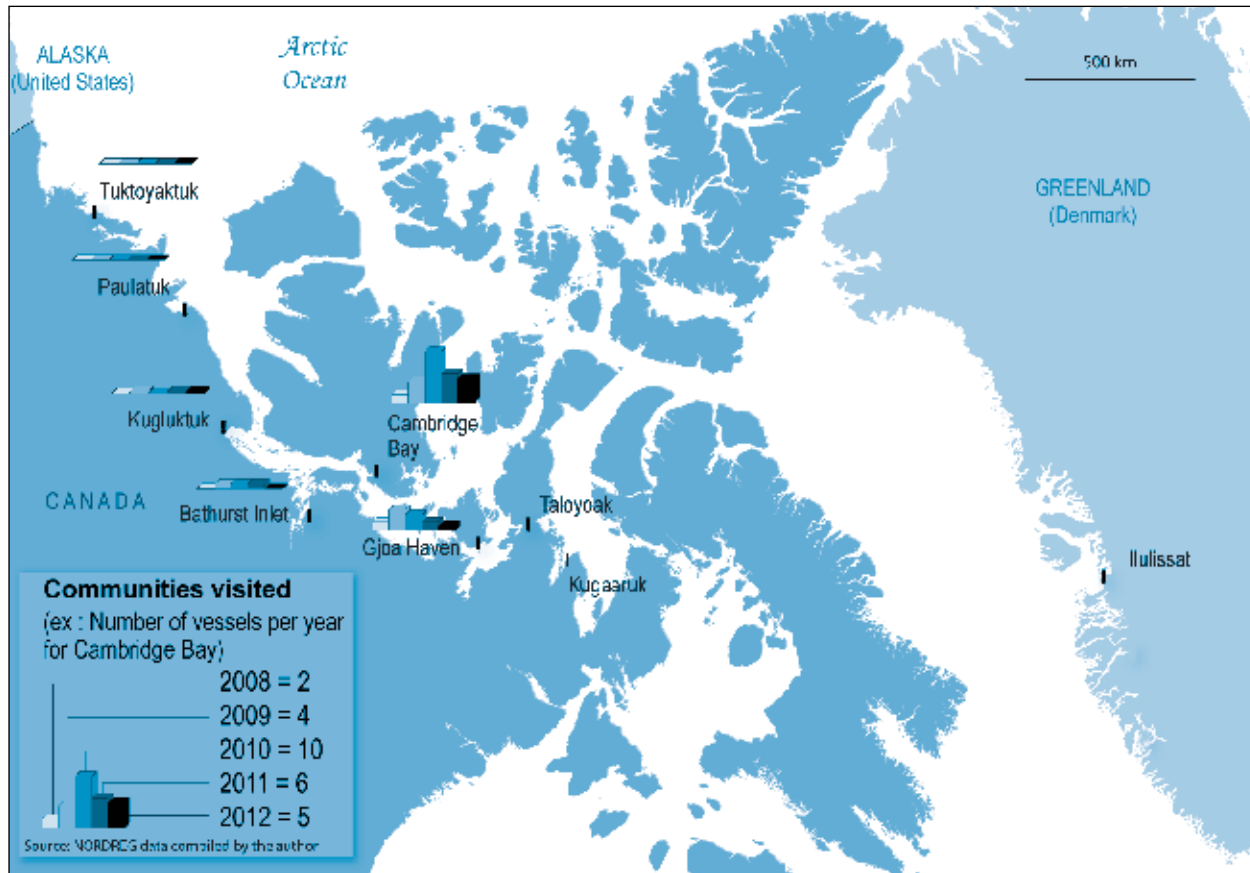


FIGURE 15. Spatial locations of communities visited from 2008 to 2012 in Nunavut and the ISR. Data sourced from NORDREG (Northern Canada Vessel Traffic Services). © Pierre-Louis Têtu

Cruise tourism in the Canadian Arctic Archipelago

In the western and central Canadian Arctic, the most popular cruise ship destinations by ships registered with NORDEG (northern Canada vessel traffic services, explicit to vessels 300+ tonnes) are Cambridge Bay and Gjoa Haven; in comparison, Paulatuk, Kugluktuk and Taloyoak received no more than two cruise ships each year from 2008-2012 (Figure 15). For the lesser visited communities in the ISR, their locations are adjacent to major sea-ice oscillation and where most cruise ships are not allowed to venture according to the specifications of their hulls. As shown in Figure 16, Kitikmeot communities which received at least one cruise ship visit from 2008 to

2010 tend to have more tourist services, amenities and attractions than communities which were not visited by cruise ships. For instance, Cambridge Bay, Gjoa Haven and Kugluktuk have more restaurants and lodging space than Kugaaruk and Taloyoak. Cambridge Bay is also the only community to have museums and heritage centres.

Despite the status of services and facilities offered by northern communities to tourists, Arctic residents share concerns of uncertainty about tourism and its impacts on their communities. A growing number of small vessels (e.g. sail boats, yachts) are making their way through the Northwest Passage each year, and residents of Gjoa Haven have stated concerns for safety, both with respect to the influence of imported substances in the community and precautions

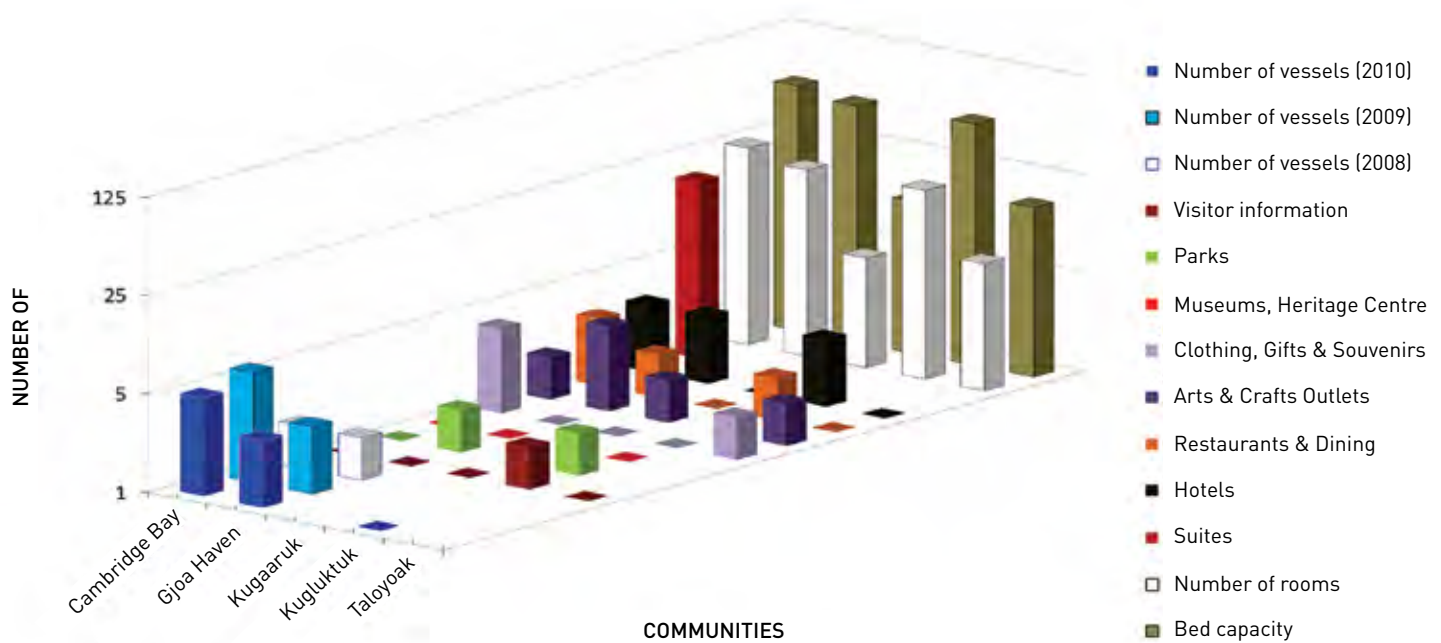


FIGURE 16. Tourist and other services offered in Kitikmeot communities in 2012. The number of vessels are reported from NORDREG. Data from Nunavut Tourism Profile Communities, compiled by Pierre-Louis Têtu.

taken for being on the water (Stewart et al. 2013). Search and rescue resources are oftentimes limited in the North; thus, requiring additional capacity for Arctic rescue missions would likely put a strain on northern communities (see Chapters 6 & 10). As mentioned earlier, community members are also concerned about infrastructure limitations and the effects of cruise tourism on wildlife. Stewart et al. (2011) report that the attitudes of northerners need to be considered and acted upon in the development of Arctic cruise tourism because the outcomes of such decisions have the greatest impacts upon the community level, affecting the Inuit way of life, socio-economy and environment.

9.3.4 Fisheries

Quantitative assessment of the resources available for commercial fisheries in the Beaufort Sea are currently underway (see Chapter 4). Although the Beaufort Sea is likely much less productive than other marine areas at similar

latitudes such as the Baffin Bay-Davis Strait and Barents Sea areas, which currently support substantial commercial fisheries, the system is connected through the Bering Strait to the North Pacific Ocean, one of the most productive marine areas in the world. While the Beaufort Sea system remains relatively unknown there are indications that there must be significant productivity because there are stocks of whales such as bowhead and beluga in the area. The western Arctic bowhead whale stock is substantial numbering around 10,000 animals (Moore and Reeves 1993; Harwood et al. 2010). Productivity to support these whales must exist but it may not be in the typical types of fishable stocks. This section is divided politically into the American and Canadian portions of the Beaufort Sea and describes the various efforts at developing commercial fisheries and speculates on the future potential of commercial fisheries in the area. It should be noted that there are presently no commercial fisheries operating in the Beaufort Sea. The American side is under a moratorium to commercial fishing while the Canadian side does not have any active

commercial fishing interests. Currently there is no consideration of a moratorium on the Canadian side as any development would proceed under the guidance of the Beaufort Sea Fisheries Management Framework, a document prepared in support of a 2011 Memorandum of Understanding between the Inuvialuit Game Council, the Inuvialuit Regional Corporation, the Fisheries Joint Management Committee, and the Department of Fisheries and Oceans (DFO). The Framework provides a decision process that protects Inuvialuit interests from potential commercial fisheries development in the Beaufort Sea. As part of this Framework existing policy documents such as DFO's Emerging Fisheries Policy would contribute to any decisions on fisheries development and protection of marine resources in the Beaufort Sea. There are considerations of having a moratorium on the Canadian side as well but currently any development would proceed as per the Emerging Fisheries Policy (<http://www.dfo-mpo.gc.ca/fm-gp/policies-politiques/efp-pnp-eng.htm>).

Historical fisheries

There have been relatively few historical commercial fisheries in the Beaufort Sea. Some fisheries have developed for short durations or have remained as exploratory operations.

American historical fisheries

Commercial fisheries for Arctic cisco (*Coregonus autumnalis*) have occurred since the 1980s (Craig 1989a, b). Arctic cisco and Dolly Varden (*Salvelinus malma*) are the primary fishery resources harvested by people living in northern Alaskan communities (Craig 1987; Pedersen and Linn 2005). These comprise important subsistence resources to Alaskan communities (Brown 2008). In the Colville River area, the subsistence and commercial fisheries can harvest up to 80,000 adult fish each fall, using gill nets strung under the ice (Fechhelm et al. 2007). There are no published reports of commercial harvest of Dolly Varden but they may be traded or bartered around among residents of North Slope communities (Brown, Alaska Department of Fish and Game, pers. comm.).

Canadian historical fisheries

There have never been viable commercial fisheries in the Canadian portion of the Beaufort Sea in spite of the fact that it contains approximately seventy-one species of fish – including Dolly Varden, wolfish, Arctic cod (*Boreogadus saida*), Arctic char (*Salvelinus alpinus*), cisco, whitefish and Pacific herring (*Clupea pallasii*) (Cobb et al. 2008).

Attempts were made to develop a Pacific herring roe fishery in Tuktoyaktuk in the 1980s (Gillman and Kristofferson 1984). The roe was tested by Japanese concerns and was considered of high quality. However, the market for herring roe declined and the fishery never fully became operational (Kristofferson, DFO, pers. comm.).

Similarly, broad whitefish (*Coregonus nasus*) were under an exploratory fishery licence for five years between 1987 and 1992 (Tallman and Reist 1997). Broad whitefish are anadromous migrating along the nearshore of the southern Beaufort Sea. The organization of the fishery by the Inuvialuit and the quality of the products produced were successful but once again market opportunities limited development.

Small-scale commercial Arctic char fisheries have developed in several communities including Paulatuk, Tuktoyaktuk, Ulukhaktok, Sachs Harbour, NT and Cambridge Bay, NU. Locally harvested char in the ISR is sold between communities and to the Inuvialuit Regional Corporation where they are in turn sold to restaurants in the South (Condon et al. 1996; Joint Secretariat 2003). In the Cambridge Bay region, Arctic char have been commercially exploited for over 50 years where six main stock complexes both on the mainland and Victoria Island have primarily been targeted (Ekalluk, Ellice, Halovik, Lauchlan, Jayco and Paliryuak rivers; Figure 17). Since the inception of the first commercial fishery over 2,000,000 kg of this species have been harvested. Meat products are sold to western Canada, Toronto, Ottawa and Montreal.

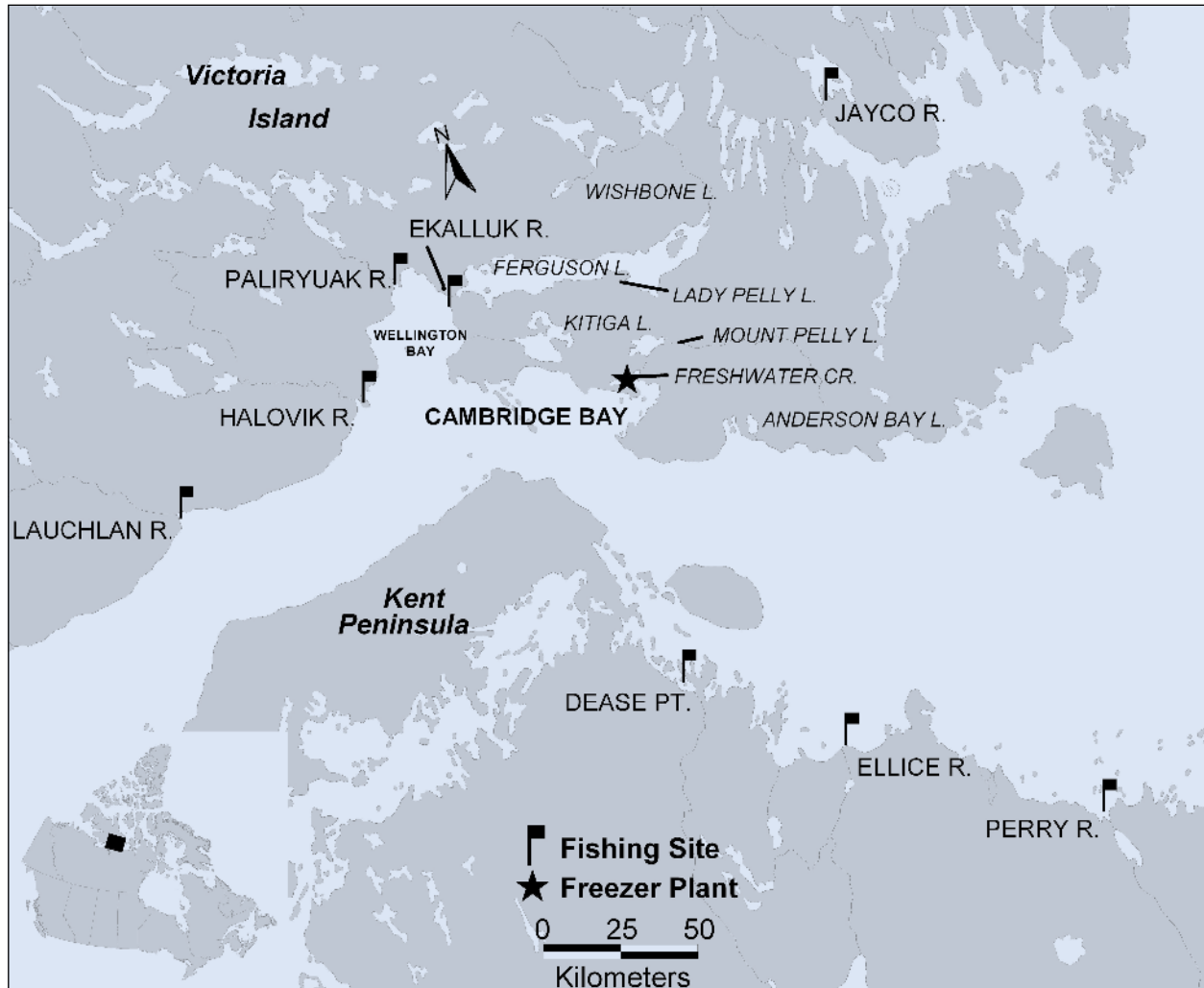


FIGURE 17. Fishing locations for sea-run Arctic char. Adapted from Kristofferson and Berkes (2005).

Potential fisheries

There is speculation that melting ice is permitting access for new industrial uses (Oceans North 2013). Commercial fishing in the Beaufort is a future possibility as marine species move north from the Bering Sea, one of the world’s richest fishing grounds. However, there is little concrete evidence that there are the resources for a sustained fishery in any part of the Beaufort Sea aside from those mentioned historically. One of the scientific uncertainties is how to bring nutrients up from the deep Canada Basin onto the

Beaufort Sea Shelf where photosynthesis can make use of these nutrients to stimulate the entire marine ecosystem. Sea ice plays a role in this uncertainty due to the timing of the sea ice relative to the shelf break and the role storms may play in this process of nutrient delivery (Tremblay et al. 2011). Small scale community-based fisheries marketing locally rather than industrial fisheries are the most likely to be successful. Speculation about new commercial fisheries must be considered only as general possibilities until proper surveys have been undertaken.

American potential fisheries

Aside from relatively small scale fisheries for Arctic cisco there is little likelihood that industrial fisheries based on the native biota can be developed. Much of the biomass is likely present in Arctic cod, however, the individuals of this species are generally under 20 cm in length and it is difficult to imagine how these could be used for commercial food fisheries. A possibility might be for fish meal. Given the likely importance to marine mammal and seabird production, the ecosystem effects of fishing Arctic cod could be devastating. Saffron cod (*Eleginus gracilis*) may be of sufficient individual size to be harvested but to date there are no indications of large biomass. Snow crab (*Chionoecetes opilio*), if present in sufficient biomass, could possibly form the basis for a commercial fishery due to its high market value.

The most likely possibilities for commercial fisheries would be if either flatfish or other groundfish from the North Pacific Ocean or if Pacific salmon (*Oncorhynchus* sp.) established themselves as invasive species. These taxa provide for large industrial fisheries and it is possible with climate warming that conditions may be suitable for their range expansion in the future. Sigler et al. (2011) hypothesized that some of the boundaries between the North Pacific and the Arctic may resist climate warming and that, in spite of future warming, there may be less of a northward shift in some faunal elements than has been suggested previously. At present there is no indication of substantial colonization to the area (Norcross et al. 2010).

Canadian potential fisheries

The prospect of industrial commercial fisheries in the Canadian Beaufort Sea is less likely than in the American portion. However, there is still much survey work to be done. Colonization by invasive species (i.e. Pacific salmon, see Chapter 3) or blossoming of low abundance species like Greenland halibut (*Reinhardtius hippoglossoides*) due to changing climate are the most likely sources of large biomass for commercial development. Recent surveys by DFO demonstrated significant amounts of Arctic cod which may

supply the marine mammals with their primary source of food. Overwintering standing stocks of Arctic cod have also been detected along the Mackenzie Shelf Break (Fortier and Cochran 2008). It is likely that commercial fisheries in the future will continue to be mainly small community-based operations.

9.4 Impact of industrial development on ISR and Kitikmeot communities

As mentioned above, the exposure to industrial development in the Inuvialuit and Kitikmeot regions of the Canadian Arctic has been predominantly related to oil and gas industries in the ISR. While there has been no significant commercial oil and gas production in the regions covered here, since the early 1960s billions of dollars have been spent on exploration activities. This exploration, and the belief that the region contains large reserves of oil and gas, can be seen as the source of the most important industrial impacts on communities in the region. While this impact was felt primarily in the ISR, the western areas of the Kitikmeot region also benefited in the form of employment and service delivery.

Popular opinion tends to see climate change as increasing the viability of resource development in the western Canadian Arctic. As pointed out above it can also be seen as placing impediments on this development. A recent forecast of oil and gas developments in the region tended to portray climate change as a neutral factor in that it is “unlikely to significantly improve the Beaufort Sea operating environment for the oil and gas industry, over... (the next 15 years)” (Callow 2012: 14). Another study utilizing a model of global energy markets estimated no significant increase in the production of Arctic oil and gas by 2030 or 2050, although it did predict an increase in related shipping activities (Peters et al. 2011).

Exploration activities associated with mining have increased significantly over the past 10 years in both the Inuvialuit and

Kitikmeot regions. These activities have had an important impact on communities in the form of direct employment and employment through service delivery. In addition to the Lupin gold mine and the Jericho diamond mine, in which the former at one time had up to 40 Kitikmeot Inuit working there (O'Reilly and Eacott 1998), western Kitikmeot Inuit have been periodically employed at other mines just south of the region. Kitikmeot Inuit have been employed in developing the Hope Bay Project, a potential gold mine located 160 km southwest of Cambridge Bay. In the ISR, exploration activities are increasing but no new projects are close to being moved into production. In Nunavut, \$3.1 billion has been spent on exploration since 1999 including \$443 million in 2012 (Senkow 2013). Almost \$200 million was spent in the Kitikmeot region in 2012.

While most impacts can be seen as a result of a range of associated factors, it is possible to isolate a range of key impacts stemming from the oil and gas activity in the ISR. One of the most important was the signing of a land claim. The discovery of important oil and gas deposits in the region is often portrayed as the main reason behind the federal government's willingness to negotiate and sign a land claim agreement with the Inuvialuit (Cournoyea 2009). The Inuvialuit Final Agreement is generally seen as having a positive influence in empowering the region (Bankes 2004). The oil and gas industry has also had a positive impact on employment among the Inuvialuit. One of the results of the Inuvialuit Final Agreement was the development of a very active Inuvialuit business presence in the oil and gas industry.

As resource exploration and development operations expand in the North, so will demands for transportation and shipping and support vessels, which ultimately depend on infrastructure availability, a limiting factor in the Canadian Arctic. For example, the building of the Dempster Highway from Dawson City to Inuvik in the late 1970s and improvements to airports in the region can be linked to the potential of oil and gas developments. Both the mineral potential in the Kitikmeot region and the hydrocarbon exploration in the Beaufort Sea have been driving support for the Bathurst Inlet Port and Road Project, as it has been

for the Inuvik-Tuktoyaktuk all-weather highway (Chapter 7, Box 3). Tuktoyaktuk has also been considered for the development of a deep water port, which would connect the entire western and central Canadian Arctic and Alaska to the Northwest Passage (Jones 2014). Meanwhile the U.S. Army Corps of Engineers is studying Alaska's potential locations for multiple ports (Restino 2014).

Concern about the impact of industrial development on Inuvialuit traditional harvesting activities is one of the reasons for a study undertaken by Usher (2002). This study compared harvesting activities in the region from the 1960s to the 1990s. It found that, while certain activities have changed, "subsistence harvesting persists as a significant economic as well as cultural preoccupation in the lives of Inuvialuit today" (18).

The Inuvialuit are generally seen to have a positive outlook towards oil and gas developments in their region (Dana et al. 2008), however there is a realistic concern that existing and potential negative impacts be identified and mitigated. This has led to the development of a social and economic impact indicators project by the Inuvialuit Regional Corporation (IRC 2013). While analysis of the indicators has been limited until now, the IRC through the Beaufort Regional Environmental Assessment process has identified social, cultural and economic indicators to better understand resource development impacts and develop mitigation measures.

9.5 Conclusions and important points for policy

The ISR and the Kitikmeot region have high potential to produce non-renewable natural resources (metals, oil and gas, diamonds) for export. Up to eight mines could begin operations in the region within the next few years.

The resources are mostly owned by local Inuit through their collective organizations. Inuit place a high value on their traditional relationship to renewable resources like fish and wildlife. Inuit policies will not permit resource

projects that pose unacceptable risks to their traditional resource species.

Inuit have policies to ensure that a fair share of economic and social benefits from extraction of natural resources will accrue to them. Future development projects will likely depend on suitable partnership arrangements between Inuit agencies and the Developers.

Training opportunities for wage employment offered through non-renewable resource industries is needed to help northerners maximize economic benefits. However, further assessment is needed on the impacts of resource extraction and shipping activities as climate-related sources of vulnerability on Arctic communities.

Oil and gas research provides the scientific knowledge base about seabed geohazards needed to support Inuvialuit and Federal agencies with policy responsibilities for environmental protection in the western Arctic offshore.

Significant hazards to hydrocarbon exploration exist in terms of thick multiyear sea ice and marine glacial ice, both of which are expected to continue for several decades. Ice hazards are increasing in speed and are becoming less predictable making it harder to develop ice management strategies to protect offshore infrastructure for marine resources.

To date science is unable to inform industry or policy regarding the detection, mitigation or impacts of an oil spill in sea ice. The research has begun but challenges remain.

The Inuvialuit Final Agreement with the Federal government signed in 1984 gave the Inuvialuit the right to assess the impact of any development on the environment. Spill prevention research supports the Inuvialuit in their assessment of hydrocarbon development on the marine environment within the ISR by contributing to the protection of renewable resources.

Aboriginal Affairs and Northern Development Canada (AANDC), the Federal department responsible for

managing the North, sets the standards and leasing policies for northern development that includes environmental protection. Spill prevention research supports AANDC management policies.

The Canadian Environmental Assessment Agency (CEAA) establishes the guidelines and regulations for environmental issues for Canada. These policies are carried out in the western Canadian Arctic offshore by the National Energy Board (NEB) of Canada.

The NEB of Canada is responsible for regulating hydrocarbon development in the western Canadian Arctic. Knowledge of the nature and extent of seabed geohazards provides the scientific framework for regulations and guidelines issued by the NEB. For example, the Blasco et al. (2013) report on the state of knowledge of seabed geohazards was used by the NEB to support the Arctic Drilling Review of 2011.

As of 1994, Federal energy policy requires that energy developments be carried out in a 'sustainable' manner. This includes environmental protection. Spill prevention research demonstrates the environmental protection aspect of the policy by reducing the potential for leaks and spills that would adversely affect the marine environment.

The impacts of climate change will be both positive (longer marine shipping seasons) and negative (less stable land surfaces to support structures). Arctic shipping routes still entail higher risks from ice and limited navigation aids than temperate routes. However, current ship owners are interested in increasing traffic to and from the Arctic to support local communities and resource projects.

The potential for ship-based tourism is high in the Arctic, but community services, infrastructure and shipping regulations may be limiting factors for growth. It is clear that northern residents' attitudes and concerns involving cruise-tourism need to be incorporated into associated planning and decisions if this economic sector is to have a positive, sustainable outcome on the livelihoods of northerners.

Although Arctic fishery resources are still under investigation, there seems little potential for the development of commercial fisheries.

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Chapter 10. Factors of Adaptation – Climate Change Policy Responses for Canada’s Inuit Population

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ABSTRACT

We identify and examine how policy intervention can help Canada’s Inuit population adapt to climate change. Communities across the Canadian Arctic are experiencing similar effects from climate change, and, as such, information from the entire region is drawn upon to provide an integrated analysis of adaptation policy opportunities that are relevant and applicable to communities located in the Inuvialuit Settlement Region and Kitikmeot region of Nunavut, and elsewhere in the Canadian Arctic. The policy responses are based on an understanding of the determinants of vulnerability identified in ArcticNet-supported research conducted with 22 Inuit communities. A consistent approach was used in each case study where vulnerability was conceptualized as a function of how people are affected by climatic risks and their capacity to deal with those risks. Vulnerability was assessed in the context of multiple stressors, climate and non-climate related, which affect how climate change is experienced and condition adaptation. Case studies involved close collaboration with community members and policy makers to identify conditions to which each community is currently vulnerable, characterize the factors that shape vulnerability and how they have changed over time, identify opportunities for adaptation policy, and examine how adaptation can be mainstreamed. Fieldwork, conducted between 2006 and 2012, included over 750 semi-structured interviews with community members, over 35 focus groups/community workshops, and over 100 semi-structured interviews with policy makers at local, regional, and national levels. Based on a synthesis of findings across the case studies, realizing adaptive capacity and overcoming adaptation barriers requires policy intervention to: (1) support the teaching and transmission of environmental knowledge and land skills; (2) improve access to, and understanding of climate, weather and sea ice information; (3) review and enhance search and rescue capabilities; (4) strengthen harvester support programs; (5) ensure the flexibility of fish and wildlife management regimes; (6) improve the ability of Inuit food systems to meet present dietary and nutritional requirements; (7) protect key infrastructure; and (8) review building codes and land-use plans in light of current and expected climate change.

10.1 Introduction

Inuit have been particularly sensitive to changing climatic conditions documented in the last decade due to their strong dependence on climate sensitive resources (e.g. harvesting of fish, wildlife and plants) for their livelihoods. Increased travel risks, compromised travel routes to hunting and fishing areas, and changes in the quality and availability of some species of wildlife important for subsistence have been noted across northern Canada (Berkes and Jolly 2002; Ford and Smit 2004; Nickels et al. 2005; Ford et al. 2006a, b; IPCC 2007b; Furgal and Prowse 2008; Furgal et al. 2008; Tremblay et al. 2008; Pearce et al. 2010b, 2011a; Prno et al. 2011; Andrachuk and Smit 2012; Ford and Pearce 2012; Ford et al. 2012; see Chapters 1 & 6). Rising sea levels, coastal erosion, and permafrost thaw are also threatening the viability of some Inuit settlements, damaging important heritage sites and compromising municipal infrastructure

and water supply (Manson et al. 2005; Solomon 2005; Hoeve et al. 2006; Martin et al. 2007; Furgal and Prowse 2008; Larsen et al. 2008; Zhou et al. 2009; see Chapter 7). Benefits have also been noted with climate change, including improved hunting opportunities with longer ice-free summers, reduced exposure to the health effects of extreme cold, enhanced opportunities for economic development including resource extraction, transportation and shipping, tourism and potential for commercial fisheries (ACIA 2005; Nickels et al. 2005; Dawson et al. 2007; Ford et al. 2008; Furgal et al. 2008; Barber et al. 2008; Wenzel 2009; Dawson et al. 2009; Stewart et al. 2010a, b, 2013; see Chapter 9). The overall impacts of current and projected climate change will vary by location but are generally believed to be negative (IPCC 2007a; Furgal and Prowse 2008; Ford and Pearce 2012). In this context, it has been argued that while mitigation is needed if we are to avoid 'runaway' climate change, adaptation policy as a response



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is needed to reduce the negative effects of current climate change and help Inuit adapt to expected future changes in climate that are now inevitable (Ford 2009).

In this chapter, we draw on Ford et al. (2010) and Pearce et al. (2011a) as well as a number of other sources to identify and examine how policy intervention can help Canada's Inuit population adapt to climate change. We recognize that communities across the Canadian Arctic are experiencing similar effects from climate change, and as such, information from the entire region is drawn upon to provide an integrated analysis of adaptation policy opportunities that are relevant and applicable to communities in the Inuvialuit Settlement Region (ISR) and Kitikmeot region of Nunavut and elsewhere in the Canadian Arctic. The policy responses are based on an understanding of the determinants of vulnerability identified in ArcticNet-supported research conducted with 22 Inuit communities. A consistent approach was used in each case study where vulnerability was conceptualized as a function of how people are affected by climatic risks and their capacity to deal with those risks (Smit and Wandel 2006). This conceptualization focuses on the biophysical and human determinants of vulnerability and how they are influenced by processes and events operating at multiple spatial-temporal scales. Vulnerability is assessed in the context of multiple stressors, climate and non-climate related, which effect how climate change is experienced and condition adaptation. Case studies involved close collaboration with community members and policy makers to identify conditions to which each community is currently vulnerable, characterize the factors that shape vulnerability and how they have changed over time, identify opportunities for adaptation policy, and examine how adaptation can be mainstreamed. Fieldwork, conducted between 2006 and 2011, included over 750 semi-structured interviews with community members, over 35 focus groups/community workshops, and over 100 interviews with policy makers at local, regional, and national levels. Based on a synthesis of findings across the case studies, realizing adaptive capacity and overcoming adaptation barriers requires policy intervention to: (1) support the teaching and transmission of environmental knowledge and land skills; (2) improve

access to, and understanding of climate, weather and sea ice information; (3) review and enhance search and rescue capabilities; (4) strengthen harvester support programs; (5) ensure the flexibility of fish and wildlife management regimes; (6) improve the ability of Inuit food systems to meet present dietary and nutritional requirements; (7) protect key infrastructure; and (8) review building codes and land-use plans in light of current and expected climate change (Table 1).

10.2 Defining terms

Key terms used in this chapter include *vulnerability* and its constituents, *exposure-sensitivity*, *adaptive capacity* and *adaptation*. In the climate change field, the term vulnerability refers to the susceptibility of a system (community) to harm relative to a climate stimulus or stimuli, and relates to the exposure-sensitivity of the community to a climate stimulus and the capacity to adapt (Ford and Smit 2004; Adger 2006; McLeman and Smit 2006; Smit and Wandel 2006). Exposure-sensitivity refers to the susceptibility of people and communities to variable conditions. It is a joint property of the community characteristics (location, livelihoods, economy, infrastructure, etc.) and the characteristics of climate related stimuli (magnitude, frequency, spatial dispersion, duration, speed of onset, etc.) (Cutter 1996; Ford and Smit 2004; Adger 2006; Smit and Wandel 2006). For example, an Inuit hunter may be physically exposed to changes in sea ice because they use the sea ice as a platform on which to travel and hunt. The hunter is sensitive to changes in sea ice because their ability to travel and hunt could be compromised. Adaptive capacity refers the potential of a community to adapt to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (IPCC 2007b). For example, some determinants of Inuit adaptive capacity in the subsistence sector include: (1) Traditional Ecological Knowledge (TEK); (2) access to capital resources (e.g. hunting equipment, supplies, fuel); (3) emergency management capability; (4) flexibility of resource management regimes; (5) sharing networks (food

TABLE 1. Summary of findings from community-based climate change vulnerability research, which this chapter draws on to identify and examine opportunities for adaptation. Adapted from Ford et al. (2010).

STUDY	COMMUNITIES INVOLVED	METHODS USED	KEY DETERMINANTS OF CLIMATE CHANGE VULNERABILITY	SOURCES OF ADAPTIVE CAPACITY
Ford et al. (2008); Pearce et al. (2010a, 2011b)	ISR: Ulukhaktok	<ul style="list-style-type: none"> • Semi-structured interviews (n=112) • Policy maker interviews, all levels (n=12) • Participant observation • Focus groups (n=10) 	<ul style="list-style-type: none"> • Erosion of land-based skills • Limited financial resources (limited number of wage jobs, lack of qualifications, nepotism) • High cost of hunting • Time constraints due to employment obligations • Substance abuse (health and well-being) 	<ul style="list-style-type: none"> • Social networks • Traditional knowledge and land skills • Flexibility in resource use • Wage employment opportunities • Devolution of governance (building codes and infrastructure planning) • Harvester support programs • Social programming • Navigation and communication technologies
Duerden and Beasley (2006); Andrachuk and Smit (2012)	ISR: Aklavik, Tuktoyaktuk, Ulukhaktok	<ul style="list-style-type: none"> • Synthesis of existing studies/observations • Semi-structured institutional interviews (n=12) 	<ul style="list-style-type: none"> • Erosion of land-based skills • Institutional capacity already stretched • Limited financial resources • Community location • High costs of hunting • Population over-turn 	<ul style="list-style-type: none"> • Traditional knowledge and land skills • Wage employment opportunities • Harvester support programs • Navigation and communication technologies
Pearce et al. (2012)	ISR: Paulatuk	<ul style="list-style-type: none"> • Focus groups (n=10) • Policy maker interviews, all levels (n=6) 	<ul style="list-style-type: none"> • Erosion of land-based skills • Reduced resource use flexibility due to quotas and restrictions (caribou) • Limited financial resources • Limited skills training programs and wage employment • Substance abuse (health and well-being) • Community infrastructure not well-adapted to a changing climate 	<ul style="list-style-type: none"> • Traditional knowledge and land skills • Harvester support programs • Nutrition and food preparation programs • Devolution of governance (building codes and infrastructure planning) • Skills training programs • Wage employment opportunities • Social programming • Navigation and communication technologies

TABLE 1. (continued)

STUDY	COMMUNITIES INVOLVED	METHODS USED	KEY DETERMINANTS OF CLIMATE CHANGE VULNERABILITY	SOURCES OF ADAPTIVE CAPACITY
Ford et al. (2006a, b, 2007, 2008, 2009)	Nunavut: Arctic Bay, Igloodik, Iqaluit	<ul style="list-style-type: none"> • Semi-structured interviews (n=216) • Participant observation • Policy maker interviews, all levels (n=26) • Focus groups (n=10) 	<ul style="list-style-type: none"> • Erosion of land-based skills • Reduced resource use flexibility due to quotas (narwhal) • Limited financial resources • Community location 	<ul style="list-style-type: none"> • Social networks • Traditional knowledge and culture • Flexibility in resource use • Navigation and communication technologies • Harvester support programs • Formal search and rescue
Stewart et al. (2010b, 2011, 2013); Johnston et al. (2012); Dawson et al. (2013)	<p>ISR: Ulukhaktok</p> <p>Nunavut: Cambridge Bay, Gjoa Haven, Pond Inlet</p> <p>Nunatsiavut: Nain</p> <p>Nunavik: Kuujjuak</p>	<ul style="list-style-type: none"> • Semi-structured interviews (n=270) • Participant observation • Policy maker interviews, all levels (n=46) • Industry interviews (n=18) • Focus groups (n=5) 	<ul style="list-style-type: none"> • Safety and security due to increased shipping activity • Negative interactions between ships and marine wildlife • Weakness of relevant regulation and policy governing new industry growth • High economic leakage • Lack of search and rescue capabilities • Absence of appropriate salvage equipment in the event of a major shipping disaster 	<ul style="list-style-type: none"> • Improve support for local economic development, entrepreneurial business and marketing training • Establish 'special marine hunting areas' prohibited to commercial shipping • Improve regional coordination of economic development initiatives • Develop policies to reduce regional economic leakage • Harmonize Arctic shipping rules and regulations via the Polar code • Improve search and rescue, charting and monitoring capabilities
Prno et al. (2011)	Nunavut: Kugluktuk	<ul style="list-style-type: none"> • Semi-structured interviews (n=31) • Participant observation 	<ul style="list-style-type: none"> • Erosion of land-based skills • Economic disparity among community members (new wealth but also enduring poverty) • Social ills (e.g. crime, poverty, suicide, low formal education) (health and well-being) • Community infrastructure not well-adapted to a changing climate 	<ul style="list-style-type: none"> • Traditional knowledge and land skills • Flexibility in resource use • Navigation and communication technologies • Wage income • Harvester support programs • Devolution of governance • Social programming

TABLE 1. (continued)

STUDY	COMMUNITIES INVOLVED	METHODS USED	KEY DETERMINANTS OF CLIMATE CHANGE VULNERABILITY	SOURCES OF ADAPTIVE CAPACITY
Furgal and Seguin (2006)	ISR: Aklavik, Inuvik, Tuktoyaktuk Nunatsiavut: Nain Nunavik: Kuujuuaq	<ul style="list-style-type: none"> • Focus groups (n=6) • Semi-structured interviews (n=8) • Community workshop/ focus groups (n=3, participants 15-20 per workshop) 	<ul style="list-style-type: none"> • Limited financial and technological resources • Decrease in generation and sharing of land-based knowledge • Erosion of land-based skills • Existing health status • Community location • Lack of formal institutional support for adaptation 	<ul style="list-style-type: none"> • Social networks • Communication networks and pathways for sharing/distribution of knowledge • Traditional knowledge and land-based skills • Financial resources (among some individuals) • Access to technology
Alain (2008)	Nunavik: Kangiqsual- ujjuaq	<ul style="list-style-type: none"> • Semi-structured interviews (n=22) • Focus groups (n=1) • On-the-land trips and personal observation 	<ul style="list-style-type: none"> • Limited financial resources • Limited access to technological resources • Limited social networks • Erosion of land-based skills and knowledge • Limited pre-existing knowledge of region • Approach to adaptation - perception and strategy 	<ul style="list-style-type: none"> • Wage employment opportunities • Social networks • Traditional knowledge and land-based skills • Knowledge of region/ area (residence time in community) • Access to technology (equipment) • Perception of risk/hazard
Tremblay et al. (2008)	Nunavik: Akulivik, Kangiqsual- ujjuaq, Kuujuuaq, Kuujuarapik	<ul style="list-style-type: none"> • Semi-directed interviews (n=15) • On-the-land trips and personal observation 	<ul style="list-style-type: none"> • Perception of risk • Erosion of land-based skills • Experience/age 	<ul style="list-style-type: none"> • Traditional knowledge and land skills • Navigation and communication technologies
DeSantis (2008); Fleming (2009)	Nunatsiavut: Hopedale	<ul style="list-style-type: none"> • Semi-directed interviews (n=80) • Policy maker interviews, all levels (n=15) • Secondary resource review • Participant observation 	<ul style="list-style-type: none"> • Traditional knowledge and skills • Community location • Changes to wildlife • Limited local employment and investment • Changing governance systems • Compromised sharing networks • Increased costs of living 	<ul style="list-style-type: none"> • Financial capital – personal mobility (connection to financial capital) • Traditional knowledge • Flexibility in resource use • Institutional support • Local information sharing norms, networks, principles of sustainability • Wage income opportunities; out-migration for jobs

and equipment); (6) availability of time; (7) technological options for adaptation (e.g. weather reports, global positioning systems (GPS), satellite phone); and (8) health and well-being (Berkes and Jolly 2002; Ford et al. 2010; Pearce et al. 2010b; Ford and Pearce 2012). Adaptation is ‘the realization of adaptive capacity’ (Brooks 2003) or ‘manifestation of adaptive capacity’ (Smit and Wandel 2006). Adaptation in the context of human dimensions of climate change refers to an adjustment in human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC 2007b). For example, in response to changes in sea ice an Inuit hunter may travel via an alternative travel route on the land or ice, hunt an alternative species of wildlife, and/or take extra precautions such as traveling with extra food and supplies in case they get stranded.

Ford and Smit (2004) describe vulnerability and its constituents in the context of human vulnerability to climate change in the Arctic and outline an approach to guide community-based vulnerability assessments. Several of the case studies described in this chapter draw on the ‘vulnerability approach’ described by Ford and Smit (2004) in their analyses. Key features of the vulnerability approach include beginning by having community members identify conditions/risks and adaptive responses that are relevant to them beyond those selected *a priori*, and climate risks are considered in the context of multiple stressors, climate and non-climate related. The vulnerability approach includes two stages of assessment. The first stage assesses current vulnerability by documenting how people are exposed and sensitive to climatic variables, and the adaptive strategies employed to deal with these conditions. The second stage assesses future vulnerability by incorporating future climate change probabilities and future social probabilities to estimate directional changes in exposure-sensitivities and associated adaptive capacities (Ford and Smit 2004).

10.3 Climate change vulnerabilities

Changing climatic conditions are having implications for Arctic communities, particularly for the subsistence hunting and fishing, and infrastructure and transportation sectors. Climate change vulnerability literature documents evidence of (1) increased travel risks on the land, water and ice, (2) constrained access to hunting and fishing areas, (3) changes in the quality and availability of some species of wildlife important for subsistence, (4) damage to municipal infrastructure, and (5) rapid economic development. Climate change is projected to continue in the future and will likely exacerbate these and other effects with further implications for Inuit lives and livelihoods.

10.3.1 Subsistence hunting and fishing

Increased travel risks

Travelling and harvesting on the land, water and ice is inherently dangerous and Inuit have long known about and coped with these risks. However, in recent years, changes in the climate have altered and in some cases increased the magnitude and frequency of hazards with which people have had to manage. This has resulted in an increase in climate-related accidents while traveling on the land, water and ice, often associated with thinning and earlier break-up of sea ice and more unpredictable weather (Chapter 6).

The case studies indicate that Inuit are autonomously employing a number of strategies to minimize risks in a changing climate. Some hunters are using safety equipment such as satellite phones, GPS, emergency beacons, very high frequency (VHF) radios and immersion suits when hunting (i.e. risk minimization strategies) and are utilizing available weather and ice forecasts to assess safety of using the land and sea ice at certain times of the year (i.e. risk avoidance strategies). Small equipment funds are offered as part of harvester support programs to help people afford these new tools for anticipating and managing risks. In some of the case study communities, the local municipality,



Adam Kolohouk Kudlak ties his *oinikhiot* (open water boat) to his *aalliak* (sled) after hunting *natik* (ringed seal) at the *aolagot* (open water lead).

hunter's organization, Canadian Rangers, and/or RCMP detachment will also loan safety equipment for short periods of time. However, proper training for using the equipment is sometimes lacking and the availability of funds and loan programs are highly variable among communities. These expensive technologies, therefore, often remain inaccessible to many Inuit who have limited access to financial means. There is a demonstrated need for enhanced financing to cover the purchase of safety equipment, training costs, and a need to review current programs (e.g. harvester support programs) offered in light of climate change. Moreover, research has indicated that some technologies, such as GPS, that are being utilized to adapt to climate change may have unintended consequences and may increase sensitivity to climatic risks if used improperly or without understanding of the risks of hunting and traveling in the Arctic environment (Aporta and Higgs 2005; Bravo 2009). As observed in other contexts, technology does not reduce vulnerability unless institutions, communities and individuals know how to use and adapt to technology effectively. There is a need for enhanced training in such technologies as part of broader skills development programming.

Constrained access to hunting and fishing areas

Changes in the nature and timing of the spring melt, wind patterns, precipitation events, sea-ice dynamics, and fluctuations in temperature have affected travel routes to some

hunting and fishing areas important for subsistence (Pearce et al. 2011a; Chapter 6). Inuit are not passive in the face of such changes and community members are autonomously adapting by utilizing new equipment and/or alternative travel routes to reach hunting areas. More ice-free open water in the summer is considered a benefit in many communities and people are using boats to take advantage of the new hunting opportunities. Although more open water can represent an opportunity for some people, boat travel often involves traveling longer distances (and hence higher costs) and sometimes raises concerns about safety due to increasingly unpredictable weather (Pearce et al. 2010b; Ford et al. 2013). At other times of the year when the ice is unsafe, all-terrain vehicles (ATVs) are being used to bypass the frozen ocean. New trail networks, which detour unsafe and impassable areas, are also being developed to access hunting and fishing areas (e.g. Berkes and Jolly 2002). However, Inuit households, especially hunting households or those without wage earning members, often do not have the financial capacity to afford adaptations. ATVs and boats, for example, are often too expensive to purchase and the costs of having to travel further and use additional fuel often exceed financial means. As Ford et al. (2008b) and chapters in Riewe and Oakes (2006) note, constrained access to adaptive options is exacerbating existing social inequalities between those households with a wage earner(s) and those without. In absence of financial support, future climate change could further increase the burden of adaptation on vulnerable groups.

Quality and availability of fish and wildlife important for subsistence

Climate change is having implications for the migration timing, population health, quality of meat and furs, and availability of wildlife species important in subsistence-based hunting across the Arctic (Chapters 3 and 4). Ringed seal (*Pusa hispida*) is a principal item in Inuit diet and is widely believed to be susceptible to climate change (Harwood et al. 2000; Harwood 2001; Smith and Harwood 2001; Burek et al. 2008; Moore and Huntington 2008). Caribou (*Rangifer tarandus*) and musk-ox (*Ovibos moschatus*) are important food sources and are sensitive to winter freeze–thaw cycles, which are expected to become more frequent (Miller and Gunn 2003; Russell 2007; Tews et al. 2007a, b; Chapter 2). Polar bear (*Ursus maritimus*) populations, which rely on sea ice for survival, could also be negatively affected by climate change (Derocher et al. 2004; Stirling and Parkinson 2006; Schliebe et al. 2008). Negative effects on the health and availability of freshwater and saltwater fish species have also been recorded in the case study communities (Vilhjálmsson and Hoel 2005; Reist et al. 2006). Warmer temperatures are also affecting the drying of fish and the length of time that fish can spend netted in the water before spoiling (Andrachuk 2008). The act of hunting, consuming, and sharing traditional foods is an important cultural activity, helping to produce and reproduce community social relations and defining what it means to be Inuit, with climate change potentially threatening these relationships (Collings et al 1998; Kuhnlein and Receveur 2007; Pearce et al. 2010b; Chapter 8).

Wildlife populations and migration patterns have always fluctuated in the Arctic. Flexibility in resource use has traditionally enabled Inuit to manage such variability and has underpinned Inuit adaptability to changes in climate documented in the last decade (Krupnik 1993; Berkes and Jolly 2002; Ford et al. 2006a). However, there is concern among community members and politicians across the North that climate change will lead to increased pressure from the international community to strengthen existing quota systems and develop quotas for currently unregulated

species (Dowsley and Wenzel 2008; Clark et al. 2008). Consequently, controversies over how to manage climate change impacts on wildlife have emerged in recent years and have destabilized management and conservation of wildlife across northern Canada (Clark et al. 2008). The recent decision to list polar bears as an endangered species in the United States and the associated ban on US sport hunters importing polar bear skins acquired on sport hunts with Inuit guides in Canada, and the designation of the polar bear as a *species of special concern* under the *Species at Risk Act* in Canada may be an indication of future conflict (George 2006; Dowsley 2009). Developing and altering quotas in response to outside pressures (e.g. the decision to reduce polar bear quotas in the Baffin region of Nunavut (Toronto Star 2010)), which do not take into account local hunting needs and the ecology of harvesting will almost certainly increase Inuit vulnerability to climate change and fail in conservation objectives. Hunting quotas developed without local input could limit the flexibility of hunting that facilitates adaptive capacity, reduce options at the disposal of communities to adapt to future change, limit the accountability and transparency of wildlife management institutions, and could have implications for economic well-being (and hence adaptive capacity) given the importance of traditional foods in Inuit diet.

10.3.2 Community infrastructure

Threats to infrastructure have been assessed, to some degree, in most communities. Built infrastructure in communities located in the Mackenzie Delta is particularly sensitive to permafrost thaw due to its construction on ice-rich flood plains (Hoeve et al. 2006). Threats to municipal and transportation infrastructure also come from coastal erosion, flooding, and warming in “shoulder seasons” (i.e. fall freeze-up, spring melt) threatening the integrity of buildings and services, and of winter roads and trail networks. These threats operate at different scales, from events that may jeopardize entire communities, to events affecting highly localized access, such as degradation of hunting trails through multiple ATV traverses over vulnerable

tundra. This degradation may accelerate as hunters respond to uncertain ocean/sea-ice environments by increasing harvests of terrestrial species. Permafrost degradation associated with warming temperatures has been documented across the region, and together with other events (e.g. increased storm surges in the Beaufort Sea, flooding in Aklavik) threatens to be costly and potentially disruptive (Zhou et al. 2009). In all communities, melting permafrost threatens the integrity of transportation infrastructure, notably roads and airport runways as well as building foundations (Chapter 7). Coastal erosion in Tuktoyaktuk and Sachs Harbour and river bank erosion in Aklavik are all critical events damaging and further threatening the integrity of infrastructure and in some cases community viability (Berkes and Jolly 2002; Andrachuk and Smit 2012). There has been substantial documentation of threats to infrastructure in Tuktoyaktuk and Aklavik because of their long exposure to physical stresses (e.g. Reimnitz and Maurer 1979; Hamlet of Tuktoyaktuk 1984; Couture et al. 2002; Manson et al. 2005; Duerden and Beasley 2006). Somewhat less is known

about the situation in other communities located in the ISR and Kitikmeot region, and this is especially pertinent for Inuvik, where size, regional importance, and functional complexity are significant characteristics.

10.3.3 Rapid economic development

Changing climatic conditions in Arctic Canada, particularly the reduction in sea-ice extent and thickness, have made the region attractive to international and national shipping as well as associated industries such as cruise tourism, resource extraction and fisheries development (Chapter 9). The expansion of economic opportunities in the region brings both benefits and risks to local residents. Identification of the community vulnerabilities and related adaptive strategies (and policy interventions) to rapid climate change-induced economic development is in its early stages – especially in comparison to our understanding of subsistence harvesting and community infrastructure.



Ulukhaktok, NWT, 09 July 2013

TRISTAN PEARCE

Several studies that focus on community vulnerability to increased resource extraction, fisheries growth and the militarization of Arctic Canada are only just beginning (e.g. Resources and Sustainable Development in the Arctic (ReSDA)). The Government of Canada and local stakeholder groups have identified sustainable and culturally relevant economic development in northern regions – in light of recent environmental and global change – as a high priority. However, there are challenges looking forward including the fact that many future opportunities will be resource-based with known consequences including unsustainable boom bust cycles, long-lasting environmental impacts, risks associated with environmental and human accidents, and increasing economic inequalities within communities. Communities in the North need to ensure that the emerging regional economy is diversified and compliments the existing subsistence economy as well as cultural traditions and local desires.

The identification and establishment of viable strategies that communities can implement will be essential in order to ensure local voices are heard in regional and national level planning. An understanding of the implications of a rapidly emerging cruise tourism economy, which saw a doubling of ships between 2005 and 2006 and 70% growth of activity in the Northwest Passage between 2007 and 2012, has been established (Stewart et al. 2010a, 2011; Johnston et al. 2012). Over 270 resident interviews, 40 policy maker interviews, 18 cruise operator interviews and five focus groups were conducted within six different communities between 2009 and 2012. Local residents are concerned about safety and security due to increased shipping activity, the negative interactions between ships and marine wildlife, the weakness of relevant regulation and policy governing new industry growth, a lack of search and rescue (SAR) capabilities, as well as the absence of appropriate salvage equipment in the event of a major shipping disaster (Stewart et al. 2011). Adaptation strategies identified include: (1) improving support for local economic development; (2) entrepreneurial, business and marketing training; (3) establishing ‘special marine hunting areas’ prohibited to commercial shipping; (4) improving regional coordination of economic

development initiatives and policies to reduce regional economic leakage; (5) harmonizing Arctic shipping rules and regulations via the Polar code; and (6) improving SAR, charting and monitoring capabilities (Dawson et al. 2013).

10.4 Entry points for climate change adaptation policy

We examine opportunities for climate change adaptation policy based on an understanding of determinants of Inuit vulnerability and adaptive capacity described above. The adaptation policy entry points identified target different levels of decision making.

10.4.1 Support the teaching of environmental knowledge and land skills

In the case study communities, and across Inuit regions, research has documented a weakening of TEK and land skills among younger generations (Collings et al. 1998; Aporta 2004; Myers et al. 2004; Aporta and Higgs 2005; Ford et al. 2006b; Bravo 2009; Pearce et al. 2010a, 2011b, 2012; Prno et al. 2011). This trend is increasing the danger of harvesting among younger generations, exacerbating the negative implication of climate change, and is a major concern for community members and leaders. TEK will remain important for identifying and managing climatic risks and adapting to change: while climate change is undermining some aspects of traditional knowledge including the ability to forecast weather conditions, predict animal migrations, and understand environmental conditions based on place names, other skills are even more important in light of new and exacerbated risks (e.g. ability to identify hazard precursors, survival skills and mentality, knowledge of animal behavior, etc.). Moreover, research has illustrated how the experiential nature of TEK has underpinned social learning to manage emerging risks with climate change (Ford 2009; Ford et al. 2009; Pearce et al. 2010a).

Policies that promote and facilitate the generation and transmission of TEK are central to reducing risks in a changing climate and have the potential to increase safe hunting practices among vulnerable groups, targeting three important aspects of reducing climate vulnerability: prevention, preparedness, and response. Cultural programs that provide land skills training are currently offered in an *ad hoc* fashion in communities across the North. The school system in Inuit regions, for example, has cultural programming as part of the curriculum, although locally these programs are often believed to be inadequate in developing necessary land skills. Training in non-traditional skills, which includes firearm safety and vehicle management, is also important in these programs. Addressing the erosion of traditional skills through the integration of traditional knowledge and land skills in education curriculum, and the creation of cultural schools/land skills programs should be part of a broader program in northern regions to place emphasis on skills training and development so that Inuit are better prepared to adapt to and take advantage of climate change alongside new economic opportunities (Fast et al. 2001; Schlag and Fast 2005). This is particularly important given the demographics of Canadian Inuit communities, where young populations will be entering the workforce and beginning to engage in harvesting activities as the effects of climate change become pronounced. In some instances, communities and researchers have developed novel approaches to help facilitate the transmission of environmental knowledge and land skills including oral history databases with information that is accessible to download using new media technologies (Pearce et al. 2011b) and interactive DVDs (Aporta 2003).

10.4.2 Improve access to, and understanding of climate, weather and sea ice information

Inuit hunters in the case studies, particularly the younger generations who do not have the detailed understanding of the environment, reported making regular use of weather forecasts provided on the radio. Some individuals also make

use of sea ice maps and forecasts from the Internet when making decisions about where and when to hunt. Improving access to climate and weather information is important so people can make the decisions about where to hunt and fish during times of uncertainty. At present, the quality of forecasting in Arctic Canada is limited. Only a few meteorologists cover Canada's Arctic region (an area larger than western Europe) and are unable to provide regularly updated weather forecasts that hunters need in a changing climate (Picco 2007). Additionally, these meteorologists are not based in the Arctic, but in southern Canada, and base their predictions upon synoptic satellite charts with limited availability of higher resolution localized data. Participants in the case studies noted regularly complaining about the unreliability of forecasts and potential safety implications. Making forecasts more locally relevant is essential as climate change increasingly challenges the ability of experienced hunters to predict the weather using their traditional knowledge. This could include providing information on parameters of interest to Inuit such as wind and visibility. Moreover, improved understanding of how Inuit use and access forecasts, and developing means of improving delivery (consider using local terminology) is also needed if we are to develop forecasting products which are important to local needs.

10.4.3 Review and enhance search and rescue (SAR) capabilities

Traveling and harvesting in the Arctic is inherently dangerous for even the most knowledgeable individuals. Even in the absence of climate change, accidents while traveling and hunting, including falling through thin ice, getting stranded on drifting ice, or being affected by bad weather, are common (Bravo 2009; Chapter 6). Also at risk are large vessels that are increasingly traveling through areas known to have hazardous conditions including shallow rock cliffs, drifting multi-year sea ice and icebergs. Beginning in the 1980s, formal SAR procedures were developed across the Canadian Arctic to provide air, ground and maritime emergency support and rescue. Jurisdiction for SAR is currently



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Inuit hunters on the sea ice in the Beaufort Sea

divided between the Canadian Coast Guard, the military (including the Canadian Rangers), RCMP, regional/territorial government departments, and municipalities. Formal SAR compliments the more informal, volunteer search teams that are mobilized locally when a person is missing or requires help. The current system involving both formal and informal response is widely believed to be effective among both community members and government officials (Breton-Honeyman and Furgal 2008). When ground or marine emergencies arise, local search teams are rapidly mobilized and involve the participation of skilled local hunters and elders; the more formal SAR operations are engaged when additional air, ground, and logistical support is required. Moreover, both formal and informal search organizations regularly review recent operations, identifying strengths and weaknesses of current rescues (Minogue 2005).

Climate change, however, presents a number of challenges to SAR, as the case studies indicate. Firstly, there is potential for new challenges which SAR organizations have

limited experience. These challenges may stress the ability to respond if there is a lack of clearly delineated responsibilities and authorities among levels of government. For example, increased opportunity for commercial and tourist ships with longer ice-free open water periods in the summer will increase the potential for marine emergencies (Stewart et al. 2007; Stewart and Dawson 2011). Jurisdiction of responsibility in responding to marine emergencies is not well specified. Secondly, SAR efforts are becoming more frequent and more dangerous, increasing the chance of injury and even loss of life (Furgal and Prowse 2008). In 2005, for instance, two local rescuers died while searching for a lost hunter in a Nunavut community. In 2010 there was a ‘near miss’ when a cruise ship carrying over 150 passengers and 100 crew grounded on the western side of the Northwest Passage for over three days until rescue vessels arrived (Stewart and Dawson 2011; see Chapter 6, Box 1). Thirdly, in the context of de-skilling among today’s younger generations, there is concern that the ability and effectiveness of local rescue teams could be compromised. Moreover, SAR operations often involve considerable risk

to those involved and time commitment; in the context of weakening social networks and emerging conflict between community members noted in some communities, fewer people may be inclined or available to be involved in local operations. In the larger communities a common complaint is a lack of local people willing or available for SAR operations. Notwithstanding, new opportunities are also emerging. In recent years with resource development in Inuit regions, mining companies have provided helicopter air time to help with search operations. Additionally, GIS and GPS offer new tools for SAR coordination and have been effectively used in searches across the North. In the context of these challenges and opportunities it is important that SAR capability and institutional arrangements be continually reviewed as the frequency, scope, and intensity of climate-related risks and impacts change as result of climate change. In particular, joint planning exercises between the different organizations involved in SAR including local, territorial and federal decision makers are required to identify weaknesses and strengths in current SAR capability. Additionally, drills and exercises, training of local SAR personnel, provision of safety equipment to rescuers, and worse case contingency planning are required to increase emergency preparedness. There is evidence that this is already occurring; the Government of Nunavut now provides financial contributions to support community-based SAR organizations. SAR personnel and planners also need to be aware of potential implications of climate change to SAR and review current procedures in light of climate predictions. In this area, formal and informal SAR are less prepared (Bird 2009). Moreover, given the increased use of GPS, GIS, satellite phones, and personal locator beacons to enhance the safety and effectiveness of SAR, local training on the use and limitations of geo-technology for local navigation and SAR should be encouraged. Lastly, as the region becomes more and more accessible to large-scale marine transportation (freight, cargo, resource industry, tourism, military, research) current navigation charts and coast guard monitoring capabilities (i.e. availability of ice strengthened ships, changes to the *Arctic Waters Pollution Prevention Act* and NORDREG, sufficient funding) require urgent attention and modernization (Stewart et al. 2013).

10.4.4 Strengthen harvester support programs

Harvester support programs for those whose livelihoods are dependent on hunting are offered in all Inuit regions of Canada by regional governments and land claim institutions. These programs do not explicitly aim to reduce vulnerability to climatic conditions – they aim to maintain a strong and thriving traditional resource use sector – but they are important in providing a safety net for households, helping hunters recover from climate-related losses and providing financing for climate adaptations. Research has shown that harvester support has a positive impact on harvester viability and food production (Dorais 1997; Kishigami 2000; Myers et al. 2004). However, many of these programs are having difficulty meeting demands placed on them due to rising fuel and equipment costs, and the future of some programs is not secure. There is also evidence that climate change is exacerbating shortcomings in funding allocation and future climate change will further increase pressure on harvester support programs. For those without access to other sources of income, harvester support could determine the sustainability of hunting in a changing climate.

Existing harvester support programs can be strengthened in several ways to increase their effectiveness in light of current and projected climate change. Firstly, enhanced financial support for harvester programs targeted at helping Inuit afford to adapt would help Inuit maintain their ability to practice culturally important activities in a changing climate. Secondly, there is potential to strengthen the effectiveness of existing programs. Complexity and lack of knowledge of existing programs have been identified as constraining uptake among hunters, many of whom lack formal education (Aarluk Consulting 2005). Better advertising and promotion to educate community members about harvester programs and their use could also increase program effectiveness. Thirdly, reviewing how funds are allocated to address concerns of nepotism within communities would help ensure that harvesters are accessing funding and strengthening community confidence in the programs (Ford et al. 2007; Pearce et al. 2010b). Fourthly, current harvester

support programs were not developed in the context of a changing climate. Reviewing current programs in light of new demands as a consequence of current and future climate change should be a priority for all Inuit regions.

10.4.5 Ensure flexibility of resource management regimes

Innovative co-management of renewable resources that integrates Inuit traditional knowledge with scientific understanding of wildlife population vulnerability to climate change and allows Inuit to exercise their (legally defined) traditional rights is likely to increase adaptive capacity by maintaining some degree of resource use flexibility (Chapin et al. 2004; Berkes et al. 2005; Armitage et al. 2008; Clark et al. 2008; Dowsley 2009). Research in Arctic

and non-Arctic contexts, for instance, demonstrates that flexible, multi-level governance can help management systems deal with change by promoting the sharing of information between actors at different scales, linking scientific and traditional management systems, permitting greater opportunity to address conflicts over competing vision or goals, and providing an arena to solve conflict (Tompkins and Adger 2004). Importantly, co-management may serve to strengthen trust between various interested parties in wildlife management. Management regimes in Inuit regions have progressed significantly in recent years, with new co-management bodies emerging in which federal and territorial/regional regulators and Inuit organizations decide annual harvest quotas (Berkes et al. 2005). This transition has been turbulent and while previous management systems have been improved, conflict still remains entrenched (Nadasdy 2003; Natcher et al. 2005; Stevenson 2006). In particular,



Roland Notaina glassing for *omingmak* (muskox) on Victoria Island, NWT



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differential power relations among various interested parties and conflict over the role of science and traditional knowledge have been noted in the case study communities as compromising effective decision-making, ultimately resulting in management outcomes unsuitable to all parties (Dale and Armitage 2011; Armitage et al. 2011).

Clark et al. (2008) identify a number of policy options to reduce conflict over wildlife management in the context of multiple stresses and competing uses, and which are relevant in a climate change context. In the short term they recommend focusing on sharing traditional and scientific knowledge in management decisions, appraisal and use of best practice from other contexts, and the co-production of knowledge on the health and status of wildlife populations. Sharing traditional and scientific knowledge is fundamentally a social process, requiring relationships, which takes time. This may be facilitated by having the same groups of people meet on a regular basis so that they can get to know one another, progressively build on the success of each meeting, promote accountability, and be well positioned to respond quickly to emerging situations. In the long term they advocate emphasis on local and decentralized decision making to increase the adaptive capacity of regional and local scale management institutions. In light of climate change, it is important that research (involving scientists and local hunters) highlights wildlife populations at risk, explores the sustainability of current wildlife harvesting, and develops response options in co-management bodies.

10.4.6 Improve the ability of Inuit food systems to meet present dietary and nutritional requirements

Food security exists when people at all times can acquire safe, nutritionally adequate, and culturally acceptable foods in a manner that maintains human dignity (Van Esterik 1999; FAO 2002; Gregory et al. 2005). The Inuit food system includes traditional foods (plants and animals) harvested from the local environment and industrial foods (non-locally produced foods sold at stores) transported from the South into northern communities by ship, road or air. Subsistence plays an important economic and social role in Inuit society and food sharing practices continue to persist in contemporary settlements (Wenzel 1995; Collings et al. 1998; Pearce et al. 2010b). It is still customary for hunters to share their catch with other households, notably Elders and those unable to hunt. There is concern, however, that some food sharing networks are not functioning as they were in the past, with some people being excluded from networks that previously provided access to food. Climate change and variability challenges food security in Inuit communities by constraining access, availability, and impacting quality of traditional foods (Chapter 8) – an observation noted in other locations (Chan et al. 2006; Guyot et al. 2006; Seguin 2008; Ford and Beaumier 2010). Further, weather variability and implications of climate change on resupply routes and food system infrastructure can have implications on the industrial food aspects of community food systems (Furgal et al. 2012). While offsetting traditional foods with store foods may be an acceptable and feasible option for some community members, particularly the young and those with a household member involved in the waged economy, traditional foods are preferred in hunting households because of their taste and cultural significance. Moreover, any decline in traditional food consumption is a concern from the point of view of dietary health, particularly if healthy, nutrient dense, traditional foods are replaced by nutrient poor store foods high in saturated fats (Young and Bjerregaard 2008; Council of Canadian Academies 2014). Additionally, for many households store foods are expensive and often not affordable to

those without jobs. High levels of baseline food insecurity in Inuit regions related to existing and ongoing challenges in the combined local (traditional) and industrial (transported) food system are likely to be exacerbated by the implications of climate change. In the context of social-economic and climatic constraints, Damman et al. (2008) argue that the federal government has obligations under international human rights law (e.g. International Covenant on Economic, Social and Cultural Rights) to ensure Inuit food security is upheld.

Strengthening the current ability of Inuit food systems to provide safe and appropriate access to adequate amounts of healthy, nutritious and desired foods that help individuals meet dietary and nutritional standards will increase the adaptability of the food system to a changing climate. This involves taking a food system level approach, addressing social barriers to subsistence and food sharing, and responding to emerging climate-related risks. Policy entry points to address food insecurity in a changing climate include: (1) subsidization of healthy store foods; (2) development of food-banks (short-term); (3) extension of the Nutrition North program to include traditional foods; (4) education on how to prepare healthy meals with traditional and store bought foods; (5) organized community hunts; (6) strategies to improve the distribution of traditional foods between communities; (7) strengthening food sharing relationships in communities; (8) harvester support; (9) the development and reinstatement of community freezers; and (10) initiatives to develop commercial ventures based around traditional foods (Boult 2004; Myers et al. 2004; Chan et al. 2006; Lambden et al. 2006; White et al. 2007; Damman et al. 2008). A number of successful initiatives are already helping Inuit meet their dietary requirements including harvester support programs, food donations, and community freezers, although communities have made it clear that more extensive programming and government support is needed (Chan et al. 2006). Notwithstanding these potential policy opportunities, research is only beginning to analyze how food systems might be affected by and respond to climate change in the North. Assessing vulnerability of Inuit food systems to climate change and assessing and

evaluating program success and adaptation options is a priority for future research (Chan 2006; Seguin 2008; Furgal and Prowse 2008).

10.4.7 Protect key infrastructure

Community viability depends on a sense of place and historical attachment (Cunsolo-Wilox et al. 2012), and the quality of the physical fabric (e.g. houses, roads, community buildings) of a community. Both are exposed and sensitive to climate change with many Inuit cultural sites (graveyards, hunting camps, etc.) and current settlements located on the coast and/or on permafrost. Sea level rise, coastal erosion, permafrost thaw, and more active slope processes (Chapters 3 & 7), threaten these sites and limit potential for new development.

Physical interventions are being considered in vulnerable communities across the Arctic to protect infrastructure. These include moving buildings, raising buildings, installing engineering structures to provide protection from wave action and permafrost thaw, and constructing all-weather-roads due to increasingly unreliable ice roads (e.g. Tuktoyaktuk) (Couture et al. 2003; Larsen et al. 2008). Any engineering-based measures, however, will be costly and will involve trade-offs between cultural benefits and economic cost in communities and regions with limited economic means. A ‘best guess’ estimate of the likely adaptation cost for building foundations in the ISR is approximately \$126,700,000 CAD (Hoeve et al. 2006). This raises the question, ‘who will pay?’ Moreover, access to local gravel deposits are essential for infrastructural developments (Chapter 7), yet not all communities have access, the availability of this important resource is limited, and historically it has been poorly managed. Multiple administrative regimes, culturally significant landscapes and environmental sensitivity are all factors constraining access to local granular resources (Borsey 2006). Importing gravel from elsewhere would be costly given the costs and difficulties of Arctic transportation.

10.4.8 Review building codes and land-use plans in light of current and expected climate change

Furthermore, community infrastructure built today (e.g. new housing developments, roads, community buildings) will be exposed to very different climatic conditions in the future, yet the assumption that future climatic variability will be like past variability continues to guide community planning and construction. There are few examples in the reviewed literature of land-use planning guiding development away from areas susceptible to permafrost thaw, coastal flooding, or erosion. In some communities, the opposite is occurring, with development taking place in high-risk areas (Catto and Parewick 2008). Given recent projections of climate change (Chapter 2), it is no longer safe to assume that the past will be a guide to the future, the so-called death of stationarity (Milly et al. 2008). In those communities that have experienced long-term threats to infrastructure, adaptive capacity may be enhanced because of their experiences and heightened awareness of the options open to them

(e.g. Aklavik and flood threat). In Tuktoyaktuk, new buildings and a new road are being constructed further inland, which will make them less susceptible to coastal erosion (Andrachuk and Smit 2012). This planning strategy was not designed to respond to climate change per se, but it does reflect a recognition that development needs to better consider risks such as sea level rise and coastal erosion (Andrachuk and Smit 2012).

Relocation of some communities (e.g. Tuktoyaktuk, Aklavik) may be inevitable for settlements threatened by sea level rise and accelerated coastal erosion. The fate of the Inupiaq community of Kivalina in Alaska, which has decided it will have to relocate if the community is to survive, is a portent for potential future threats affecting communities along Canada's Arctic coastline. The costs of relocation will be extremely high although they will likely be less than protecting communities at all cost. For example, the Canadian government conservatively estimated a cost of \$50 million CDN to relocate the community to Tuktoyaktuk (population 900). Political challenges of relocation will



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be considerable. The current location of the majority of Inuit communities in Arctic Canada reflects church, trading post, and government policy in the 1950s and 1960s which sought to sedentarize semi-nomadic Inuit hunting groups through the provision of housing, health care and education. Many of the communities that were developed this way were located significant distances from traditional Inuit hunting areas, with many Inuit reluctant to move (Damas 2004). Significant acculturative stress was associated with relocation and thoughts of relocation again raise bad memories for many Inuit in the North.

10.5 Discussion

Inuit are highly adaptable to climatic variability, change, and extremes as the case studies indicate. However, speed of change, financial, institutional, and knowledge limitations are constraining adaptive capacity and increasing exposure-sensitivity to climate change risks. We identify a number of priority areas for reducing vulnerability and enhancing adaptive capacity, including: (1) support the teaching and transmission of environmental knowledge and land skills; (2) improve access to, and understanding of climate, weather and sea ice information; (3) review and enhance search and rescue capabilities; (4) strengthen harvester support programs; (5) ensure the flexibility of fish and wildlife management regimes; (6) improve the ability of Inuit food systems to meet present dietary and nutritional requirements; (7) protect key infrastructure; and (8) review building codes and land-use plans in light of current and expected climate change. These adaptation policy interventions are derived from the findings of completed vulnerability research including interviews with policy makers. A key characteristic of these recommendations is that while explored here in the context of adaptation to climate change, they also concern ongoing policy initiatives and priorities in areas of economic, social, health, and cultural development, and can bring immediate benefits in the form of reduced vulnerability to current climatic variability, change, and extremes. What is new is that these policy goals are re-emerging in the unique context of climate change. As such,

there is agreement among many scholars and policy makers that ‘mainstreaming’ or ‘normalizing’ climate change adaptation into policies intended to broadly enhance adaptability to risk is likely to be the most effective means of reducing vulnerability to climate change (Dovers et al. 2009).

Important to all adaptation interventions is that communities and policy makers are actively involved in identifying, proposing, enabling, assessing, and enforcing adaptation policy (Ford et al. 2007; Ford and Pearce 2012; Pearce et al. 2012). This is central in linking research to policy. Interventions will be more successful if they are identified and developed in co-operation with local actors and policy makers, who will be more likely to trust them and find them consistent with their goals, norms, and policy objectives (Newton et al. 2005; Chapin et al. 2006). Involving communities and policy makers was a key feature of the research on which policy interventions identified in this chapter are based. The adaptation policy opportunities described here are general in their focus and are relevant to communities throughout the Canadian Arctic.

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Units of Measure and Acronyms

Units of measure

°C – degrees Celsius	km ² – square kilometre
cm – centimetre	L – litre
D – dimension	m – metre
dB – decibel	m ² – square metre
deg – degrees	m ³ – cubic metre
g – gram	µg – microgram
h – hour	mm – millimetre
Ha – hectare	mmol – millimole
ind – individuals	mPa – milliPascals
kcal – kilocalorie	nm – nautical mile
kg – kilogram	s – second
kHz – kilohertz	t – tonne
km – kilometre	y (or) yr – year

Acronyms, abbreviations and symbols

AANDC	Aboriginal Affairs and Northern Development Canada
AB	Alberta
ACIA	Arctic Climate Impact Assessment
AHPP	Aklavik <i>H. pylori</i> Project
AK	Alaska
ALD	active layer detachment
AMAP	Arctic Monitoring and Assessment Program
AMJ	April, May, June
AMOP	Arctic and Marine Oilspill Program
AR5	Assessment Report 5 (referring to IPCC)
ARI	Aurora Research Institute
ATV	all-terrain vehicle
AUS	Australia
BC	British Columbia
BMI	body mass index
BREA	Beaufort Regional Environmental Assessment
CAA	Canadian Arctic Archipelago
CAD	Canadian Dollar
CANGRD	Canadian Gridded Temperature and Precipitation Anomalies
CANHelp	Canadian North <i>Helicobacter pylori</i>
CAPP	Canadian Association of Petroleum Products
CARMA	CircumArctic Rangifer Monitoring & Assessment
CASES	Canadian Arctic Shelf Exchange Study
CAVM	Circumpolar Arctic Vegetation Map

CBC	Canadian Broadcasting Corporation
CBz	chlorobenzenes
CBM	Community-based monitoring
CBMN	Community-based monitoring network
CC	Community Corporation
CCGS	Canadian Coast Guard Ship
CD	chart datum
Cd	cadmium
CEAA	Canadian Environmental Assessment Agency
CEO	Chief Executive Officer
CEOS	Centre for Earth Observation Science
CFL	Circumpolar Flaw Lead
CGCM	Canadian Global Climate Model
CHARS	Canadian High Arctic Research Station
CHL	chlordanes
CHONe	Canadian Healthy Oceans Network
CHS	Canadian Hydrographic Service
CI	confidence interval
CIMP	Cumulative Impact Monitoring Program
CIS	Canadian Ice Service
CMC	Canadian Meteorological Centre
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CRCM	Canadian Regional Climate Model
CSL	Canada Steamship Line
CSS	Canadian Survey/Scientific Ship
CWS	Canadian Wildlife Service
DBP	diastolic blood pressure
DD	degree-days
DDE	dichlorodiphenyldichloroethylene
DDT	dichlorodiphenyltrichloroethane
DEW	Distant Early Warning
DFO	Department of Fisheries and Oceans
DND	Department of National Defense
DOE	Department of Environment
DVD	digital video disc
dw	dry weight
ECHAM	European Centre Hamburg Model (global climate model)
EEZ	Exclusive Economic Zone
EIRB	Environmental Impact Review Board
EIS	Environmental Impact Statement
EISC	Environmental Impact Screening Committee
Elev	elevation
ERA	ECMWF (European Centre for Medium-Range Weather Forecasts) Re-Analysis

UNITS OF MEASURE AND ACRONYMS

ESRF	Environmental Studies Research Funds	MANICE	Manual of Standard Procedures for Observing and Reporting Ice Conditions
ESRL	Earth System Research Laboratory	Max	maximum
FAO	Food and Agriculture Organization	Max _{zn}	maximum snow accumulation
FDD	freezing degree-days	MB	Manitoba
FJMC	Fisheries Joint Management Committee	MGP	Mackenzie Gas Pipeline
FW	freshwater	MHg	methyl-mercury/methyl-Hg
GCM	global climate model	Min	minimum
GDD	growing degree-days	MV	motor vessel
GHG	greenhouse gases	MYI	multiyear ice
GIS	geographic information system	M _{zn}	mean snow accumulation
GMSL	global mean sea level	NARR	North American Regional Reanalysis
GN	Government of Nunavut	NC ³	Nunavut Climate Change Centre
GNSS	Global Navigation Satellite System	NCMS	Northern Coastal Marine Studies
GNWT	Government of Northwest Territories	NDVI	normalized difference vegetation index
GPCP	Global Precipitation Climatology Project	NEB	National Energy Board
GPR	ground-penetrating radar	NCAR	National Centre for Atmospheric Research
GPS	global positioning system	NCEP	National Centres for Environmental Prediction
GSC	Geological Survey of Canada	NGMP	Nunavut General Monitoring Plan
HBCDD	hexabromocyclododecane	NIRB	Nunavut Impact Review Board
HCH	hexachlorocyclohexane	NL	Newfoundland and Labrador
HDL	high density lipoprotein	NLCA	Nunavut Land Claim Agreement
Hg	mercury	NLUP	Nunavut Land Use Plan
Hgb	hemoglobin	NOAA	National Oceanic and Atmospheric Administration
HL	Husky Lakes	NORDREG	Northern Canada Vessel Traffic Services
HMS	Her Majesty's Ship	NRCan	Natural Resources Canada
HTC	Hunters and Trappers Committee	NRI	Nunavut Research Institute
HTO	Hunters and Trappers Organization	NS	Nova Scotia
IFA	Inuvialuit Final Agreement	NSA	Nunavut Settlement Area
IGC	Inuvialuit Game Council	NSERC	Natural Sciences and Engineering Research Council
IHS	Inuit Health Survey	NSIDC	National Snow and Ice Data Centre
IK	Inuvialuit contemporary and traditional knowledge	Nthaw	number of winter thaw (events)
IMS	Ice Mapping System	NTI	Nunavut Tunngavik Inc.
IOM	Integrated Ocean Management	NU	Nunavut
IOMP	Integrated Ocean Management Plan	NWB	Nunavut Water Board
IPCC	Intergovernmental Panel on Climate Change	NWMB	Nunavut Wildlife Management Board
IPG	Institution of Public Government	NWT/NT	Northwest Territories
IPY	International Polar Year	OHC	organohalogen compounds
IQ	Inuit Qaujimajatuqangit	OH-PCBs	hydroxylated polychlorinated biphenyls
IRC	Inuvialuit Regional Corporation	ON	Ontario
IRIS	Integrated Regional Impact Study	OND	October, November, December
ISR	Inuvialuit Settlement Region	Pb	lead
ISR-CBMP	Inuvialuit Settlement Region - Community-Based Monitoring Program	PBDE	polybrominated dipheyl ether
JAS	July, August, September	PBT	persistent, bioaccumulative and toxic
JFM	January, February, March	PCB	polychlorinated biphenyl
JS-ISR	Joint Secretariat-Inuvialuit Settlement Region	PCSP	Polar Continental Shelf Program
KIA	Kitikmeot Inuit Association	PFCA	perfluorinated carboxylic acids
Lat	latitude	PFOS	perfluorooctane sulfonate
LDL	low density lipoprotein	PFSA	perfluorinated sulfonic acids
LOMA	Large Ocean Management Area	POP	persistent organic pollutant
Long	longitude	Precip	precipitation
lw	lipid weight	P _s	solid precipitation

P_t	total precipitation
QC	Québec
RAC	Regional Adaptation Collaborative
RCMP	Royal Canadian Mounted Police
RCP	Representative Concentration Pathway
ReSDA	Resources and Sustainable Development in the Arctic
RIA	regional impact assessment
ROS	rain on snow (events)
RTS	retrogressive thaw slump
SAR	search and rescue
SBP	systolic blood pressure
SBS	Southern Beaufort Sea
SCE WG	Social, Cultural and Economic Working Group
SCD	snow cover duration
SHR	sitting height ratio
SRES	Special Report on Emissions Scenarios
SS	Survey/Scientific Ship
SSL	summer season length
SST	sea surface temperature
STD	standard deviation
SWE	snow water equivalent
T_a	air temperature
TAC	Transportation Association of Canada
TCWR	Tibbitt to Contwoyto Winter Road
TDD	thawing degree-days
TEK	Traditional Ecological Knowledge
Temp	temperature
TK	Traditional Knowledge
TSBC	Transportation Safety Board of Canada
UNB	University of New Brunswick
UNCLOS	United Nations Convention on the Law of the Sea
UNGA	United Nations General Assembly
US/USA	United States of America
USACE	US Army Corps of Engineers
USD	United States Dollar
USGS	United States Geological Survey
USNS	United States Naval Ship
WAIS	West Antarctic Ice Sheet
WARC	Western Arctic Research Centre
WKSS	West Kitikmeot Slave Study
WKSSS	West Kitikmeot Slave Study Society
WMAC (NS)	Wildlife Management Advisory Council (North Slope)
ww	wet weight
WWF	World Wide Fund for Nature
YG	Yukon Government
YT	Yukon Territory

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