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Canada



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## FOREWORD

The Greater Hudson Bay Marine Region is unique. It is home to 40 coastal communities with a total population of over 45,000 people. Over the last 50 years, the Inuit and Cree living in the region have seen rapid changes in the physical environment, ecosystems, fish, and wildlife, concurrent with economic development and institutional change associated with land claim settlements.

The environmental and ecological transformation occurring throughout the region affects communities in many ways. Altered freeze-up and break-up patterns and less predictable weather increase the risks associated with travelling on the ice and the coastal waters. Changes in fish and wildlife affect the availability and quality of country foods. Modernization and development provide opportunities but also impact the environment. Increased shipping improves sea-lift services to some communities but increases the potential for spills and contamination.

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 climate change. 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 prepare for the full impacts of environmental, economic and societal changes in the Canadian Arctic and Subarctic regions.

The Integrated Regional Impact Study (IRIS) for the Greater Hudson Bay Marine Region presented herein summarizes the knowledge collected during the past fifteen years of ArcticNet, identifies data gaps, and gives recommendations for the future. The assessment and recommendations aim to inform decision making and the development of adaptation strategies in the region. Our vision is a future where communities, scientists and governments work jointly towards a sustainable development of northern Canada that will foster the health and biodiversity of its ecosystems; the wellbeing and empowerment of Inuit, northern First Nations and Metis; the environmentally-safe exploitation of mineral, shipping, energy and tourism resources; and Canada's international leadership in the scientific study of the changing Arctic.

We sincerely thank the community members, local, regional and national representatives, and researchers including network investigators, technical staff and students, and all contributors to this IRIS report. The Hudson Bay IRIS steering committee and the dedicated editorial team were responsible for bringing this important document through to completion, and we would like to express our sincere gratitude to them.



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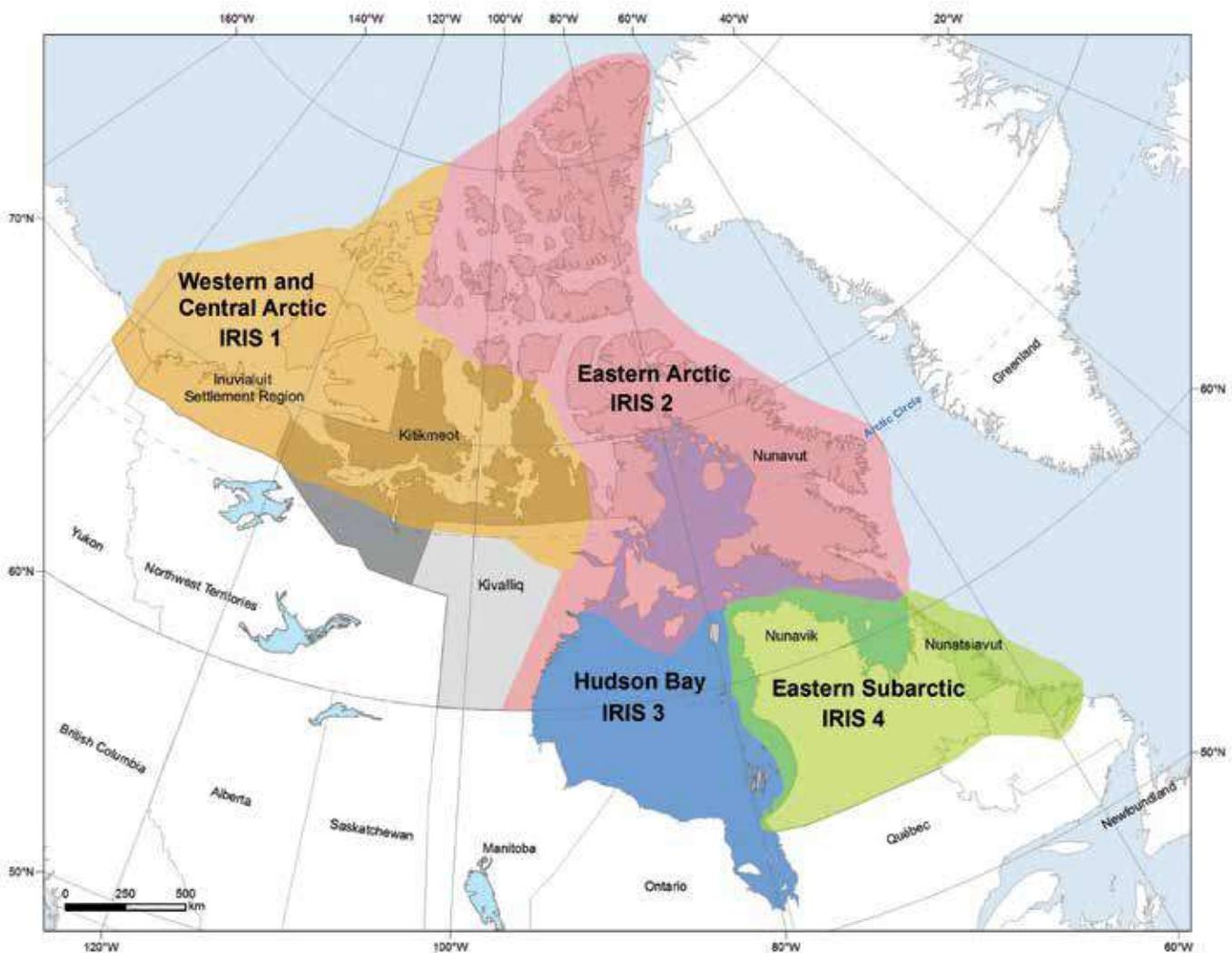
## PREFACE

ArcticNet is a Network of Centres of Excellence of Canada that brings together researchers and 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's research program has been multidisciplinary, addressing a wide variety of topics ranging from the physical to the biological, from oceanography to human health, from scientific research to Inuit knowledge. Its geographic scope has included the Canadian Arctic north of about 55°N latitude—at sea, on land, and on the sea ice.

To try to integrate research results and communicate them to communities, northern organizations and other interested parties, ArcticNet initiated an *Integrated Regional Impact Study (IRIS)* process. For this process, the North was divided into four,

broadly-defined regions: Western and Central Arctic, Eastern Arctic, Greater Hudson Bay Region, and the Eastern Subarctic. The regions do not reflect land claim boundaries but rather similarities or commonalities in important aspects of the environment. For instance, for the Eastern Subarctic IRIS, the focus is the peninsula shared by Nunavik and Nunatsiavut. The Western and Central Arctic IRIS focuses on the Beaufort Sea.

The Greater Hudson Bay Marine Region IRIS focuses on the interconnected water bodies of Foxe Basin, Hudson Bay, James Bay, Ungava Bay and Hudson Strait. This region is bordered by land masses of Nunavut, Manitoba, Ontario, and Québec. It has more than 40 communities distributed in the coastal region. The Qikiqtaaluk and Kivalliq regions of Nunavut are represented in the north; the Inuit region of Nunavik extends along the east coast of Hudson Bay and the south coast of Ungava Bay and Hudson Strait; the Cree homeland of Eeyou Istchee lies along



eastern James Bay, and six First Nation bands are represented in the Ontario region of western James Bay and southwestern Hudson Bay.

The Greater Hudson Bay Marine Region IRIS is unique among the ArcticNet IRISes in focusing exclusively on the marine and coastal environment. Our discussion of the terrestrial system is limited to the watershed and the perspective of what the rivers deliver to the marine system. This IRIS report incorporates results from scientific studies, traditional knowledge compiled in 'Voices from the Bay' (McDonald et al., 1997), the perspectives of Inuit and Cree represented through the IRIS steering committee and input from a variety of stakeholders who contributed to the editorial team. Human interactions with the marine and coastal environments are incorporated into the report, as appropriate, but in general, human-focused topics (e.g., human health surveys) are included in other IRIS reports. For Nunavut communities, refer to the Eastern Arctic IRIS (IRIS 2); for Nunavik communities, refer to the Eastern Subarctic IRIS (IRIS 4).



This IRIS aims to address the knowledge gaps for the Greater Hudson Bay Marine Region and to strengthen evidence-based decision making by broadening and integrating knowledge bases. The IRIS consists of two parts: a large report of science based knowledge, and a synthesis of this knowledge along with resultant policy-related recommendations.

The best way to understand the Hudson Bay IRIS report is not as an end, but as a substantial step in the continual process of bringing together knowledge to inform decision-making. Much of the content of this report is retrospective. However, just as important as what we do know and are able to report, is what we do not yet know. Findings presented in the document



M. KAMUUA

create a picture of what is happening in the Marine Region, and will likely happen in the future. Just as or even more importantly, embedded in the report is also a roadmap of questions that need to be addressed next to deepen our understanding of changes in the Greater Hudson Bay Marine Region, what they mean for the populations that depend on these waters and ecosystems, and what actions are needed to support the Marine Region's long-term health and its sustainable use.

This IRIS is a product of close collaboration between the University of Manitoba editorial team and the Steering Committee for the Hudson Bay IRIS, a portion of which is pictured. The Hudson Bay IRIS Steering Committee met annually at the ArcticNet Annual Scientific Meetings (December 2014, December 2015, December 2016, December 2017). The committee also met by teleconference once a month. Members of the committee were actively involved in reviewing materials developed for this IRIS document and preparing the Synthesis and Recommendations.

The University of Manitoba team has also provided updates on the IRIS process and document to interested regional organizations and stakeholders, including the [West] Hudson Bay Neighbours Regional Roundtable, Winnipeg Manitoba (April 12–13, 2018), the Hudson Bay Summit, Montréal, Québec (February 27–March 1, 2018), [West] Hudson Bay Neighbours Regional Roundtable, Churchill, Manitoba (February 11–12, 2016), Manitoba Hydro Meeting, Winnipeg, Manitoba (August 12, 2015), and the East Hudson Bay/James Bay Regional Roundtable, Chisasibi, Québec (November 7–9, 2016).

An aerial photograph of a vast sea of icebergs. The icebergs are of various sizes and shapes, some appearing as large, flat sheets and others as more jagged, blocky chunks. The water is a deep, clear blue, and the sky is a pale, hazy blue, suggesting a bright but slightly overcast day. The overall scene is one of a remote, cold, and desolate environment.

# **SCIENCE-TO-POLICY SYNTHESIS:**

**KEY MESSAGES AND  
RECOMMENDATIONS  
FOR POLICY MAKERS**

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## INTRODUCTION

The Greater Hudson Bay Marine Region—that is, Hudson Bay, James Bay, Foxe Basin, Hudson Strait and Ungava Bay—is an integral part of both Inuit and Cree homelands. These extensive marine waters and the coastal environments that border on them have supported Inuit and Cree health, livelihoods, mobility, and culture for millennia. For Inuit, movement over the ice and water to harvest marine mammals is integral to culture and health, while coastal, freshwater, and terrestrial areas are of central importance to both Cree and Inuit. Today, there are 40 communities, largely Inuit and Cree, distributed along the coasts of this large marine region. Residents continue to depend on many aspects of the marine system, relying on fish and wildlife for traditional food security, travelling on the coastal waters or the sea ice, and developing a variety of economic opportunities ranging from char fisheries to ecotourism to commercial shipping.



Coastal communities surrounding the Greater Hudson Bay Marine Region have been observing and adapting to environmental changes for some time. Scientific studies looking at these changes and their underlying causes are more recent. The ArcticNet research programme has helped invigorate efforts to observe the Greater Hudson Bay system since 2004. The Integrated Regional Impact Study (IRIS) of the Greater Hudson Bay Marine Region marks the culmination of this programme. As the pace of climate change continues to accelerate, the IRIS aims to provide decision makers at all levels with credible, accessible, context-appropriate information that can be integrated into decision-making processes.

To contribute to evidence-based decision making for this important marine region, this science-to-policy synthesis contains: **1) key scientific findings related to current and anticipated future changes in the Greater Hudson Bay Marine Region**, and **2) recommendations for action directed at policy makers and decision makers**. As one of

four IRIS reports produced by ArcticNet, this IRIS is focused on the marine and coastal environment of the Greater Hudson Bay Marine Region. To develop the key messages and recommendations presented here, the IRIS Steering Committee considered the scientific findings detailed in the topical chapters of the full report together with regional and community priorities. While James Bay was not included in the initial ArcticNet research program, resulting in a scarcity of recent data, it is nonetheless included in the IRIS due to its strong physical and biological linkages with Hudson Bay. It is essential to consider the James Bay and Hudson Bay systems in relation to each other in future research stewardship efforts.

There are numerous jurisdictions with authority over parts of the Greater Hudson Bay Marine Region or its surrounding lands. This complexity is a legacy of inherited federal and provincial boundaries, and the results of initiatives of the Cree and Inuit to assert self-determination through land claim processes. As with all decision making processes, in the management of this Marine Region there are knowledge choke points, where important information is not shared, poorly understood, or culturally divergent. Nonetheless, there is widespread agreement about the need for broadening knowledge bases to support communities as they adapt to ongoing environmental change. Where there is disagreement, climate change adaptation processes must focus on local to global approaches. Regional approaches to resource management are essential to long-term success, and cooperation at high levels is critical for ensuring that regional programs succeed.

The primary audience for this synthesis and recommendations are coastal communities surrounding the Greater Hudson Bay Marine Region in Nunavut, Manitoba, Nunavik and Eeyou Istchee in Québec, and Mushkegowuk region of Ontario and their respective governments and land claim organizations. The audience includes Nunavut Tunngavik Incorporated, Makivik Corporation, Kativik Regional Government, Cree Nation Government (Québec), Mushkegowuk Council, and the Governments of Nunavut, Manitoba, Ontario, and Québec. It also includes the Institutions of Public Government (regional commissions and boards) created by the major land claim agreements, which are charged with responsibilities for implementing wildlife management, land use planning and environmental impact assessment throughout much of the region. The synthesis and recommendations are also directed at the relevant departments of the federal government and stakeholders ranging from non-governmental organizations, to marine transportation companies, hydroelectric utilities, and resource development groups, and to organizations such as the Arctic Council, Inuit Circumpolar Council (ICC) and Inuit Tapiriit Kanatami (ITK)—all of which may make decisions that have consequences for the region. These decision makers can



and should respond to current and projected future changes in the Greater Hudson Bay Marine Region in a way that supports the ecological integrity of the marine area and bolsters the sustainability, wellbeing, and adaptive capacity of communities that depend on it. The document also seeks to inform those involved in ongoing and future research and monitoring enterprises. With all the complexities caused by interjurisdictional challenges, differences in land claim implementation and

community capacity for engagement across this vast region, it is particularly important that researchers and practitioners seek to find common ground and bridge differences both in the arena of knowledge acquisition and policy development.



L. CANDLISH



LANDSAT-7/U.S. GEOLOGICAL SURVEY



F. WANG

## KEY MESSAGES AND RECOMMENDATIONS

### Knowledge of the physical environment

Scientific observations confirm that the climate has changed in the Greater Hudson Bay Marine Region during the last 30–40 years. Winter air temperatures monitored at coastal stations have become warmer and/or more variable and the open-water season has increased by 3–5 weeks. People living in the region have observed these changes firsthand as a longer open water season along the coast, less predictable weather and coastal sea ice conditions. There have also been increases in the frequency and severity of extreme events including entrapments of wildlife in sea ice and winter rain.

During the same period, river flows and properties of wetlands/peatlands have changed due to climate warming, hydroelectric development, and other human activities. Hydroelectric development, including the cumulative effect of river diversions, along the Nelson and La Grande systems has significantly increased river flows in winter, while decreasing flows in spring and summer. These rivers also experience short-term fluctuations in flow. Regulation also affects the flows of the Churchill River in Manitoba, the Moose River in Ontario and the Eastmain, Rupert, La Grande, Caniapiscau, and Koksoak rivers in Québec. Inuit and Cree encounter unpredictable water levels in the lower reaches of some river systems. The changes in the watershed also affect the salinity of coastal waters, ice conditions, and transport of sediment, nutrients and carbon. However, these complicated land-ocean interactions are the most difficult to assess, and an assessment of the combined effects of modified river flows, together with climate change, has yet to be accomplished.

Although climate models and appreciation of their uncertainties are still evolving, several climate scenarios (representations of future climate) have been produced for the watershed of the Greater Hudson Bay Marine Region during the last decade. With fairly high confidence, model projections for 2050 show a general warming of winter air temperatures (5–7°C) in the watershed. Increasing precipitation during winter is likely both in Nunavik and the Kivalliq region. Summer precipitation is projected to increase slightly only in these northern regions of the watershed. The predicted overall effect of these changes is an increase in annual (and winter) runoff in Nunavik, eastern James Bay and the Kivalliq region. Changes in precipitation and evapotranspiration are more uncertain than changes in temperature and the two factors together will determine future runoff.

Regional sea ice–ocean models projecting future ocean conditions are still at an early stage for the Greater Hudson



J. EHN

Bay Marine Region. In this region, models have been applied to predict impacts of atmospheric warming without taking into account changes in river runoff. In a scenario with regional air temperatures increasing by 4°C, models indicate that the sea-ice season would be reduced by 7–9 weeks and summer sea-surface temperatures would increase by 3°C in central Hudson Bay and as much as 5°C in southeastern Hudson Bay, along the Nunavik coast and in James Bay. If these changes come to pass, they may lead to altered ocean circulation, changes in seawater pH, changes in nutrient and oxygen distribution and impacts on the food web.

The ability to monitor climate change at a regional level is strongly dependent on the availability, distribution and effectiveness of climatological stations. Along the coastlines of Hudson Bay, James Bay, Foxe Basin, Hudson Strait and Ungava Bay, relevant stations are too few in number and unevenly distributed. There are also major hydrographic regions for which reliable runoff data are scarce or non-existent, which limits analysis of changing precipitation and runoff relationships. The lack of long-term climate, precipitation, and runoff monitoring stations reduces the ability to evaluate regional climate change models and determine regional climate trends. Similarly, ocean moorings (observatories) are needed to monitor and track changes in the properties of offshore and basin waters.

Inuit and Cree who hunt, fish and travel on the coastal waters and sea ice have observed significant changes in recent decades, such as unprecedented rapid freezing of the biologically-important flow leads and polynyas in the Belcher Islands area of southeast Hudson Bay. However, there have been few scientific studies of coastal ice and ocean processes and the influence of hydrologic change.

- **Gaps in our understanding of the coastal ice-ocean system and impacts of increased winter river inputs should be addressed through scientific studies, application of Cree and Inuit knowledge, and studies in which there is opportunity for co-development of knowledge such as collaborative community-based monitoring programs.**
- **Existing networks for gathering long-term meteorological and hydrological data should be critically reviewed and augmented as required to improve spatial distribution.**
- **Climate information and expertise needs to be made available to regional policy makers to support adaptation to climate change.**



J. HIGDON

## Ecosystems, fish and wildlife monitoring and management

Marine plant life, including microscopic algae, kelp, and coastal eelgrass, support the diverse food webs that occur throughout the Greater Hudson Bay Marine Region. In coastal areas, plants receive some of the nutrients they need from rivers. However, further away from the river mouths, the fresh river water forms a cap over the system that prevents deep ocean nutrients from mixing up into the upper sunlit layer of the water column, where algae can grow. For these reasons, the productivity of the ecosystem (abundance of marine life) varies throughout the region, from high in Hudson Strait and southern Foxe Basin to moderate in coastal Hudson Bay and very low in the offshore waters of Hudson Bay.

Although very little is known about the oceanography of James Bay, the productivity in offshore waters appears to be low. Coastal eelgrass ecosystems that were once highly productive declined during the 1990s and have not fully recovered. In relation to future climate change, it is expected that changes in the physical environment (ice, salinity and temperature and other properties of the water) will lead to changes in plant ecology and organisms at the base of the food web, which will then influence higher levels of the food web including fish, birds and marine mammals that are harvested.

Coastal and marine fish species vary greatly throughout the region and this variation is reflected in the subsistence fisheries as well as the commercial fisheries in the Kivalliq region and Hudson Strait. There has been a shift in the presence and abundance of some fish species and locally there are observations of new species not normally found in those areas.

However, relatively little is known about the biodiversity, distribution and abundance of coastal fish and invertebrate species, nor the life histories of the key anadromous species in the region.

- **Baselines need to be established for both fish and aquatic invertebrates and more monitoring is required, particularly in what are predicted to be the most affected areas.**
- **More ecological studies including fish and invertebrates should be conducted in coastal areas because of their particular sensitivity to climate change.**

The coasts of the Greater Hudson Bay Region are critical to several bird species. Populations of these species are changing due to a combination of factors, some of which are not specific to this region. In some areas, populations have grown and are negatively impacting shoreline habitat. In other areas, populations have decreased and/or migratory routes have changed, which has impacted subsistence harvesting.

- **Data collection at long-term seabird monitoring stations should be continued and expanded to other sites to improve the spatial distribution of information.**
- **Additional bird surveys should be conducted to better understand bird movements and population dynamics. Additional studies should also be conducted to improve knowledge of habitat use.**
- **Community capacity building should be supported to allow increased collaboration among communities**



K. ELLIOT

**and regional, national and international institutions in relation to bird monitoring efforts, particularly in relation to larger scale efforts to understand shorebird and songbird ecology and impacts of climate change.**

Decreases in summer sea ice concentration and changes in winter ice distribution and thickness are expected to affect all of the marine mammal populations in the Greater Hudson Bay Marine Region including the ice adapted whales, beluga, narwhal, and bowhead whales, the ice adapted seals (ringed and bearded seals), and the walrus. Marine mammal migration behaviour is affected by changing water temperature, diets are expected to shift with changing food availability, and expansion of the range of the killer whale into the region's waters could affect beluga, narwhal, and bowhead numbers. Decreases in the health and abundance of whale, walrus, and seal populations will affect people's ability to find and use these resources, impacting traditional subsistence harvesting.

- **Regional studies are required to understand the importance of specific habitats to marine mammal use (e.g., estuaries, sea ice, migration corridors).**
- **Relevant scientific studies and maintaining long-term monitoring programs are important and should be**

**continued to help predict how changes in climate will impact the region's marine mammal populations.**

- **Management strategies should be reviewed with the inclusion of communities and Cree and Inuit knowledge to address issues as they arise.**

Because of the fundamental relationship between the welfare of polar bears and sea-ice availability, scientific consensus is that continued warming and declines in the seasonal extent and thickness of sea ice may negatively affect polar bears over the long term. However, negative effects of warming have not been documented on some polar bear subpopulations and other subpopulations are apparently still faring well. Local Inuit knowledge from Inuit in Nunavik and the Kivalliq region of Nunavut have been documenting greater numbers of polar bears over the last half century and report that overall the observed polar bears seem healthy. Polar bears continue to be important to Inuit in regards to culture and mental health, safety, sustenance, and economy.

- **Polar bears and other wildlife made vulnerable in the long term by anthropogenic climate warming are a reminder about the local impacts of global actions/inactions.**
- **Wildlife boards and other agencies mandated with polar bear management need access to the best available scientific information and Inuit and Cree knowledge to inform their decision-making processes.**



L. CANDLISH



C. HORNBY

## Parks and protected areas

Although several land-based parks in the Greater Hudson Bay Region include coastal areas, there are as yet no marine protected areas. Concerted efforts are required by planning partners to identify and move forward with proposals for marine protected areas that protect ecological integrity and reflect areas that are considered important by Inuit and Cree for food security and cultural identity. Parks and marine protected areas, when created, will have a positive impact on biodiversity, education, and conservation.

- **In the creation of parks and marine protected areas, local educational benefits should be maximized, together with biodiversity and conservation.**
- **Inter-jurisdictional coordination for the development and management of parks and protected areas needs to be improved.**
- **Indigenous protected areas should be explored as a new conservation tool to include Cree and Inuit knowledge in shaping conservation objectives and share decision-making among all key parties.**



L. CANDLISH

## Transportation and safety

Due in part to the lengthening open-water season, there has been an increase in the number of vessels coming into the Greater Hudson Bay Marine Region each year. Increased ship traffic means there is increased risk of accidents and spills. For communities, changing ice conditions, weather events, lack of infrastructure and shortage of baseline and real-time information about conditions make travel on the ice and coastal waters less safe. Most communities in the region have very limited marine transportation infrastructure. Search and rescue capability and emergency response capacity within the region is also very limited.

- **Ice is critical travel infrastructure for communities. Remote sensing and other real-time observation tools (weather cameras) can complement community observations to help communities adapt to the changing ice and weather conditions. To improve the safety of travel, there is a need to further develop both these tools and the capacity to use them.**
- **The deterioration and thinning of ice cover particularly near river mouths is a significant factor in local and coastal travel. Plumes of relatively warm water released in winter from reservoirs used for hydro-electric energy production can impact the safety of travel. The La Grande Complex in northwest Québec could be used as a case study to understand the practical challenges faced by communities downstream from such developments and to identify adaptation strategies.**
- **For safety and marine access, priority should be given to maintaining community infrastructure in Nunavik, and assessing needs and constructing infrastructure as required in Nunavut and James Bay communities.**
- **Regulations and protocols related to major transportation corridors and cruise ships should be regularly reviewed with community and regional input.**
- **Regional and local search-and-rescue capabilities and coordination must be improved. Risk reduction and emergency preparedness plans must be a priority.**
- **The regional importance of the rail line to Churchill and associated deep-water port must be recognized and its future security ensured.**



M. KAMULA

## Contaminants

Contaminants are present in the Greater Hudson Bay Marine Region as they are throughout the North due to both local and distant sources (i.e., air pollution). Through existing programs, several species are being monitored at a few sites. Regulations are helping to reduce sources of mercury and the concentrations in some wildlife tissues have begun to decrease. There are no public health advisories associated with fish consumption in either Nunavik or Nunavut. However, in northern Ontario and Québec along the western James Bay and Hudson Bay border, where there is a long history of industrial activities in the watershed, mercury concentrations remain elevated in some inland fish and wildlife and numerous consumption advisories are in effect. There are also new and emerging contaminants that have been found throughout the region and further research is needed to understand the impact of these contaminants on the environment, wildlife and people.

- **Current efforts to monitor contaminants in this region through programs such as the Northern Contaminants Program and other initiatives should be continued.**
- **Regional action plans that will communicate about the risks associated with contaminants should be developed with appropriate communities and health professionals.**

- **Canada's implementation of the United Nations' *Minamata Convention on Mercury* should include continued support for research and monitoring to address remaining uncertainties, in particular those related to mercury cycling in subarctic ecosystems and methylmercury toxicology.**
- **Efforts to reduce and eliminate the use of lead shot should be continued and supported as lead has negative effects on the environment and human health.**



J. DUROIS / ARCTICNET



## Tourism

Tourism is of emerging economic importance within most communities in the Greater Hudson Bay Region and the ecotourism industry is growing and diversifying. However, an increase in tourism in the region may have adverse impacts on small communities and wildlife and most communities need better infrastructure to receive tourists.

- **There should be investment in tourism infrastructure, including parks, to encourage tourism and increase local benefits and opportunities.**
- **Regional protocols to manage tourism in relation to respect for culture, capacity, and wildlife should be developed.**
- **Steps should be taken to encourage the integration of western and Indigenous knowledge as part of ecotourism activities when and wherever practical.**



L. CANDLISH

## Research and monitoring processes

There is tremendous value in communication and collaboration between researchers and communities, and among communities within the region. There is also much to be gained by the co-production of knowledge. Given the rapid rate of change in the Greater Hudson Bay Marine Region and in all Arctic regions, relevant knowledge informing Arctic adaptation actions and policies is required in accessible formats as soon as it is produced.

- **Cree and Inuit knowledge and knowledge holders should be included early in research processes, and specifically in the identification of knowledge gaps and research priorities. Processes for appropriate inclusion of Indigenous knowledge must be determined in partnership with communities and knowledge holders.**
- **Sponsors of research and monitoring programs should provide better support to community-researcher partnerships to improve capacity for community involvement in research and help sustain community-driven programs.**
- **Indigenous peoples' ownership of their traditional and living Indigenous knowledge should be recognized. Through a living data management plan, data ownership and data licenses should be discussed and clearly laid out during research partnerships.**
- **Plans for communication of research results should be developed with local and regional guidance.**
- **Having forums such as Regional Roundtables and Summits, to share information across jurisdictions on a regular basis, would be beneficial.**
- **Knowledge mobilization efforts such as those undertaken by ArcticNet need to be maintained over the long term and adapted to respond quickly and efficiently to the evolving needs of decision makers and end-users of the research.**





HUDSON'S BAY COMPANY ARCHIVES, ARCHIVES OF MANITOBA

## Introduction

# For Inuit and Cree, These Waters Are Home: An Introduction to the Greater Hudson Bay Marine Region and its Peoples

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## 1. Introduction

**T**he Greater Hudson Bay Marine Region (“the Marine Region”)—comprising Hudson Bay, James Bay, Foxe Basin, Hudson Strait and Ungava Bay—occupies an area of 1.3 million km<sup>2</sup>. For scale, this vast area is equivalent to nearly a fourth of the total surface area of Canada’s oceans and Great Lakes, or just over one-eighth of Canada’s land mass. The Marine Region has a nearly complete sea ice cover between November and June and becomes ice-free each summer. A massive amount of freshwater enters the Marine Region from its large watershed, which covers a third of the Canadian land-mass, as well as seasonal sea ice melt. The sea ice is a central component of the ecosystem, providing habitat for wildlife and a critical platform for harvesting and travel for residents of the area. Because of the large spatial extent of the Marine Region, the ecosystems and food webs are broad and varied, with both year-round presence and seasonal abundances of fish, birds, and marine mammals.

The significance of environmental change in the Greater Hudson Bay Marine Region is undoubtedly most profound for Inuit and Cree, who have depended on these waters and icescapes for their food, culture and identity, mobility, and livelihoods for millennia. While Inuit terrestrial and freshwater land use is extensive, Inuit are primarily known as people of the sea ice; Inuit expertise regarding the Arctic marine environment is inseparable from the importance of marine mammals to Inuit diets and culture. For Cree living around Hudson and James Bays (Mushkegowuk or Swampy Cree in western James Bay and the Hudson Bay Lowland, and Eeyouch in Eeyou Istchee around eastern James Bay and southeastern Hudson Bay), the muskeg or wetland—and the wildlife that uses it—is of critical importance. Cree land use predominantly revolves around the coastal and freshwater environments along the Bays, but also extends for hundreds of kilometers inland from the coast. Currently, forty communities are located on or near the shores of the Marine Region (Figure 1); of these, 25 are Inuit communities (11 in Nunavut; 14 in Nunavik, Québec), 13 are Cree First Nations





FIGURE 1. Communities located on or near the shores of the Greater Hudson Bay Marine Region.

(five in Eeyou Istchee, Québec; two in Manitoba; six in Ontario), and two are municipalities with significant Indigenous populations (Churchill, Manitoba and Moosonee, Ontario).

Inuit and Cree communities have maintained detailed knowledge of and a close relationship to their environment despite experiencing significant disruptions to their societies stemming from varied government policies of colonization and assimilation. These distinct histories have led to the different levels of political autonomy and different socio-economic realities in communities and jurisdictions around the Marine Region. In recent decades, Indigenous efforts to assert rights to self-determination and concurrent northern expansion of resource development activities have led to the settlement of large comprehensive land claims in Nunavut, Nunavik, and Eeyou Istchee with associated changes to governance and resource management structures. Large-scale hydroelectric

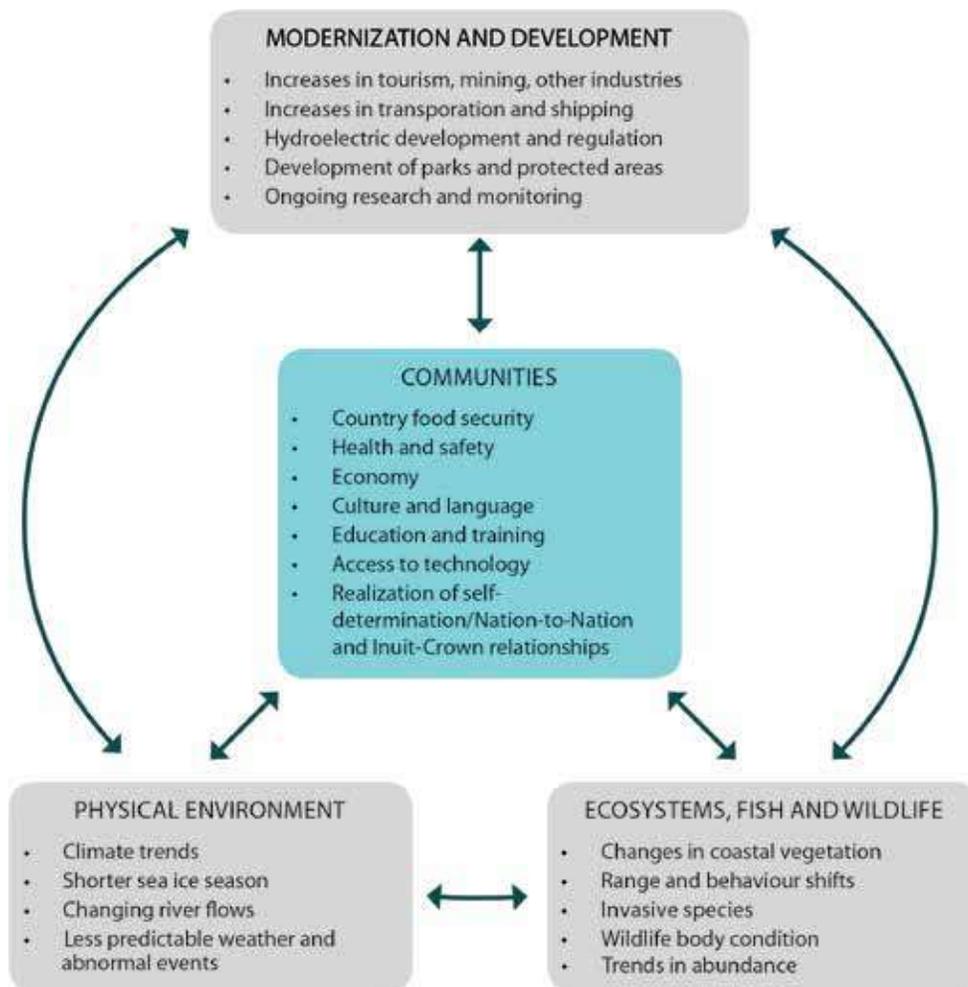
energy projects have been or are currently under development on a number of rivers in southwest Hudson Bay and James Bay, manipulating river inflow and likely producing significant change in the near shore oceanography of these systems. At the same time, the marine area has experienced increases in shipping related to mining and commercial activities. Economic and cultural globalization has also been contributing to changes in the ways of life for communities along the Marine Region's coasts.

Intersecting with these social, political and economic changes are growing impacts of climate change. The Greater Hudson Bay Marine Region supports the most southern Arctic marine ecosystems in the world, increasing its vulnerability to the strong climate signal already evident in the Arctic. Projections of future climate change, while uncertain in the timelines and the details at the local scale, are all in agreement

that it will continue to get warmer in the Greater Hudson Bay Marine Region. The warming and associated changes in the watershed and ice-ocean system will have far-reaching consequences for physical and biological processes in the Marine Region as well as for communities, in relation to critical issues such as food security, culture, infrastructure, and transportation and safety. Adaptation is not new to Inuit and Cree communities around the Marine Region; adaptive and innovative practices to address environmental change have been integral to prospering in a challenging Arctic and sub-Arctic environment and are embedded in Inuit and Cree knowledge systems. In a context of already immense socio-economic shifts, there is a need to build on the strengths of Inuit and Cree communities to support them as they continue to respond to impacts of climate change and other types of environmental change.

Strengthening adaptive capacity requires that communities and decision makers at all levels have accurate and contextually-appropriate knowledge of current and anticipated future changes to the natural environment and their consequences for human society.

This IRIS aims to address the knowledge gaps for the Greater Hudson Bay Marine Region and to strengthen evidence-based decision making by broadening and integrating knowledge bases. Figure 2 shows the relationships envisioned between the three main knowledge areas addressed by the chapters in this IRIS (Physical Environment; Ecosystems, Fish and Wildlife; and Modernization and Development) and key community priorities and concerns. The intended audience of the IRIS is diverse, from regional decision makers to newcomers to Hudson Bay, and the text thus strives



**FIGURE 2.** Inter-relationships among community priorities and the three knowledge areas addressed in the chapters of this IRIS: the Physical Environment, Ecosystems, and Modernization and Development.

to strike the appropriate balance between accessibility and technical details. As knowledge of many aspects of this vast and complex marine region remains limited, this IRIS is but a first step in consolidating knowledge for this region. However, in providing this first step, the IRIS lays a foundation for building better linkages between increasing knowledge of the marine and coastal environments of the Greater Hudson Bay Marine Region and the strong human connections and implications of this knowledge.

This chapter provides background and context for the chapters in this IRIS. It provides a descriptive overview of the geography and biophysical traits of the Hudson Bay IRIS study region; a brief introduction to Indigenous knowledge and land use in the region as well as issues and pressures driving change; an overview of key governance elements; and a brief socio-economic overview.

## 2. The geography of the Greater Hudson Bay Marine Region

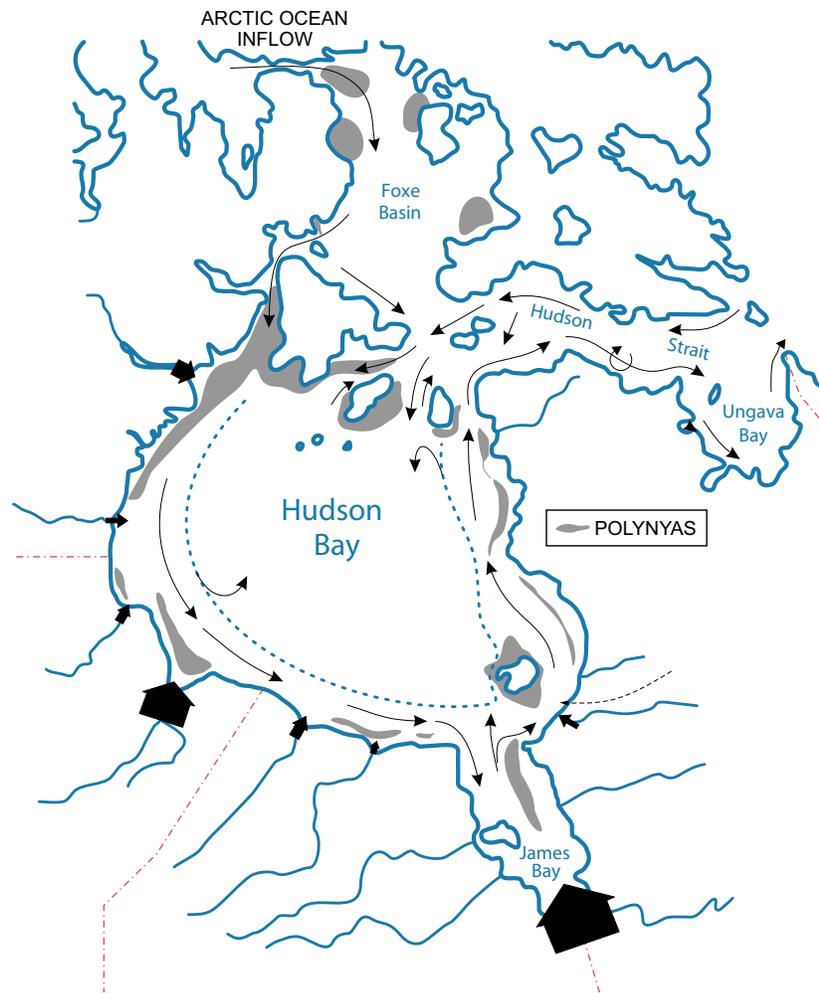
As a whole, the Greater Hudson Bay Marine Region represents one of the largest inland seas in the world (Figure 3). Its nearly complete ice cover during the winter and nearly ice-free condition in summer make it unusual among the world's oceans. It is also defined by the large volume of freshwater runoff it receives. The total drainage basin (about 3.8 million km<sup>2</sup>) is the largest watershed in Canada, extending over five Canadian provinces (Alberta, Saskatchewan, Manitoba, Ontario, Québec) and into the Northwest Territories and Nunavut. The terrestrial catchment is larger than the combined St. Lawrence and Mackenzie River watersheds and represents an area about four times the size of Hudson Bay. From this extensive catchment area, approximately 960 km<sup>3</sup> of freshwater drains into the Marine Region annually (see Theme I. Chapter iv). The Marine Region is unusually cold relative to other areas at the same latitude, particularly in its southern reaches, because of the cold Arctic waters and seasonal sea ice cover. There is extreme variation in the range of average temperatures and total precipitation, both seasonally and annually. There is typically less than 200 mm of precipitation in the northwest compared to over 800 mm per year in the southeast (Stewart and Lockhart 2005), although climate change is modifying these averages. There is also strong regional asymmetry in sea ice, with thicker ice cover in the eastern part of Hudson Bay compared to the northwestern region and Foxe Basin because of ice movement and drift (Landy et al. 2017). The sea ice is important both as a seasonal source of freshwater (sea ice melt), which adds to the river runoff present in the surface layer of the ocean (see Theme I. Chapter v.); and as a central component of the



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ecosystem, providing habitat for wildlife such as seals and polar bears, and finally as a critical platform for harvesting and travel for residents of the area.

The coastal domain, herein defined as the region within which terrestrial and marine ecosystems connect (Carmack et al. 2015), is very important within the Greater Hudson Bay Marine Region. In addition to the shores of Foxe Basin, Hudson Bay, James Bay, Hudson Strait, and Ungava Bay there are thousands of islets and islands making a vast near shore zone, where fish, seabirds, ducks and geese, and marine mammals all tend to be most abundant. It is also the most important area for activities of the human population. The coastline varies from steep and rugged areas that are cut into Precambrian bedrock, to flat-lying areas of gentle gradients and expansive tidal flats. A common factor along the entire coast is emergence due



**FIGURE 3.** Overview of circulation in the Greater Hudson Bay Marine Region (after Macdonald and Kuzyk 2011). Black arrows represent regional distribution of river runoff. Grey shading represents polynyas and leads.

to isostatic rebound, as the land continues to respond to the disappearance of the ice sheet that occupied this area more than 8,000 years ago (Martini 1986). The rate of uplift is highest in the southern parts of region at approximately 0.75–1.0 m/century (Sella et al. 2006). The rebound of the land means that coastal areas are affected by falling relative sea level, in contrast to most other northern coastal areas (e.g., Beaufort Sea). Eventually, global eustatic sea-level rise due to global climate change may reverse this trend but not within the next 100 years (Allard, personal communication).

In the marine environment, the properties of the coastal domain are spatially variable and determined in large part by the aggregate of river runoff which brings not only freshwater but also heat, nutrients and carbon into the coastal waters. The coastal waters circulate around the system in a cyclonic

(counter-clockwise) direction, gradually accumulating freshwater as they flow from Foxe Basin and northern Hudson Strait into northern Hudson Bay, around Hudson Bay and James Bay, and ultimately flow through southern Hudson Strait into the North Atlantic (Figure 3). The waters of the coastal domain are modified in other ways during this transport, particularly by ice formation during winter, which ejects salt into the surface waters underneath the ice (Granskog et al. 2011). The sea ice melt and formation cycle, together with river runoff, contributes to regional differences in coastal water properties, such as winter stratification in southeast Hudson Bay (Eastwood et al. submitted). Compared to offshore waters, the coastal waters are generally fresher and more nutrient- and carbon-rich and provide a coastal pathway for the dispersal and migration of marine biota. It is thought that the coastal domain

**TABLE 1.** Characteristics of the Greater Hudson Bay Marine Region

Area ( $\times 10^3$ km <sup>2</sup> )		
Foxe Basin	~200	Defossez et al. 2010; Ingram and Prinsenberg 1998; Saucier et al. 2004
Hudson Bay	~810	
James Bay	~60	
Hudson Strait (including Ungava Bay)	~200	
<i>Greater Hudson Bay Marine Region</i>	~1270	
Mean Depth (m)		
Foxe Basin	90	Defossez et al. 2010; Saucier et al. 2004; Straneo and Saucier 2008
Hudson Bay	125	
James Bay	20	
Hudson Strait (excluding Ungava Bay)	300	
Maximum Depth (m)		
Foxe Basin	450	Defossez et al. 2010; Saucier et al. 2004; Straneo and Saucier 2008; *note that depths >300 m were found in Wager Bay
Hudson Bay	220*	
James Bay	60	
Hudson Strait (excluding Ungava Bay)	900	
Drainage Basin Area ( $\times 10^3$ km <sup>2</sup> )		
Foxe Basin	~260	Déry et al. 2011; Theme I. Chapters iv. and v.
Hudson Bay	~2575	
James Bay	~718	
Hudson Strait (including Ungava Bay)	~433	
<i>Greater Hudson Bay Marine Region</i>	~3900	
Freshwater Inflow (km <sup>3</sup> yr <sup>-1</sup> )		
Foxe Basin	40	Déry et al. 2011; Theme I. Chapters iv. and v.
Hudson Bay	388	
James Bay	326	
Hudson Strait (including Ungava Bay)	161	
<i>Greater Hudson Bay Marine Region</i>	915	
Average Sea-ice Thickness in April (m) (2003-2016)		
Foxe Basin	2.12	Galbraith and Larouche 2011; Granskog et al. 2011; Prinsenberg 1984; Sibert et al. 2010; Landy et al. 2017
Hudson Bay	1.45	
James Bay	1.44	
Hudson Strait (including Ungava Bay)	1.59	

and associated waters may become even more prominent in physical, biological and biogeochemical processes as terrestrial runoff, permafrost thaw and northward vegetation shifts increase in the future (Carmack et al. 2015; Macdonald et al. 2015).

The ecological importance of the coastal domain within the Greater Hudson Bay Marine Region cannot be overstated. In James Bay and southern Hudson Bay (Hudson Bay Lowland), extensive wetlands support a diverse flora and fauna; these areas are of international importance because they contain critical breeding and feeding grounds of migratory birds. In northern Hudson Bay and Foxe Basin, the coastal waters and islands host great numbers of marine mammals and seabirds. Understandably, it is the coastal areas within this Marine Region that matter the most to the Region's Inuit and Cree communities.

Although there are close oceanographic ties between Foxe Basin, Hudson Bay, James Bay, Ungava Bay and Hudson Strait, each of the water bodies represents a distinct oceanographic bioregion (Dunbar 1982; Table 1). There is a diversity and broad range of ecosystems contained within each bioregion, supported by the unique habitats created by environmental factors. The various physical and ecological characteristics of each region are reflected in the lifestyles of the people who live there.

## 2.1. Foxe Basin

Foxe Basin is a large basin, 550 km long and 360 km wide, in the most northerly part of the Greater Hudson Bay Marine Region (Figure 3; Table 1). It is located between Baffin Island and Melville Peninsula within the territory of Nunavut, and is



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### Igloolik, Nunavut

crossed by the Arctic Circle (66.56°N). Two Inuit communities in Nunavut's Qikiqtani Region—Igloolik and Hall Beach—are located on its shores. Foxe Basin is connected to the Arctic Ocean via the Gulf of Boothia and Fury and Hecla Strait, to Hudson Bay via Roes Welcome Sound and the strait between Southampton Island and Nottingham Island, and to the Labrador Sea via Hudson Strait.

Sea ice dominates the waters of Foxe Basin for much of the year, with most of it being first-year ice. Open water typically appears in the northwestern part of the Basin around May, ice break-up typically occurs around late July, and freeze-up typically begins in October (Laidler et al. 2009). In the summer, second and multi-year ice frequently enters the Basin from the Gulf of Boothia, through Fury and Hecla Strait. The same channels bring in Arctic Ocean waters and shape Foxe Basin's marine character (Figure 3).

Foxe Basin may be divided into four parts (Prinsenberg 1986; Defossez et al. 2008). The northeastern part is less than 50 m deep. In this section of the basin, strong tides and wind-induced currents result in sediment being stirred up during the fall and incorporated into the growing ice layer. Discoloured ice and sediment-laden water is commonly seen in the spring when melting begins (Markham 1986). The western part along Melville Peninsula is a shallow, widening and gently sloped channel reaching 100 m in depth. A large amount of ice is produced in the leads (polynyas) that occur in this western part of the Basin, particularly in the vicinity of Hall Beach and at Lyon Inlet (Defossez et al. 2008; 2010). The third part of the Basin is Foxe Channel, a channel 400 km long and 100 km wide that reaches depths of 450 m. The cold brine-rich (salty)

water produced in association with the rapid ice formation in the polynyas along Melville Peninsula sinks down to form the deepest water mass in Foxe Channel and possibly overflows to form the deepest waters in Hudson Bay. The fourth, smaller but relatively deep (~200 m) part of Foxe Basin is called Repulse Bay and lies in the southwest part of the basin where it connects to Hudson Bay via Roes Welcome Sound. The community of Naujaat is situated in Repulse Bay.

Although very little is known about primary productivity and the lower trophic levels of the food web, Foxe Basin contains a great diversity of marine mammals. This includes walrus and narwhal, which are an important food resource for Inuit in the surrounding communities of Igloolik and Hall Beach as well as other nearby communities, such as Naujaat. The ice forms a hunting platform from which walrus, ringed seal, bearded seal, and polar bear are harvested (Ford et al. 2009). Numerous studies of Inuit sea ice use around Foxe Basin have documented observations of changing ice conditions since the mid 1990s, which correspond to ice and weather data showing later ice freeze-up, earlier break-up, and changes in ice dynamics (Ford et al. 2009; Laidler et al. 2009; Laidler and Ikummaq 2008).

## 2.2. Hudson Bay

Hudson Bay is an estuarine system of approximately 830,000 km<sup>2</sup> with a mean depth of about 125 m (Table 1). Numerous jurisdictions are located along its shore. Along the northwest border are six Inuit communities in the Kivalliq region of Nunavut, while Churchill is the only community in Manitoba directly on the Bay. On the southwest Ontario shore are two Cree First Nations, with another Cree First Nation on the southeastern shore in Eeyou Istchee, Québec. Along the eastern coast are six Nunavik, Québec communities, while Sanikiluaq, a Nunavut community, is located on the southeastern Belcher Islands.

At its northern end, Hudson Bay receives inflows from Foxe Basin around Southampton Island through Roes-Welcome Sound and also from western Hudson Strait (Prinsenberg 1987, McDonald et al. 1997). Within Hudson Bay, waters circulate counter-clockwise. Flow in the northwest is generally southward past the Nunavut communities along western Hudson Bay down past Churchill. The coastal waters become strongly diluted by river runoff in southwestern Hudson Bay and then progressively more diluted in southeastern Hudson Bay after they are joined by James Bay outflow (Figure 3). Excluding the runoff into James Bay, Hudson Bay receives approximately 400 km<sup>3</sup> of river runoff annually. About 34% of that runoff comes in along the northwest shore, 50% along the southwest shore, and the remainder (16%) along the east shore (Theme I, Chapter v.). Thus, northern Hudson Bay is often considered a

separate bioregion from southern/southeastern Hudson Bay, which accumulates of all the 'upstream' discharge in Hudson Bay as well as discharge through James Bay.

*The rivers really boost the marine current system because so many of them flow into Hudson Bay. The freshwater pushes the sea water, and the volume of water coming in from the rivers makes the currents stronger.* (Lucassie Iqaluk, Inukjuak and Joshua Sala, Umiujaq, quoted in McDonald et al. 1997, p. 11)

Because of the cold inflow of marine waters from Foxe Basin and north Hudson Strait, northwestern Hudson Bay is very much an 'Arctic' marine ecosystem. It has the earliest dates of freeze-up and highest rates of sea ice production within Hudson Bay (Landy et al. 2017). The coastal waters are believed to be very productive, and seals and other wildlife are abundant. Offshore areas of northern Hudson Bay reach maximum water depths of about 220 m (Table 1) but a deeper basin of over 300 m has been found recently in Wager Bay, an inlet along the northwest coast and the site of Ukkusiksalik National Park in Nunavut.

The southern Hudson Bay marine ecosystem is shallower and more dilute than the northern part. Freshwater runoff from

the land is a defining characteristic and a variety of warm-water plant and animal species are found there that are absent elsewhere in Canada's Arctic waters (Stewart and Lockhart 2005). Large estuaries provide vital habitat for anadromous fishes and in some cases beluga whales. For example, the number of belugas in the area of the Nelson River estuary in July 1987 was estimated at 19,500 animals, which is the largest reported single concentration of belugas in the world (Stewart and Lockhart 2005 and references therein). The flow regimes of the Churchill and Nelson rivers, which drain into southwest Hudson Bay, have been significantly altered by hydroelectric developments.

In winter and early spring, ice floes are kept in constant motion by the wind; winds blowing offshore create leads, which are important habitats for overwintering species such as eiders and migratory birds and mammals (Stewart and Lockhart 2005). There are a number of recurring polynyas present, including around the Belcher Islands, near islands along the coast of southeastern Hudson Bay, in Roes Welcome Sound and near Coats Island, which also create important habitats. Predominance of westerly and northwesterly winds also push ice towards the eastern side of Hudson Bay, where it piles up into thick ridges. Because of this ice movement, the spring ice cover is on average 40 cm thicker in eastern Hudson Bay



Arviat, Nunavut

compared to the northwestern region (Landy et al. 2017). As the sea ice melts in summer, winds also play a role in redistributing it towards the southern part of the Bay.

Presence of and access to wildlife in different parts of the Bay inform harvesting practices. For example, for Inuit in Sanikiluaq, ringed seal, bearded seal, common eider, and sea-bottom animals like mussels and sea urchins are considered dietary staples, and seasonal abundances (e.g., Arctic char in early winter, late spring and summer, Canada goose from spring to fall) inform harvesting patterns (McDonald et al. 1997).

### 2.3. James Bay

On the Ontario and Québec shores of James Bay lie eight Cree communities and one municipality (Moosonee in Ontario). The extensive marine sediments deposited during the retreat of the Laurentian ice sheet and the marine invasion associated with the Tyrrell Sea define the coastal ecosystems of southern James Bay. There are several major rivers that discharge along the western James Bay coast, including the Attawapiskat, Albany, Moose and Harricana rivers. Strong currents around Cape Henrietta Maria circulate water from Hudson Bay into northwest James Bay, where it continues south towards Attawapiskat, splitting around Akimiski Island (McDonald et al. 1997). On the east side of the island the water turns north, and on the west it flows south towards Moosonee, where currents circulate water northward between islands and along the east coast of James Bay. The largest tidal ranges in James Bay (of the order of 3.5 m) occur near Akimiski Island, compared with two meters on the east coast of the Bay.

In eastern James Bay, hydroelectric projects have altered the flow regimes of the La Grande, Eastmain, and Rupert Rivers. Major river diversions have dramatically reduced freshwater

discharge into the Eastmain, and to a lesser extent, Rupert estuaries, with corresponding increases in flow in the La Grande River system as it received the diverted flows. The La Grande discharge was also augmented by flow diverted from the Caniapiscou Watershed, which formerly drained to Ungava Bay. Flow regulation for optimization of energy production concentrates discharge from the La Grande complex in the months of December to March and largely eliminates the natural spring freshet. The winter discharge of the La Grande River has increased approximately eight-fold (Stewart and Lockhart 2005). Increased methylmercury levels in the La Grande system have been a significant community concern (Rosenberg 1997). There are also concerns about ecological impacts in the coastal waters north of the La Grande due to the altered flows. Furthermore, the distribution of ice cover in winter has been affected by the relatively warm water released in winter from reservoirs of the La Grande system, which must be taken into account in local travel.

James Bay has become increasingly shallow in recent geologic time (last ~8000 years) because of isostatic adjustment. In addition to several thousand small islands, the shallow areas are already dominated with shoals, sandbars and boulders, which make navigation hazardous (Martini 1986). Adding further to these hazards, near the estuaries of the rivers diverted for hydroelectric development, lowered river levels are encountered. In addition to reduced flows, sedimentation patterns may be affected by the disruption of natural processes including high flows of spring freshet and formation of ice-jams (Duboc et al. 2016). Under natural conditions, the breaching of large ice-jams can cause very strong flows that scour the river bed and move sediment further offshore.

Another important feature of James Bay are the rich coastal marshes of the western shore and the subtidal eelgrass beds on the eastern shore, which are both important for migrating Arctic-breeding shorebirds and waterfowl, particularly geese and ducks. These birds are a critical component of local harvests and the way of life for coastal Cree communities. In view of declines in eelgrass (Consortium Genivar-Waska 2017), a collaborative research program was recently launched to improve understanding of the ecology of eelgrass and the relationship with migrating waterfowl in the coastal region of Eeyou Istchee. The program is overseen by a committee consisting of representatives from coastal Cree communities, regional Cree organizations, Hydro-Québec, the Canadian Wildlife Service and others.

In the winter, James Bay is ice covered, similar to Hudson Bay further north. Landfast ice extends offshore in places for distances of 15–30 km depending on the winter, mobile ice lies further offshore, and a lead parallel to the shore opens up intermittently as the mobile ice is blown about by the



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Moosonee, Ontario / Moose Factory, Ontario

wind. River plumes spread more widely under the landfast ice in part because wind-mixing is not influencing the surface waters (Freeman et al. 1982; Ingram and Larouche 1987). Tidal amplitudes and velocities are also dampened by the ice cover (Prinsenbergh 1987). River plumes can also be steered by rough under-ice features. The break-up of coastal fast-ice platforms has ecological implications with regard to the stability of coastal vegetation, including eelgrass.

## 2.4. Hudson Strait

Hudson Strait is a long, narrow and deep channel (200 m in the west, 900 m in the east) that connects Hudson Bay to the Labrador Sea and North Atlantic Ocean (Straneo and Saucier 2008). It is bounded by Baffin Island, Nunavut to the north, including the communities of Cape Dorset and Kimmirut; Southampton Island, Nunavut to the west; and Nunavik, Québec to the south, including the communities of Ivujivik, Salluit, Kangiqsujuaq, and Quaqaq.

Seawater flows west towards Hudson Bay along the north side of the Strait, and a strong coastal current moves water eastward out of Hudson Bay along the southern side (Figure 3). Hudson Strait has large, powerful tides. It is influenced by freshwater runoff into Ungava Bay and low salinity water from Hudson Bay and Foxe Basin, as well as high salinity water from the Labrador Sea.

Hudson Strait is usually ice covered, but the timing of sea ice advance and retreat can vary year to year by up to a month from long-term means. The effects of strong currents in the Strait on ice timing and extent affect land use in communities; for example, hunters in Cape Dorset can use boats year round, so they focus their harvesting efforts along the floe edge and at polynyas, as well as at cracks created by the movement of the ice with the tides (Laidler et al. 2011).

Hudson Strait has a very productive marine ecosystem, with deepwater fish species that are absent in other parts of the Marine Region. It also provides habitat for marine mammals such as whales, seals, walrus and polar bears, as well as numerous waterfowl. The Strait is a significant shipping route, providing access to the remainder of the Marine Region from the Atlantic Ocean. As a result, concerns have been expressed by communities regarding shipping impacts on wildlife and the safety of travel. Communities have also reported observations of environmental changes, including greater weather variability; longer and cooler winters; fewer polynyas; and faster freezing and poorer quality ice, in addition to changes in wildlife population numbers and locations (Furgal et al. 2002; McDonald et al. 1997).

## 2.5. Ungava Bay

Ungava Bay is approximately 50,000 km<sup>2</sup> and generally less than 150 m deep, although depths extend to 300 m in some areas.

It is bounded by Nunavik on its western, southern, and eastern shores, and is open to Hudson Strait in the north. Five Nunavik communities surround the Bay: Kangirsuk, Aupaluk, Tasiujaq, Kuujuaq, and Kangiqsualujuaq.

A number of rivers discharge into the Bay, the major ones being, from west to east: Arnaud, Aux-Feuilles, Koksoak, False, À-la-Baleine and George rivers. The Koksoak River has the largest annual discharge into Ungava Bay and the largest spring freshet due to snow melt (Déry et al. 2005). Since 1982, the flow in the Koksoak has been reduced from natural levels due to partial diversion into the La Grande system to increase hydroelectric energy production.

Tides in Leaf Basin in Ungava Bay may be among the world's highest with a range of up to 16.8 m (Arbic et al. 2007). The funnel-like shape of Ungava Bay contributes to intensifying the tides southwestward to this area. The tides generate strong tidal currents around capes, fjords, straits and estuaries (Drinkwater 1986).

Each year Ungava Bay experiences a seasonal sea ice cycle, where it is completely covered in sea ice during winter and is open water during late summer. The coast is greatly affected by sea ice dynamics (e.g., ice-push, ice-gouging, ice-rafting), which are still understudied, and continually evolving in response to a context of fast climate warming that started in the early 1990s in northern Québec. Sea ice begins to form in late October, and



GOOGLE EARTH

Salluit, Québec



GOOGLE EARTH

Kangiqsualujuaq, Québec

the coastline is usually ice-free in late July. Seal, walrus, beluga, sea-bottom animals such as mussels, and various species of fish are all typically harvested by inhabitants of the Bay (Furgal et al. 2002).

### 3. Indigenous Knowledge, relationships to place, and changes in use of the environment

The description of the physical geography and oceanography of the Greater Hudson Bay Marine Region, above, is important for developing an understanding of the forces that shape this Marine Region. We can broaden and enrich this understanding by turning our attention to the knowledge of Indigenous peoples that have lived in, observed, and relied on the Greater Hudson Bay Marine Region for millennia. Reports such as *Voices from the Bay* (CARC 1997) and publications assembled by wildlife boards and other regional entities (cf., NMRWB 2018) increasingly make this knowledge accessible to researchers as well as decision makers.

#### 3.1. Indigenous knowledge and ways of knowing

There is no one definition of Indigenous knowledge (also referred to as Traditional Knowledge, Traditional Ecological Knowledge, local knowledge and also specific terms related to the Indigenous group that are the knowledge holders). Further, Indigenous peoples have expressed concerns about

the extraction of their knowledge from its context and its use in scholarly definitions and literatures. With these caveats, we provide a modest introduction to Indigenous knowledge to orient readers to Indigenous ways of knowing and what this means for relationships between people and the environment in the Greater Hudson Bay Marine Region. This also provides a context for the Indigenous knowledge reported in the chapters of this IRIS on subjects such as wildlife, environmental conditions, climate change, and paths to a sustainable future in the region.

Battiste and Henderson, both Indigenous scholars, state that while no short answer exists for a definition of Indigenous knowledge, that:

*Perhaps the closest one can get to describing unity in Indigenous knowledge is that knowledge is the expression of the vibrant relationships between people, their ecosystems, and other living beings and spirits that share their lands... All aspects of knowledge are inter-related and cannot be separated from the traditional territories of the people concerned... To the Indigenous ways of knowing, the self exists within a world that is subject to flux. The purpose of these ways of knowing is to reunify the world or at least to reconcile the world to itself. Indigenous knowledge is the way of living within contexts of flux, paradox, and tension... (Battiste and Henderson 2000, p. 42)*

McGregor (2004), an Anishinaabe scholar, describes how in a First Nations context Indigenous knowledge is regarded as a gift from the Creator and provides instructions for appropriate conduct to all of Creation and its beings, including humanity. As McGregor explains, Indigenous knowledge is thus a way of living, based in knowledge passed down over thousands of years, that ensures relationships between Creation and its beings are maintained and enhanced. It is not just a product (knowledge), which is what is most often documented and integrated with Western science; more fundamentally, it is a process of living (i.e., an action) that is rooted in place and cannot be separated from people themselves.

*Inuit Qaujimagatuqangit* (IQ) (meaning Inuit traditional knowledge) is a term with prominence in Nunavut and less frequent use in other Inuit regions. Arnakak describes how the essence of IQ is “healthy, sustainable communities regaining their rights to a say in the governance of their lives using principles and values they regard as integral to who and what they are” (Arnakak 2000, para. 4). For example, these principles include *Avatittinnik Kamatsiarniq* (respect and care for the land, animals and the environment), *Qanuqtuurniq* (being innovative and resourceful), and *Piliriqatigiinniq/kajuqigiinniq* (working together for a common cause) (Government of Nunavut n.d.). Arnakak’s

statement underlines how use of Inuit knowledge comes from and ought to be grounded in personal and community autonomy; this is useful for understanding how Indigenous knowledge can be applied to diverse topics including land use planning, wildlife management and climate change adaptation.

### 3.2. Land use, relationships to place, and implications of changes

Relationships with the land, land and resource use, and implications of environmental changes on land use for peoples living around the Greater Hudson Bay Marine Area have been well documented. For example, studies of Inuit land use and occupancy, including in areas around Hudson Bay, Foxe Basin and Hudson Strait, supported the formation of Nunavut (Freeman 1976). Many studies documented land use and assessed potential hydroelectric impacts in the James and Hudson Bay areas before large hydroelectric projects were established, such as Weinstein's (1976) study regarding land

use of the Cree of Chisasibi. In *Voices from the Bay*, McDonald et al. (1997) describe Cree and Inuit knowledge from communities around the Hudson and James Bay areas related tidal and surface currents, sea ice conditions, food webs, seasonal foods, and environmental values. Other studies have documented Cree knowledge and land use (Berkes et al. 1995; Freeman and Carbyn 1988), Cree knowledge of climate change impacts in James Bay (Tam et al. 2013), Inuit knowledge of sea ice and climate change impacts in Foxe Basin (Aporta 2010, 2004; Ford et al. 2009; Laidler et al. 2009; Laidler and Ikummaq 2008), Inuit knowledge of climate change in Nunavik (Furgal et al. 2002) and Inuit knowledge in marine mammal management (Armitage 2005), amongst many others. Here, we highlight some key points with reference to these topics.

Land-based activities such as hunting, travel on water or ice, trapping and spending time on the land with family rely on Indigenous knowledge and also affirm it. In this way they support culture, identity, and connections to ancestors;



HUDSON'S BAY COMPANY ARCHIVES, ARCHIVES OF MANITOBA



GOOGLE EARTH

### Hall Beach, Nunavut

relationships to place; and holistic health and well-being. Harvesting wildlife also provides material benefits: country food consumption provides nutritional and caloric benefits while harvesting furs and other materials from the natural environment supports livelihoods. Inuit and Cree traditional resource management systems have developed over millennia and continue to be used alongside or integrated into more recently established legal systems and instruments. For example, for Cree of Eeyou Istchee, the system of hunting organization is based around some three hundred distinct hunting territories—generally elongated and aligned east-west—that are identified with distinct families or family groups and a senior hunter who plays a major role in providing access to wildlife resources. The hunting territories generally do not extend to the offshore environment, although there are some exceptions; for example, some families are associated with certain islands. Travel is part of the way of life in Arctic and sub-Arctic regions, based on a close connection to seasonal movement of wildlife. For Inuit, freedom of movement over the landscape, whether land, water, or ice, is culturally significant and important for well-being.

Inuit and Cree use of the environment, while culturally and place-specific, continues to be important to ways

of life around the Marine Region and is a key aspect of the mixed economy. These strong connections have withstood numerous disruptions and pressures, such as more sedentary lifestyles, relocations of families and communities, slaughter of sled dogs, and residential schools (RCAP 1996; Truth and Reconciliation Commission of Canada 2015). These disruptions have not been without serious consequence; many Indigenous communities are working to overcome resulting social, cultural, and economic issues such as intergenerational trauma and breakdowns in intergenerational knowledge transfer of land-based knowledge (see for example, the National Inuit Suicide Prevention Strategy: ITK 2016). For some changes, such as rapid technological change, the implications are more complex, with communities adapting in various ways to maximize benefits of changes (e.g., by using various technologies together with traditional knowledge of the environment to bolster land-based safety in the context of changing environmental conditions) (Aporta and Higgs 2005).

Industrialization and economic development have brought numerous changes. In the context of the Marine Region, the high level of hydroelectric development on rivers that flow into Hudson and James Bays requires specific attention. Hydroelectric development has been ongoing in northern Manitoba since the

1960s, with the diversion of the Churchill River into the Nelson River and the development of six generation stations on the Nelson River, with another (Keeyask) soon to be completed. These developments are dwarfed by the magnitude of the James Bay hydroelectric project in Québec, however. Phase I of the La Grande Complex, completed by 1986, established the Robert-Bourassa, La Grande-3 and La Grande 4 generating stations; five reservoirs; and diversions of the Eastmain (~92%) and Caniapiscou (~32%) rivers into the La Grande River. Phase II of the Complex, completed in 1996, involved constructing five additional generating stations (La Grande-1, La Grande-2A, Laforge-1, Laforge-2 and Brisay) and three new reservoirs. Another hydroelectric development (the Great Whale River project) was anticipated but was suspended in 1996.

In 2002, an agreement between the Grand Council of the Crees and the Québec government (*Québec-Cree New Relationship Agreement*, which is also known as *Paix des Braves*) led to new infrastructures being added to the existing La-Grande Complex, including two new generating stations (Eastmain-1A and Sarcelle), a new reservoir and diversion of the Rupert River. Although the Eastmain-1 project was viewed by Hydro-Québec and Québec as part of the project defined in the *James Bay and Northern Québec Agreement* (JBNQA), this was not the case for the Rupert diversion, thus triggering an environmental impact assessment (EIA) for the Eastmain-1A–Sarcelle–Rupert project. The review of the Rupert project was restricted to incremental impacts of the project on the existing infrastructure but some cumulative impacts were also considered. As part of this project, which was completed in 2012, a portion of the flow of the Rupert River was diverted to the Eastmain 1 Reservoir (and ultimately to the La Grande Complex) through a series of diversion canals and tunnels. The discharge of the Rupert River at its mouth into Rupert Bay was reduced by an average of 50% annually under an “environmental flow regime.” As the Rupert River is one of several rivers that discharge into the Rupert Bay estuary, total river inflow to Rupert Bay was decreased by about 18%, resulting in lowered water levels and saltwater intrusion upstream. Reports on hydraulic conditions and patterns of saltwater intrusion in post-diversion conditions using data collected during 2008-2010 have been prepared, in accordance with the project’s conditions of authorization (Environnement illimité 2011).

The combined area of the La Grande Complex reservoirs is approximately 13,000 km<sup>2</sup>, with approximately 10,800 km<sup>2</sup> of land area flooded as a consequence of this development (Bilodeau et al. 2017). Various works suggest that the developments have had major consequences for Eeyou Istchee, the Cree homeland in Québec, and its people, as well as coastal wetlands near James Bay (Niezen 1993; Feit 1995; Rosenberg 1997; Desbiens 2007). For example, flooding of organic matter

during reservoir creation has led to the formation of methylmercury and its uptake into the aquatic food chain, which is an important food source for Cree communities in the area (Rosenberg 1997). There are also concerns among Cree coastal communities regarding declines in eelgrass (*Zostera marina*), a change which some suspect may be linked at least in part to hydroelectric development, although there is no scientific evidence to either support or reject this hypothesis. Declines in eelgrass beds are believed to have contributed to the lower numbers of waterfowl such as Canada geese and brant available in the area particularly in fall, which has impacted the harvests by Cree hunters.

It is important to note that the development of the La Grande hydro-electric project took place over a period of more than forty years (1971 – 2014). During this period, the relationship with the Cree and Hydro-Québec evolved and the major changes in the hydroelectric development scheme for the region were the subject of successive bilateral agreements. Other subjects were pursued, including vocational training, mercury, water supply and the design of waste water collection and treatment systems. Many of the agreements were consolidated in 2004 in a single, simplified overarching agreement known as ‘Niskamoon’ (which literally means ‘I agree’ in Cree). With the hydro-electric development now at a fully operational stage, the ‘Niskamoon Corporation’, whose board includes representation from the Cree First Nations and Hydro-Québec, continues to be supported financially by Hydro-Québec as a long-term institutional arrangement for addressing issues arising from the development. Niskamoon Corporation has oversight over a recently initiated research program that aims to combine scientific and Cree Traditional Ecological Knowledge to develop a better understanding of the oceanography and ecology of the coastal region of Eeyou Istchee, with a focus on eelgrass and links with waterfowl and other wildlife.

In summary, at the same time as there has been significant socio-cultural change, economic development, and political and institutional changes associated with land claim settlements, there have been changes in the physical environment and ecosystems. Some of the environmental changes that have been reported, such as increasing air temperatures, longer ice-free season, and less predictable weather, are caused primarily by global climate change. Other environmental changes such as altered river flows, thinner estuary ice, and changes in the saltiness of coastal waters, may result from a combination of climate change, hydroelectric development and river flow regulation, and other human activities in parts of the watershed. Some changes that have had impacts on the Marine Region have been driven by still other factors. Contaminants transported by air and sea from distant sources are present in the tissues of the region’s wildlife (Donaldson et al. 2010). In

another example, the mid-continent population of Lesser Snow Geese has increased dramatically from under 2 million to over 12 million adults in recent decades due to better food supply along their migration routes, with significant impacts on the near-shore zone of the southern Hudson Bay coast (Canadian Wildlife Service 2018). The combined changes in the physical environment affect ecosystems and wildlife. Some communities have noticed changes in the species of fish found along the coast, in the timing of marine mammal and bird migrations, and in the distributions and numbers of some subpopulations. Contaminants in the Arctic and sub-Arctic food web are of concern to Indigenous populations that depend on country food for sustenance.

Looking ahead, the environmental and ecological changes occurring throughout the Marine Region will continue to be significant for communities in many ways. Altered freeze-up and break-up patterns and less predictable weather raise concerns about the safety of community members when travelling on the ice and coastal waters. There is a longer season during which large ships are entering the region and increased activity by ships with no ice classifications. While community resupply by sea-lift may benefit from the reduced sea ice, future potential changes in fish and wildlife raise concerns about the security of country foods. With increased shipping there is also an increased likelihood of a spill and risk of introducing contaminants into the marine environment. These changes have contributed to strong interest in coastal and marine science and coordinated stewardship amongst many communities in the Marine Region—particularly around Hudson Bay—in addition to giving added impetus to larger-scale regional efforts around self-governance and increased control over resource development.



Sanikiluaq, Nunavut

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## 4. Governance

Governance in the Greater Hudson Bay Marine Region is multifaceted, with a combination of federal, provincial, territorial, and municipal authorities; Cree Nation bands; Cree and Inuit regional governments and other bodies created as a result of land claims agreements, such as rights-holding bodies and Institutions of Public Government (co-management boards). Further, while the federal and Ontario government exercises authority over the traditional territories of the Cree of western James Bay in Ontario, there are continuing disagreements regarding the interpretation of Treaty 9 between Cree Nations and the Crown and thus jurisdiction over these areas. While it may be complex, governance of the Marine Region today is a significant improvement over the regime just over four decades ago, before settlement of modern treaties region began with the JBNQA of 1975. Current levels of local and regional autonomy are a proud achievement for Indigenous populations around the Marine Region. It is also worth noting that some of the land claims settlements in this region and the institutions created by them are very young, with implementation in early stages (e.g., Nunavik Inuit Land Claims Agreement came into effect in 2008, and the Eeyou Marine Region Land Claims Agreement came into effect in 2012). Over time and with continued implementation of agreements and devolution, the current system will continue to evolve and mature. A challenge for the future is finding avenues to improve communication and collaboration between distinct political and administrative constituencies where they do not formally exist. Also, there is a need for patience amongst all workers because in any region, implementation of new governance regimes is a slow, uncertain and uneven affair. The legal and jurisdictional complexities sometimes give rise to an array of conflicting interpretations about responsibilities and authority, which poses a challenge for communities and regional authorities and may impact research processes (e.g., permitting). It is thus important for all newcomers, including research teams, to understand at least some aspects of the institutional and jurisdictional challenges and take them into consideration when working in the region.

This section aims to provide a brief overview of key authorities in the Marine Region and their powers, and is not exhaustive. A growing body of literature addresses international governance of Arctic marine waters and resources and how this intersects with and influences domestic governance (e.g., Fernandez et al. 2016); these issues are not discussed here. For more detailed discussion of governance in the Marine Region, see Daoust et al. (2010), Wilson et al. (2015), Rodon (2014) and Benoit (2011); much of the content of this section is derived from these sources. Additionally, the IRIS-4 report for Nunavik

and Nunatsiavut has detailed information regarding governance in Nunavik in its historical context (Allard and Lemay 2012).

#### 4.1. Governance in the Inuit homeland

##### 4.1.1. Nunavut

The Nunavut Land Claims Agreement (NLCA) (1993) and the subsequent establishment of the Government of Nunavut has had overarching significance in the region. Roughly half of the Marine Region is bordered by the territory of Nunavut, including the west coast of Hudson Bay, Foxe Basin, northern Hudson Strait and the Belcher Islands.

The NLCA protects the traditional rights of the Inuit throughout the Nunavut Settlement Area and provides direction for Inuit involvement in its management and governance. For example, the NLCA recognizes the legal rights of Inuit to harvest wildlife up to the full level of their economic, social, and cultural needs throughout Nunavut, barring exceptional circumstances (e.g., conservation concerns). Nunavut Tunngavik Inc. (NTI) represents Inuit beneficiaries of NLCA and ensures the agreement's proper implementation. There are three Regional

Inuit Associations that hold title for Inuit-owned surface lands and represent the rights of Inuit. Two of these Associations represent regions that border on the Marine Region: the Kivalliq Inuit Association for the Kivalliq Region bordering on northwestern Hudson Bay and the Qikiqtani Inuit Association for the Qikiqtani Region (formerly Baffin), and which includes Sanikiluaq. The NLCA includes the requirement that Inuit Impact and Benefit Agreements (IIBA) to be negotiated prior to the establishment of any new parks and protected areas; NTI and the appropriate Regional Inuit Association would have primary responsibility for negotiating these IIBAs. Each Nunavut community also has Hunters and Trappers Organizations that manage harvesting at that level.

The NLCA also established five Institutions of Public Government (IPG) that are co-management boards; four of these play roles in marine planning and management. These IPGs have federal, territorial (Government of Nunavut), and Inuit representation; they have no decision-making authority and fulfill an advisory role to the federal and territorial government. The Nunavut Wildlife Management Board is the main



Cape Dorset, Nunavut

instrument through which Nunavut Inuit can participate in decision making about wildlife management, including marine wildlife. It can also establish or change the boundaries of conservation areas. The Nunavut Planning Commission is responsible for land use planning (including water, wildlife, and offshore areas) and various aspects of environmental reporting and management. The Nunavut Impact Review Board is responsible for identifying and monitoring the ecosystem and socio-economic impacts of development projects, and recommends terms and conditions for authorizations. The Nunavut Water Board is responsible for the regulation of inland fresh-water use in Nunavut (not marine areas). In 2012 the Nunavut Marine Council was established as a mechanism for the four IPGs listed above to coordinate, share knowledge and address marine issues that are broader than any one organization's mandate. As the Nunavut Marine Council is mandated under the NLCA, the federal government must consider its advice and recommendations in making decisions that affect the Nunavut Settlement Area. However, like all IPGs, the role of the Council is advisory in nature and of limited authority alone. Currently, the management of the marine environment in Nunavut remains exclusively under the jurisdiction of the federal government. However, new devolution negotiations between the federal and territorial government and NTI began in 2016. NTI has advocated for devolution and gaining greater powers related to the territory's marine areas (NTI 2007).

#### **4.1.2. Nunavik, Québec**

Nunavik covers much of the Québec territory above the 55th parallel, an area of approximately 660,000 km<sup>2</sup>. The boundary has little to do with the history of territorial relationships between the Cree and Inuit (there is Cree presence and interest north of this line and Inuit presence and interest south of the line); it was created with the signing by Inuit of the JBNQA in 1975. This agreement is unique in that it was the first modern treaty in Canada and it was negotiated before the federal Comprehensive Land Claims Policy was established (indeed it may have prompted the federal policy). The JBNQA created three regional public bodies: the Kativik Regional Government (KRG), the Kativik School Board, and the Nunavik Regional Board of Health and Social Services. The activities of the Kativik Regional Government's Department of Renewable Resources, Environment, Land and Parks include supporting harvesting activities through the Inuit Hunting, Fishing and Trapping Support Program; co-developing and managing parks; administering the Uumajuit warden program for wildlife protection; and liaising between the province, region, and communities on environmental issues. Whereas KRG is the governing body for the region, Makivik Corporation represents and protects the rights and interests of Nunavik Inuit and manages the

financial compensation provided as a result of the land claim agreements. A core element of Makivik's mandate is economic development and job creation. It also operates a research centre in Kuujuaq that carries out scientific research on wildlife and the environment, and supports Hunting, Fishing and Trapping Associations in each community.

The JBNQA did not address rights of Nunavik Inuit to the offshore. Discussions began during the 1970s and were on and off for many years. Ultimately, the Nunavut settlement provided the institutional framework for the *Nunavik Inuit Land Claims Agreement* (NILCA) (2007), which addresses these offshore rights. NILCA establishes the Nunavik Inuit Settlement Area, comprising the Nunavik Marine Region (NMR) and the Labrador Inuit Settlement Area portion of the Nunavik Inuit/Labrador Inuit overlap area. The NMR extends off the coast of Nunavik starting in eastern James Bay and up through eastern Hudson Bay, encompassing all of Ungava Bay and extending across a significant portion of Hudson Strait. The NILCA establishes Inuit ownership of 80% of all of the islands in the NMR, totaling 5,300 km<sup>2</sup>. It also establishes three IPGs: the Nunavik Marine Region Wildlife Board, the Nunavik Marine Region Planning Commission, and the Nunavik Marine Region Impact Review Board. As with other IPGs, these co-management boards do not have a decision-making role, but an advisory one. The Nunavik Marine Region Wildlife Board is the primary instrument for wildlife management in the NMR, and has responsibilities for the regulation of wildlife harvesting, directing and funding research and advising co-management partners on wildlife issues. The Nunavik Marine Region Planning Commission is responsible for co-developing planning policies and objectives and developing land use plans for the NMR. Nunavik Marine Region Impact Review Board carries out screening and review of projects and makes recommendations regarding project approvals and conditions.

## **4.2. Governance in the Cree homeland**

### **4.2.1. Eeyou Istchee, Québec**

The term 'Eeyou Istchee' is often used to define the Cree territory in northwestern Québec. The region extends west from the limits of the James Bay watershed in Québec, from approximately the 49th parallel in the south to the 56° 30' parallel in the north (the region around the Clearwater Lakes and Lake Minto). 'Eeyou Istchee' overlaps the Nunavik territory north of the 55th parallel.

The JBNQA (1975), followed by a number of successor agreements, serves to define the political and institutional framework for industrial development in this region, with the focus on hydro-electric development and forestry. The JBNQA was a product of litigation arising from hydro-electric development, but it also serves as a land claim settlement,

and in important respects contributes to the definition of Cree government structures in this region. There are currently nine Cree First Nation communities, each with an allocation of Category I lands, which includes a block of Category 1 A lands, the 'administration, management and control' of which is transferred to the Government of Canada while 'bare ownership' and subsurface title remains with Québec, as well as I B and I B Special lands, held by village land holding corporations, and subject to Québec's municipal legislation. Cree have exclusive wildlife harvesting rights over Category I lands as well as Category II lands, which are in the Québec public domain. According to the terms of the *Cree and Naskapi Act (of Québec), 1984*, and similar to the West coast of James Bay, the designation of Category I A lands was based on an allocation of one square mile for each family of five (in 1974). In 2012, the Cree and Québec signed an agreement that established the Eeyou Istchee - James Bay Regional Government with respect to Category III lands. This body has governmental responsibilities of a municipal nature over nearly half of the Cree coastline in James Bay. Bill C-70, 'The Cree Nation of Eeyou-Istchee Governance Agreement Act', which was given royal assent in March of 2018, enacts the Cree Nation Governance Agreement and the Cree Constitution, providing Cree First Nations of Eeyou Istchee to exercise authority over Category I A lands by establishing laws rather than by-laws and removing the oversight of the Minister of Crown-Indigenous Relations with respect to Cree laws and financial administration. The legislation replaces, for the Crees, the Cree and Naskapi Act of 1984. Thus, since 2014, Category II lands have been the responsibility of the Cree Nation Government—which functions as a regional-level government for Cree society for Eeyou Istchee as a whole. Roughly 55% of the coastal zone falls into one of these land categories; the intertidal zone in front of these land categories is also part of Category II.

Canada has pursued its policy of settling Indigenous territorial claims in the offshore regions around northern Québec that were not included in the Nunavut Land Claim Settlement. In the Cree case, the claim settlement is referred to as the Eeyou Marine Region Land Claims Agreement (EMRLCA) (2012). The western boundary of the Eeyou Marine Region extends from the Ontario border with Québec northwards through central James Bay, and then curves along the eastern Hudson Bay shoreline, ending before the 58<sup>th</sup> meridian (the Nastapoka Islands). The corresponding Nunavik Marine region extends south along the east Hudson Bay coast as far as the mouth of the La Grande River. The overlapping area between the NMR and EMR is the subject of a joint administration under the terms of an Overlap Agreement which forms part of both the EMRLCA and the corresponding Inuit NILCA. Within the EMR, most of the islands are owned by the Cree Nation Government—either



Eastmain, Québec

outright or jointly with the Inuit. Further offshore, North Twin Island and the western half of South Twin Island remain Federal Crown lands. The islands in the EMR are subject to Nunavut territorial jurisdiction, although there is continuing uncertainty about the location of the boundaries between Québec, Nunavut and federal waters. As with the NILCA and following the model of the Nunavut agreement, the EMRLCA involved the creation of a Wildlife Management Board, an Impact Review Board, and a Planning Commission. Coordination between these Cree and Inuit IPGs and the Cree Nation Government and Makivik (as owners of the islands) will play a significant role in the implementation of these offshore agreements.

#### 4.2.2. Cree Nations in Northeastern Ontario

Ontario borders on the Greater Hudson Bay Marine Region, extending along southern Hudson Bay and western James Bay coasts for over 1,000 km. There are seven communities along the Ontario coastline: Fort Severn First Nation and Weenusk First Nation at Peawanuck are situated on rivers flowing north into Hudson Bay, while Attawapiskat First Nation, Kashechewan First Nation, Fort Albany First Nation, Moose Factory, and Moosonee are located on rivers flowing into western James Bay.

Moose Factory and Moosonee are both located on the Moose River and connected by water taxi and by ice road in the winter. Moose Cree First Nation is located in Moose Factory, where it has two reserves. Also in Moose Factory is the MoCreebec Council of the Cree Nation, an association that represents Moose Factory Cree of Québec and who do not have a reserve. While Moosonee is a town and not a First Nation reserve, its population is about 85% Cree. Kashechewan and Fort Albany First Nation, while being separate communities, are



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both located on one reserve on the banks of the Albany River. Attawapiskat has a long history with Akimiski Island, which has both terrestrial and marine protected areas. However, because the island is within Nunavut's jurisdiction, it is officially managed by an office in Iqaluit. Weenusk First Nation at Peawanuck is surrounded by the lands of the Polar Bear Provincial Park.

All of the aforementioned communities and nearly all of the coastal areas of northern Ontario lie within the Treaty 9 territory. Treaty 9 was negotiated in 1905–1906, with adhesions in 1908 and 1929–1930. The Royal Commission on Aboriginal Peoples (RCAP) describes Treaty 9 as a “resource development treaty in whole or in part” (RCAP 1996 v. 2, p. 467). According to the RCAP, while reserves were set apart out of the territories covered by the agreement—often in a formula of 640 acres per family of five—the nations that participated were

reassured that they would not be forced to reside on those lands, nor would their traditional economies be interfered with. First Nations interpretations of Treaty 9 are that their ancestors agreed to peaceful co-existence and sharing of the land (RCAP 1996), while federal and provincial government interpretations are that First Nations of northern Ontario ceded their title to the land in exchange for reserves, financial compensation, and harvesting rights. As a result, recognized jurisdiction of Cree First Nations in northern Ontario is limited to reserve lands and the quasi-municipal powers of band councils set out in the *Indian Act* (i.e., they have the power to make and enforce by-laws within reserve boundaries), and does not encompass what these nations would consider to be their traditional territory. A significant disparity exists between Cree nations of eastern James Bay in Québec that signed the JBNQA and those in western James Bay in Ontario that took

part in Treaty 9, with the former having more economic tools, more land, more rights to resources, more capital and the legitimacy of their institutions recognized in provincial law (RCAP 1996). Free, prior and informed consent and Supreme Court decisions have supported the authority of First Nations across Treaty 9, who continue to challenge and fight for policies consistent with their understanding of the treaty as well as their inherent rights.

There are also two regional First Nations organizations of importance to communities along the Marine Region's Ontario coast. Attawapiskat, Kashechewan, Fort Albany, and Moose Cree First Nations are part of the Mushkegowuk Council, a regional chiefs' council comprising of eight member communities. Attawapiskat, Fort Albany, Fort Severn, Kashechewan, Moose Cree and Weenusk First Nations, plus MoCreebec Council of the Cree Nation, are all part of the Nishnawbe Aski Nation, a political organization for First Nations in the Ontario portion of Treaties 5 and 9 consisting of 49 member communities.

### 4.3. Municipalities and First Nations in Northern Manitoba

Churchill is currently the only community on Manitoba's coastline, and has exerted considerable influence on the Marine Region through its role in the re-supply and shipping industry of the region, a role enabled in large part by the Hudson Bay Railway and the Port of Churchill. However, the port was closed in 2016 and operations of the railway suspended indefinitely in June 2017 after flood damage. Purchase of the Railway and Port in August 2018 by a consortium is the first step in repairing and restoring the rail line and signals a potential return of Churchill's role in shipping and re-supply.

There are no First Nations located directly on Manitoba's coast, but a number of Manitoba's First Nations have a close connection with the coast nonetheless. For example, in 1957 the York Factory First Nation was relocated from their homeland along the Hudson Bay coast to Kawechiwasik or York Landing, a site on Split Lake (on the Nelson River system) about 230 km straight-line from Hudson Bay. Shamattawa First Nation and Fox Lake Cree Nation are the closest First Nations in Manitoba to Hudson Bay, at about 145 km and 165 km away from the coast, respectively. York Factory First Nation was a parent reserve for Fox Lake Cree Nation, which is also on the Nelson River and thus also has historical ties to Hudson Bay. Two other First Nations are located on or near Split Lake: War Lake and Tatakweyak.

Treaty 5 (1875, 1908, adhesions in 1908, 1909, 1910) covers all of northern Manitoba with the exception of the north-eastern corner, which falls within Treaty 9. No comprehensive land claim settlements exist or are currently being negotiated in northwestern Manitoba. Thus, despite several Manitoba

First Nations viewing their traditional territories as extending up to Hudson Bay, for none of them, to our knowledge, has jurisdiction adjacent to the Marine Region been recognized. As described in section 4.2.2 for Ontario, matters relating to First Nations and First Nations reserves are governed foremost by the *Indian Act*, and without a comprehensive claim, modern treaty or self-government agreement, the recognized jurisdiction of First Nations is limited to reserves. As a result, most of northern Manitoba along the Hudson Bay border is provincially managed apart from Wapusk National Park, a 11,475 km<sup>2</sup> park about 45 km south of Churchill and bordering on Hudson Bay, and the municipality of Churchill. In addition, the National Historic Sites at Prince of Wales Fort (near Churchill) and York Factory (near the Nelson River estuary) are under the jurisdiction of Parks Canada.

### 4.4. Provincial authorities: Québec, Ontario, Manitoba

Provinces have wide authority on matters of economic development, property rights and natural resources, including land management, mining, forestry, and hydroelectric development and provincial parks. Provinces also create and apply environmental impact assessment legislation. Although the major responsibility for Indigenous affairs lies with the federal government, the provinces play a significant role in the negotiation and resolution of outstanding specific and comprehensive land claims. Motivated by resource development opportunities, Québec has taken the most proactive role in terms of its relationship with Indigenous peoples in the northern parts of the province, resulting in modern treaties and self-government agreements. Ontario and Manitoba have been less successfully engaged in comprehensive land claims negotiations by Indigenous populations in their northern regions. For example, as of 2017, no comprehensive land claims have been settled in Ontario, although negotiations with Algonquins of Ontario have been ongoing since 1991.

Each province also has specific legislation and initiatives related to its northern regions, and which have relevance for the Marine Region. In Ontario, the *Far North Act* (2010) aims to involve First Nations in northern Ontario in land use planning. It creates a process for First Nations to develop community land use plans in partnership with Ontario and subject to government approval. The Act requires the eventual setting aside of an interconnected protected area of at least 225,000 km<sup>2</sup> (21% of area of Ontario) in Ontario's northern region. The Act also prohibits certain development activities (e.g., commercial timber harvest, oil and gas development, energy development, electrical or transportation infrastructure) in Ontario's northern region without a provincially-approved community land use plan. The Act was unanimously objected to by

members of the Nishnawbe Aski Nation related to lack of free, prior and informed consent (Nishnawbe Aski Nation 2017). As of December 2017, none of the First Nation on the Ontario coastline have a draft or approved community land use plan under the Act (Government of Ontario 2017).

Manitoba’s current northern development strategy, while not packed under a single initiative, continues a half-century of hydroelectric development. The Nelson River system, home to many of the First Nations discussed in section 4.3, had been developed for hydroelectric energy generation. Generating stations were established at Kelsey in 1960, Kettle in 1974, Jenpeg in 1979, Long Spruce in 1979, and Limestone in 1992 and Wuskwatim in 2012. The 695 MW Keeyask project is currently under construction. Diversion of the Churchill River into the Nelson River to further boost energy generation was completed in 1977. These projects have had consequences for the timing and quantity of discharge of freshwater into Hudson Bay.

Québec has participated in or driven numerous initiatives and agreements in northern Québec. The most salient outcomes of these initiatives for the Marine Region have been detailed in sections 4.1.2 and 4.2.1 regarding Nunavik and Eeyou Ishotee, respectively. Details of hydroelectric developments in Québec can be found in section 3.2. The IRIS-4 report can also be referred to for more information (Allard and Lemay 2012).

#### 4.5. Federal authority

The federal government has jurisdiction over fisheries, shipping, and navigation, even within provincial or territorial boundaries; has ultimate jurisdiction over aquatic species (including marine mammals), migratory birds, and species at risk; and has responsibilities for regulating water resources in Nunavut (e.g., ensuring compliance with water licenses and authorizations) (Becklumb 2013). Legislation that relates to federal environmental management of waters and resources in the Marine Region includes the *Canadian Environmental Assessment Act (2012)*, *Migratory Birds Convention Act (1994)*, *Species At Risk Act*, *Canada Wildlife Act*, *Canada Water Act*, *Canada Shipping Act (2001)*, *Navigation Protection Act*, *Arctic Waters Pollution Prevention Act*, *Fisheries Act*, *National Marine Conservation Areas Act*, and *Oceans Act*. Another relevant piece of legislation is the *Indian Act*, administered by Crown-Indigenous Relations and Northern Affairs Canada, and which governs in matters pertaining to status, bands, and reserves and outlines Crown obligations to First Nations peoples. Fisheries and Oceans Canada (DFO) is the lead federal government agency with regard to marine planning and management; Environment and Climate Change Canada (Canadian Wildlife Service) establishes and co-manages National Wildlife Areas, Marine Wildlife Areas and Migratory Bird Sanctuaries; Parks Canada establishes and co-manages National Parks with marine components and National Marine Conservation Areas, and Indigenous and Northern Affairs is responsible for the control and management of terrestrial, marine and mineral resources, and oil and gas in Nunavut.

#### 4.6. Integrated management efforts

As the above sections illustrate, the governance of the Marine Region is complex and involves multiple jurisdictions. This situation may be viewed as problematic in terms of sustainable development around activities that may impact the ecosystem across jurisdictional boundaries, for example, industrial shipping. Considering the connected biological, oceanographic and geophysical processes that give the region its distinct character, many would argue there is a lot to be gained through coordination and stewardship efforts that consider the region as a whole. To attempt to address this issue, there have been several efforts to formalize coordinated stewardship.



J. HEATH/THE ARCTIC EIDER SOCIETY

Community-Driven Research in East James Bay

One of the first coordinated efforts across the region was undertaken by the Hudson Bay Programme, established by the Environment Committee of Sanikiluaq and the Canadian Arctic Resources Committee in 1992. Its aim was to address cumulative impacts and to promote sustainable development in the region. The complexities of coordinated stewardship are particularly manifest in southeastern Hudson Bay where the land claim agreements of the Nunavut, Nunavik and Eeyou Marine Regions overlap, particularly along the coastal region near the communities of Sanikiluaq, Inukjuak, Umiujaq, Kuujjuaraapik/Whapmagoostui and Chisasibi. Between 1992 and 1997, the Hudson Bay Programme brought together the Indigenous knowledge of 28 Inuit and Cree communities to build an integrated regional-scale picture of environmental change from the point of view of the Hudson Bay and James Bay communities. This culminated in *Voices from the Bay* (MacDonald et al. 1997), a key foundational document and critical resource for environmental stewardship and collaboration in the region.

In 1997, the adoption of the federal *Oceans Act* gave the DFO the mandate to lead integrated management for all marine, coastal and estuary activities including the Hudson Bay Region. This led to the establishment of the Hudson Bay Ocean Working Group in 2000, beginning a planning process that primarily focused on the western side of Hudson Bay. Working groups were initially active and published documents on coordinated management and ecosystem health, but the group became largely inactive by 2003.

In 2004, the Nunavut Hudson Bay Inter-Agency Working Group (Nunavuummi Tasiujarjuamiuguqatigiit Katutjiqatigiingit, NTK) was formed through a partnership between the Environment Committee of Sanikiluaq, NTI, Qikiqtani Inuit Association, and the Government of Nunavut. Scientific and technical assessments were prepared on impacts of freshwater from the La Grande Complex on the Hudson Bay Marine ecosystem in relation to the Rupert River Eastmain 1-A hydroelectric development. This development created a strong rationale for forming a framework for inter-jurisdictional coordination and implementation of large-scale research and monitoring programs for the James Bay and Hudson Bay ecosystems (NTK 2008). However, the capacity to create and implement such a framework extended beyond any single government entity. NTK spearheaded efforts to develop a community-based monitoring and assessment network (Municipality of Sanikiluaq and NTK 2008; Stewart and Hamilton 2007). NTK also partnered with the International Institute for Sustainable Development (IISD) to develop the Hudson Bay Inland Sea Initiative in 2010. One of the results of the partnership with IISD was a report of the governance structure and issues in the Hudson Bay region (Benoit 2011).

While a loss of funding led to the dissolution of NTK in 2011, the Arctic Eider Society (AES) was founded the same year. Based in Sanikiluaq, AES is a charity that aims to advance the efforts that had been previously led by NTK and IISD. They established a Community-Driven Research Network with the communities of Sanikiluaq, Inukjuak, Umiujaq, Kuujjuaraapik and Chisasibi that has linked communities, federal departments, the Government of Nunavut, IPGs and university researchers to address gaps in oceanography, sea ice, wildlife ecology and contaminants. These programs have begun addressing key knowledge gaps in coastal areas of Hudson and James Bays, leading to some of the first baseline data for these areas on priority indicators.

The research program on coastal habitat in Eeyou Istchee overseen by the Niskamoon Corporation represents an attempt to coordinate efforts to address key knowledge gaps at the regional scale. The Steering Committee has representation from the Cree Nation Government, Hydro Québec, and representatives of the Cree Nations of Chisasibi, Wemindji, Eastmain and Waskaganish. Results are presented at symposia where the program also attempts to engage Cree Regional organizations such as the Cree Trapper Association and the EMR Wildlife Board, Governmental organizations (e.g., CWS, Plan Nord), and non-governmental organizations.

On the western side of Hudson Bay, the Hudson Bay Neighbours Regional Roundtable was formed in 2002 and brought together communities in the Kivalliq region of Nunavut and northern Manitoba to coordinate and advance issues of mutual concern including social, environmental and economic issues. Because Sanikiluaq uses Manitoba health services, they have also been a part of the western Hudson Bay group. In 2012 it was revived after five-year dormancy and has since been meeting regularly.

In November, 2016, an inaugural East Hudson Bay/James Bay regional roundtable was held in Chisasibi. This event was organized by the Hudson Bay Consortium, which is the current initiative attempting to improve interjurisdictional coordination around environmental stewardship and sustainable development in the region. The Hudson Bay Consortium was officially launched at a Hudson Bay Summit held in Montreal in February 2018.

Reviewing the history of efforts to improve interjurisdictional coordination and stewardship in this region reinforces the complexity of these undertakings in a region with multiple overlapping jurisdictions. Certainly it is undesirable to add any additional layers of complexity as far as decision-making is concerned. However, the benefits of improving communication and sharing knowledge are widely recognized. The history also indicates the key role that local and regional bodies and communities have had in pushing forward dialogue and

cooperation. One positive outcome of the various efforts has been increasing capacity in communities and local and regional bodies for engagement in knowledge exchange activities. There has also been a building of relationships and an improved appreciation of differences and similarities in perspectives among regions. The increased interest in and capacity for research and monitoring at the local level is relevant to the discussion in the final chapter of this volume regarding looking forward with research and monitoring in the Marine Region.

## 5. Socio-economic overview

Forty diverse communities are located on or near the shores of the Greater Hudson Bay Marine Region. As previously mentioned, twenty-five of these communities are Inuit and located within Nunavut or Nunavik; 13 are Cree First Nations or communities within Ontario and Eeyou Istchee, Québec; and two are municipalities (Churchill and Moosonee) with sizeable Indigenous populations (Table 2). In total, 46,673 people live on the coast of the Marine Region, including about 24,340 Inuit residents, 15,260 First Nation residents (almost entirely Cree), and 260 Métis residents (Statistics Canada 2017a). Sizes of communities vary, from under 200 in Peawanuck, Ontario where Weenusk First Nation is located, to approaching five-thousand in Chisasibi Cree Nation in Eeyou Istchee. Each community is unique with a distinct character and different socio-economic characteristics, a result of the intersection of characteristics of the environment in which they are located, resource development influences, historical factors including diverse histories of settler contact and colonization, level of political autonomy, and culture. For example, some communities have become permanent settlements more recently than others; Fort Albany, Moose Factory, Fort Severn, Attawapiskat and Whapmagoostui all housed Hudson's Bay Company fur trading posts (established at the former three in late 1600s), while Umiujaq was established in the 1980s by Inuit that chose to relocate from Kujjuarapik due to expected hydroelectric project impacts. The large number of communities around the Marine Region precludes providing an introduction to each community and thus reflecting their diversity. Instead, this section provides a brief sketch of socio-economic characteristics for each region bordering on the Greater Hudson Bay Marine Region.

Nunavut is home to approximately 37,000 residents distributed over 25 communities, 84% of whom are Inuit (Nunavut Bureau of Statistics 2016). The population of Nunavut is young; by 2035 it is projected to increase to 48,000 (Nunavut Bureau of Statistics 2014). The economy is a mix of wage-based

(e.g., mining, exploration, tourism, fisheries, art) and land-based activities. In 2014, Nunavut's GDP was \$2.35 billion, with mining, specifically metal ore mining, contributing about one-fifth of the GDP quarter (Statistics Canada 2017b). Another major employer is public administration, which in the same year was about one-quarter of the GDP. As in all of Inuit Nunangat (the Inuit homeland in Canada), Nunavut's economy is historically based on harvesting traditions. Harvesting wildlife provides for food, fur and skin for clothing, and bones for tools and art. Harvesting seals and other marine mammals is an especially important part of the Inuit cultural way of life for its coastal communities. For example, two-thirds of Inuit adults in Nunavut reported that at least half of the meat and fish eaten in their household is wild or country food (Tait 2008). The harvesting economy in Nunavut is estimated to be worth approximately \$40 million annually (Government of Nunavut 2017), in addition to making invaluable contributions to holistic health and wellbeing and cultural continuity. Nonetheless, Nunavut faces major challenges with regards to food security; in 2012, 56% of Inuit adults in Nunavut lived in a household that faced food insecurity in the previous 12 months (Arriagada 2017).

Nunavut has major commercial turbot, shrimp, and char fisheries, with the offshore turbot fishery acting as a major employer in the Qikiqtani region. In 2011, the offshore turbot quota allocation was over 9,500 metric tonnes and had a landed value of approximately \$70 million (Government of Nunavut 2017). While there is a great deal of research activity within Nunavut, most of the socio-economic benefits of research have flowed to institutions and personnel outside of the territory. There are efforts underway to change this; for instance, the Government of Nunavut purchased a research vessel—the *Nulijuk*—in 2011 that has a mandate of encouraging community participation in fisheries, providing training and employment opportunities for Nunavummiut (Nunavut residents), and to gather knowledge about marine life. Tourism is an increasing industry, with around 17,000 visitors in 2015 (Government of Nunavut 2015); tourism is also important to Nunavut's arts and crafts industry. Housing needs are slightly greater in Nunavut communities along the Marine Region's coast than in Nunavut as a whole, with a 58% and 55% average rate of dwellings that are overcrowded and/or require major repairs in the five Qikiqtani communities and six Kivalliq communities surrounding the Marine Region, respectively, compared to 49% in Nunavut (Nunavut Bureau of Statistics and Statistics Canada 2011).

The population of Nunavik was about 13,500 in 2016, all located in 14 communities along the Hudson Bay, Hudson Strait, and Ungava Bay coasts and thus within the Greater Hudson Bay Marine Region (Institut de la statistique du Québec

**TABLE 2.** Population and percentage of Inuit, First Nations, and Métis residents in communities around the Greater Hudson Bay Marine Region as reported by Statistics Canada (2017a).

Region & Community	Location	Total population	% Aboriginal Population		
			Inuit	First Nation	Métis
<b>Nunavut</b>					
<i>Qikiqtani region</i>					
Igloodik	Foxe Basin	1,682	95%		
Hall Beach	Foxe Basin	848	96%		
Cape Dorset	Hudson Strait	1,441	93%		
Kimmirut	Hudson Strait	389	94%		
Sanikiluaq	Hudson Bay	882	96%		
<i>Kivalliq region</i>					
Naujaat	Foxe Basin	1,082	95%		
Coral Harbour	Hudson Bay	891	96%		
Chesterfield Inlet	Hudson Bay	437	94%		
Rankin Inlet	Hudson Bay	2,842	82%	1%	1%
Whale Cove	Hudson Bay	435	94%		
Arviat	Hudson Bay	2,657	95%		
<b>Manitoba</b>					
Churchill	Hudson Bay	899	5%	44%	19%
<b>Ontario</b>					
Fort Severn First Nation	Hudson Bay	361	100%		
Peawanuck (Weenusk First Nation)	Hudson Bay	195	100%		
Attawapiskat First Nation	James Bay	1,501	97%		
Kashechewan First Nation <sup>a</sup>	James Bay	1,404	100%		
Fort Albany First Nation <sup>b</sup>	James Bay	759	94%		
Moosonee	James Bay	1,481	1%	74%	3%
Moose Factory (Moose Cree First Nation) <sup>c</sup>	James Bay	2,232	93%		
<b>Eeyou Istchee, Québec</b>					
Waskaganish Cree Nation	James Bay	2,196	96%		
Eastmain Cree Nation	James Bay	866	97%		
Wemindji Cree First Nation	James Bay	1,444	95%		
Chisasibi Cree Nation	James Bay	4,872	1%	93%	
Whapmagoostui First Nation	Hudson Bay	984	4%	90%	
<b>Nunavik, Québec</b>					
Kuujuarapik	Hudson Bay	686	74%	16%	
Umiujaq	Hudson Bay	442	96%		
Inukjuak	Hudson Bay	1,757	97%		
Puvirnituq	Hudson Bay	1,779	94%		
Akulivik	Hudson Bay	633	100%		
Ivujivik	Hudson Strait	414	95%		

Region & Community	Location	Total population	% Aboriginal Population		
			Inuit	First Nation	Métis
Salluit	Hudson Strait	1,483	97%		
Kangiqsujaq	Hudson Strait	750	94%		
Quaqtaq	Hudson Strait	403	94%		
Kangirsuk	Ungava Bay	567	95%		
Aupaluk	Ungava Bay	209	98%		
Tasiujaq	Ungava Bay	369	95%		
Kuujuaq	Ungava Bay	2,754	73%	1%	
Kangiqsualujuaq	Ungava Bay	942	95%		
<b>Total population</b>		<b>46,673</b>			

a North part of Fort Albany 67 Indian reserve

b South part of Fort Albany 67 Indian reserve

c Includes Factory Island 1 and Moose Factory South

2017a). Wild or country food harvesting practices remain strong in Nunavik. In 2012, an average of 85% of Nunavik adults surveyed had hunted, fished, or gathered, or trapped in the previous year (Wallace 2014), demonstrating the strength of subsistence activities within the mixed economy of the region. Economically, government activities are an important industry. Government jobs in the health and education sectors represent over 40% of all employment; adding in the other government services, this figure would likely surpass 50% (Allard and Lemay 2012). All communities can only be accessed by airplane and boat in the summer, electricity is diesel generated, and internet service is satellite-based and generally slow. Population increases have created substantial pressures on housing in Nunavik, which has the highest rate of overcrowded dwellings in Canada at 49% (Rodon 2014).

The level of resource development in Nunavik has increased significantly over the last decade. In 2003, mineral, oil and gas exploration comprised 18.7% of the Nunavik economy, while by 2012 this portion had more than doubled to 40.3% (Duhaimé and Robichaud 2007; Robichaud and Duhaimé 2015). An increase in the length of the summer shipping season is expected to generally improve marine shipping access (Furgal and Prowse 2008), with the expectation that increased shipping access will further facilitate Arctic mining expansion in Nunavik (Ford et al. 2012). Currently, there are two large mining developments in Nunavik (Glencore's Raglan Mine and Canadian Royalties' Nunavik Nickel Mine) with additional large mining projects in advanced development. Previous agreements between the province of Québec and Makivik and Grand Council of the Crees, respectively, allow the sharing of royalties from resource development projects initiated by Québec.

In 2016, the Cree population of Eeyou Istchee was approximately 17,700, with approximately 60% of this population

living along the Hudson and James Bay coasts, while the Jamesian (non-beneficiary) population was 13,810 (Institut de la statistique du Québec 2017b). Hydroelectric development has been extensive in the region, as discussed throughout the introduction; this has led to a combination of employment, transfer payments from land claim settlements and subsequent agreements with the province. Mineral exploration has also rapidly expanded in Eeyou Istchee in the last decade; as of 2016, there were over 470 active mining exploration projects within Eeyou Istchee (Cree Mineral Exploration Board 2016). In 2016, the first diamond mine in Québec—the Renard diamond mine—opened in Eeyou Istchee. These developments have brought changes to the economy of Eeyou Istchee, but Cree residents nonetheless remain strongly rooted in their homeland and ways of life. Most communities in Eeyou Istchee are connected to the Québec road network and the power grid (as of the 1980s/90s) and increasingly, high-speed internet. In Eeyou Istchee, overcrowded housing is at 33%, compared to 2% in Québec as a whole (Rodon 2014).

Churchill is the only Manitoba community on the Hudson Bay coast, with a population of about 900. A large portion of the remainder of the Manitoba-Hudson Bay coastline is occupied by Wapusk National Park. The median individual income in Churchill is about \$41,100, and only about 3% of dwellings have more than one person per room (Statistics Canada 2017a). Major economic drivers in Churchill are tourism and ecotourism, Arctic research, public administration, and until recently transportation (link between rail and marine transport at the Port of Churchill). Overall, northern Manitoba garnered 530,000 person-visits and \$116 million in tourism expenditures in 2014 (Travel Manitoba 2016); Churchill is a strong contributor to these numbers, by drawing international and domestic tourists for polar bear and beluga viewing opportunities. Rail

service to Churchill was suspended by its owner, Omnitrax, in June 2017 after a combination of damage from severe spring flooding, as well as Omnitrax's closure of the Port of Churchill and related reductions in need for rail service. Millions of dollars in repair costs led to Omnitrax to subsequently abandon rail repair plans, leading to major consequences for Churchill regarding tourist access and re-supply and a conflict between Omnitrax and the federal government regarding contractual obligations to service the line. After a period of negotiations between the owner of the Port and Railway, the provincial and federal governments and possible third-party buyers, the Port of Churchill, Hudson Bay Railway and marine tank farm were sold to Arctic Gateway Group in August 2018. The consortium includes Manitoba communities, First Nations, Toronto-based Fairfax Financial Holdings and Saskatchewan-based grains company AGT Food and Ingredients. Repairing the rail line was the first priority of the consortium, and the signing of a 99-year management agreement signals the intention to maintain and build the importance of this transportation corridor over the long-term.

The Churchill Northern Studies Centre is an independent, non-profit research and education facility that has been operating since the 1970s; Arctic research based out of Churchill will expand significantly in coming years, with a \$32 million Churchill Marine Observatory dedicated to studying the arctic marine environment.

About 7,900 residents reside in the seven communities on the Ontario coastline of Hudson and James Bays, in what is largely Mushkewoguk Cree territory. The municipality of Moosonee has Ontario's only marine port. As with Cree communities in Eeyou Istchee, traditional hunting and fishing activities are an important part of the mixed-wage economy. Despite this, there are serious challenges with food security in the region, including the high cost of market food and limitations in financial means to access country food. For example, Skinner et al. (2014) reported a 70% household food insecurity rate in Fort Albany, of which 17% of households had severe food insecurity. Industrial resource development has been limited compared to nearby Eeyou Istchee, with no hydroelectric development and one mining operation. De Beers' Victor



GOOGLE EARTH

Churchill, Manitoba



M. KAMULA

### Coral Harbour, Nunavut

diamond mine opened about 90 km west of Attawapiskat in 2008, and is scheduled to close in 2019. Ontario's *Far North Act*, discussed in section 4.4, requires the setting aside of at least an 225,000 km<sup>2</sup> interconnected protected area—about 21% of Ontario's land mass and about half of what Ontario defines as its far north. Polar Bear Provincial Park, the largest park in Ontario at over 23,000 km<sup>2</sup>, borders on Hudson Bay near Weenusk First Nation at Peawanuck. The park operates as a wilderness area, with no visitor facilities and air-only access. The creation of the large protected area and prohibition of a range of development activities in the absence of a provincially approved community land use plan under the *Far North Act* suggests that industrial development on the Hudson Bay and James Bay coasts will remain as it is in the short term, with potential changes coming through development of the 'Ring of Fire' – the massive area of proven (nickel and chromite) and potential (gold) mineral reserves in central northern Ontario (about 250 km from Attawapiskat). In 2017, the Ontario government announced that construction will soon begin on a series of all-weather roads connecting First Nations communities within the Ring of Fire region to the provincial highway system. The roads, which are expected to take at least five years to build, will be a first crucial step toward opening up the mineral-rich area to resource development and all the associated social and environmental change.

## 6. Concluding comments

Ouranos Consortium, an independent, non-profit climate services cluster in Québec, stated that, "*scientific assessments are credible when they are understandable, and climate science proves to be challenging in this regard since it is far from intuitive*"

(Huard et al. 2014, p. 1220). This sentiment can be expanded to much of the natural sciences, where even experts in related fields cannot at times understand each other because of the technical nature of their work and abundance of discipline-specific language.

The IRIS report for the Greater Hudson Bay Marine Region, as with the other reports in the IRIS series, attempts to go against the predominant current. In bringing together researchers from across disciplines, it attempts to construct a comprehensive snapshot of what we know regarding the Greater Hudson Bay Marine Region, in a way that will be relevant for decision makers. Legitimacy in the process and understandability and salience in the product are the ultimate goals, and significant efforts have been put towards these aims, for example, through the leadership of Hudson Bay IRIS Steering Committee, a group with wide regional representation. Some topics are more intuitive than others, and it can be difficult at times to convey the limitations of work (to increase credibility and transparency) without sacrificing understandability. With guidance from end users, this report attempts to strike a balance in this regard.

The best way to understand this IRIS report is not as an end, but as a substantial step in the continual process of bringing together knowledge to inform decision-making. It follows other significant efforts to do so for the region, such as McDonald et al. (1997) report, *Voices from the Bay*. Much of the content of this report is retrospective. However, just as important as what we do know and are able to report, is what we do not. Findings presented in this document create a picture of what is happening in the Marine Region, and will likely happen in the future. Just as or even more importantly, embedded in the chapters is also a roadmap of questions that need to be addressed next to deepen our understanding of changes in the Greater Hudson Bay Marine Region, what they mean for the populations that depend on these waters, and what actions are needed to support the Marine Region's long-term health and its sustainable use.

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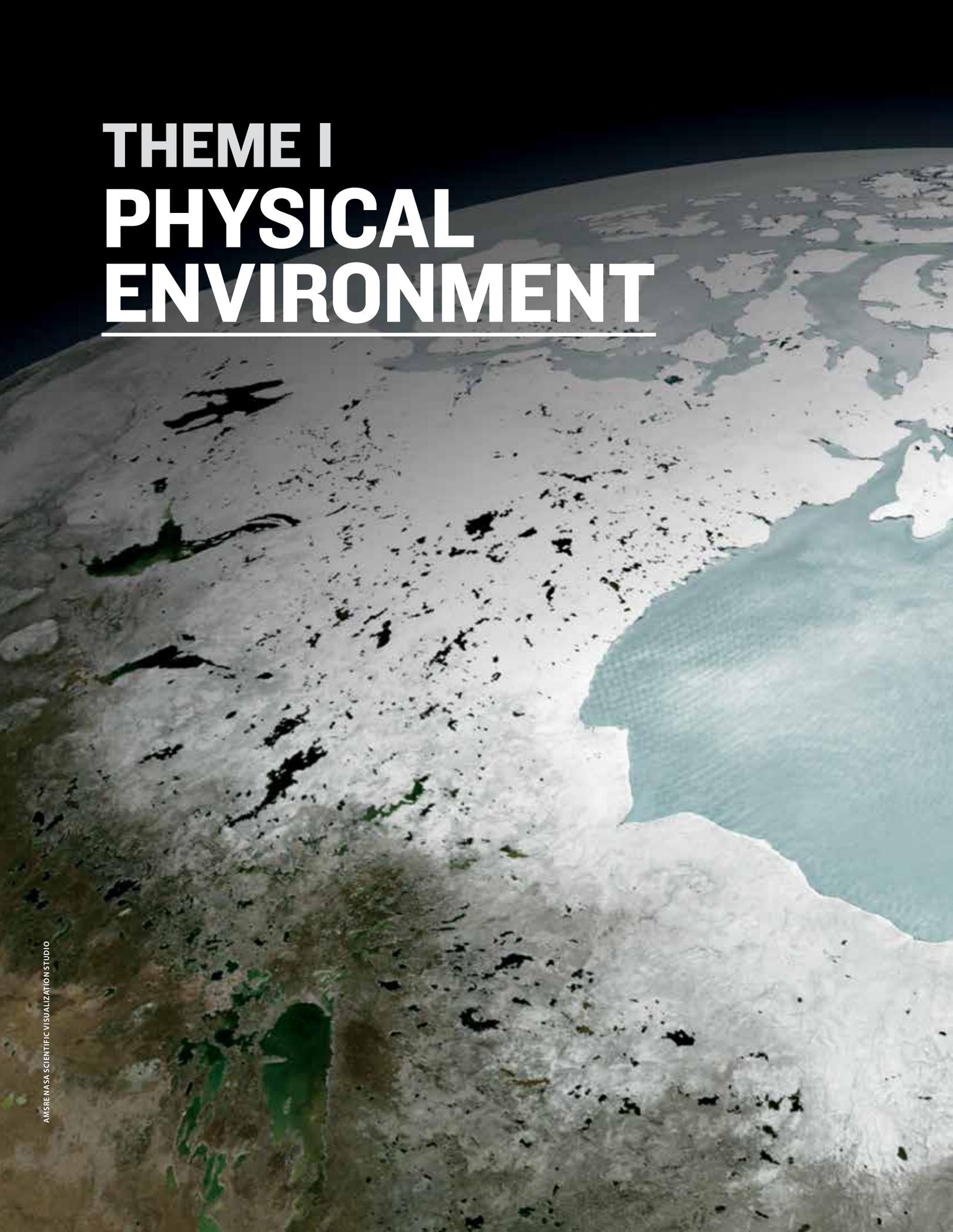
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# THEME I PHYSICAL ENVIRONMENT

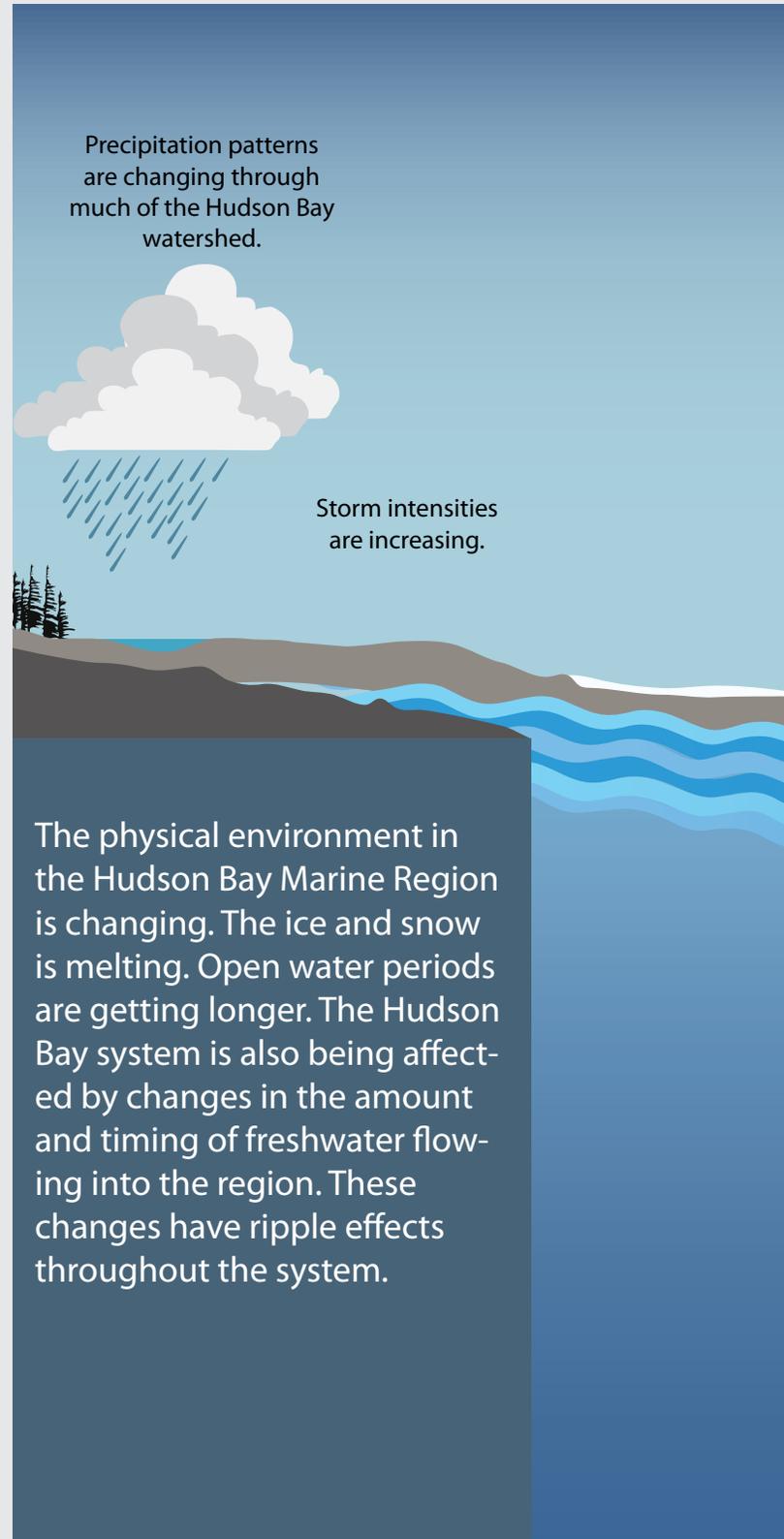
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The Greater Hudson Bay Marine Region encompassing Foxe Basin, Hudson Bay, James Bay, Ungava Bay and Hudson Strait is a unique extension of typical Arctic (oceanic, atmospheric) conditions down to subpolar latitudes. Defining characteristics of the Region are the large volumes of river runoff it receives and the seasonal sea-ice cycle. The atmosphere, ocean, ice cycle and river runoff interact to structure the physical environment and drive variability and change, which ultimately shapes ecosystems.

In the following set of chapters, we describe the physical environment and processes associated with the exchange of heat and freshwater between the atmosphere, ocean, sea ice and watershed. We first address each component in turn, beginning with the atmosphere (i) and sea ice (ii); we then give climate projections (iii) based on interactions between the ocean, sea ice and atmosphere. In section (v), we describe the watershed and describe future projections for river runoff. In section (vi), we address freshwater-marine interactions and discuss how changes in freshwater supply, both ice and river runoff, impact the coastal and marine environments. Future projections for oceanographic conditions in the Hudson Bay System are not yet available but will be developed as a product of the ongoing Hudson Bay Marine Region Study (BaySys project).



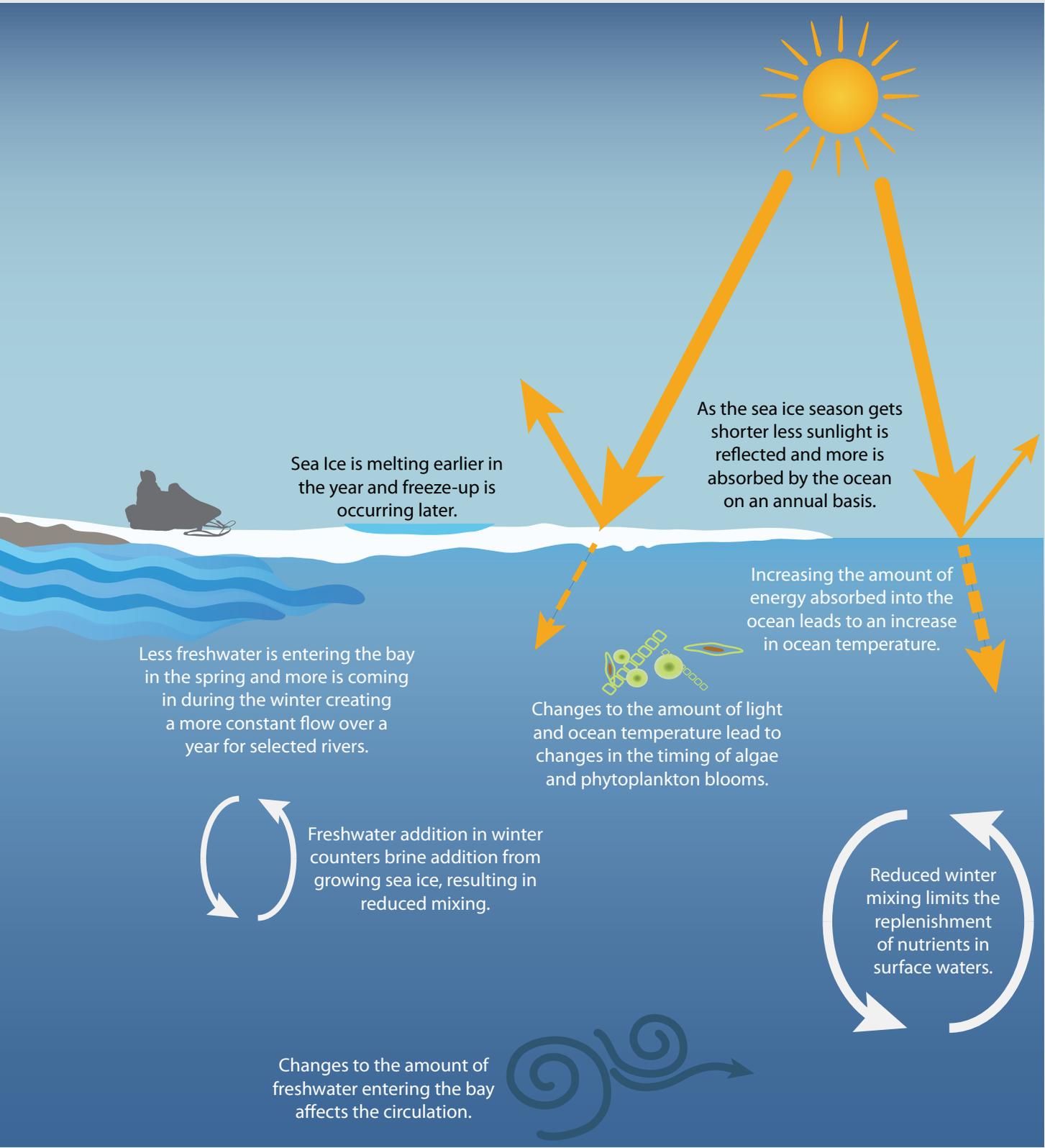


FIGURE MODIFIED BY L. CANDLISH FROM SKETCHES CREATED BY H. HINAM





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# Climate and Weather in the Greater Hudson Bay Marine Region

## AUTHORS

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## Summary

**W**eather is the day-to-day state of the atmosphere (temperature, humidity, precipitation, cloudiness, visibility, wind, etc.), the climate of a region is its average weather measured over a long period of time. The term climate change refers to change in the long-term average weather of a region. Climate change includes changes in a region's average annual rainfall, average air temperatures for a given month or season, or changes in winds or storms. Some of the most significant impacts of climate change will relate to damages caused by extreme events. Although specific storms cannot be attributed to climate change, the frequency of storms and other extreme events may be affected by climate change. Within the Greater Hudson Bay Region, scientific observations and reports from Elders agree that winters are getting warmer and shorter and summers are getting longer. The open-water (ice-free) season is lengthening, although some communities see more ice along the coast in the spring because of the movement of the mobile pack ice within the Bay. Inuit and Cree in some communities also report that there are stronger wind events and winter rain events, which can be dangerous. There are few scientific studies of adverse weather and storms in the region with the exception Nunavik, where storm surges have received recent study. With the ocean, ice, and weather being less predictable, community members express concern about personal safety when traveling. Another key concern in some areas is vulnerability of coastal infrastructure to changes in storm tracks and storm surges. Improved monitoring, including tools such as weather cameras that are being installed in some communities, will help address some of the concerns and provide better information about the current conditions and should be considered widely within the region.

## Key Messages

- **Seasonal air temperatures have increased over the past 30-40 years. There has been an increase of approximately 1.5-3 degrees Celsius during winter, spring and summer. The warming is even greater during the fall season, with increases of 4-5 degrees Celsius.**
- **Wind patterns have changed in recent years with generally stronger monthly average winds throughout the Hudson Bay Region.**

- **Only in Nunavik have there been studies looking at the changes in adverse weather and storms. Further studies should look at the intensity and frequency of storms, blizzards and other extreme events in other parts of the region.**
- **Because changing weather patterns have made snow, sea conditions and ice conditions more difficult to predict, it is important to address the gaps that exist in predicting weather in the region and making the information available to communities.**

## 1. Introduction

The difference between weather and climate is based on the period of time under consideration: weather reflects the conditions of the atmosphere over a short period of time, and climate is how the atmosphere behaves over relatively long periods of time. Most people think of weather in terms of temperature, humidity, precipitation, cloudiness, brightness, visibility, wind, and atmospheric pressure (high and low pressure). Climate change refers to detectable changes to long-term averages and trends in daily or seasonal weather on time scales of decades.

The Greater Hudson Bay Marine Region extends from approximately 50°N to 70°N, and from 100°W to 70°W. The Region is characterized by some of the harshest climate conditions on the North American continent. When there is limited or no ice cover on the Bay, the cold ocean waters affect the temperature and humidity of the surrounding coastal areas, keeping these areas cooler than areas further inland. According to Traditional Knowledge, there have been many changes in weather patterns and various aspects of climate within the Hudson Bay Region during recent decades (Voices from the Bay 1997; Elder's Report on Climate Change 2001). Similar to the changes described in other parts of the Arctic, Elders in Hudson Bay report that winters are getting shorter and summers are getting longer. The open water season is lengthening. The dominant wind regimes are shifting and there are stronger wind events occurring, which can be dangerous. Sanikiluaq (NU) community members have noted:

*"Even if we try to predict what it is going to be like tomorrow . . . the environmental indication isn't what the Elders said it would be. . . . Our knowledge isn't true all the time now. We're being told that maybe if we put January, February, or March one month behind, our knowledge of weather would be more accurate, because the weather in those months isn't the same anymore."*

Lucaassie Arragutainaq, Sanikiluaq (Voices from the Bay 1997)

*"It is now impossible to predict our weather; our ancient methods of forecasting weather are no longer yielding the predicted patterns. Even now the weather in Sanikiluaq is changing. Once it starts melting, there is no longer any delay in the melt. Whereas it used to freeze over at night, it no longer does and this has resulted in throwing off our entire schedule for the spring break activities on our island."*

Joe Arragutainaq, Sanikiluaq (Elder's Report on Climate Change 2001)

The trends and averages of key indicators of climate including air temperatures, rain and snow, winds and adverse weather and the data gaps are described in the sections below.

## 2. Climate variables and data sources

Within the Greater Hudson Bay Marine Region it is difficult to precisely characterize the climate because there are few climate stations and uneven distribution of stations throughout this vast area. The stations that exist also have inconsistent data records. Climate data are subject to random and systematic errors related to observers, instrumentation, and changes in measurement site and observing procedures. Satellite data can help fill in the gaps in surface networks for some variables but the period of coverage tends to be relatively short and there are few surface observations for validating satellite products over the Region. In addition, a number of reanalysis products are available (e.g., reconstructions of past wind conditions) but these products can include biases and discontinuities related to changing sources of information. The challenges of using these data to assess climate trends in particular areas emphasize the need for consideration of Traditional Knowledge and multiple sources of information when evaluating changes in climate and their implications. This chapter uses a combination of station data, satellite data, reanalysis data and model data, together with Traditional Knowledge compiled in documents such as Voices from the Bay.

Air temperatures, winds, rainfall and snowfall records are obtained from Environment Canada and Climate Change stations. Unfortunately, due to inconsistencies in the collection of station data, only a few weather stations in the Region have sufficient datasets for long-term climate averages or normals. Climate normals (sometimes referred to as climate averages or climate means) are monthly averages calculated over a 30-year period using Environment Canada's historical station data. Environment Canada follows the guidelines set out by the World Meteorological Organization (WMO) for climate normal calculations. Thus, the climate normals are computed over a 30-year period of consecutive records, starting January 1st and ending



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December 31st. In addition, the WMO established that normals should be arithmetic means (averages) calculated for each month of the year from daily data with a limited number of allowable missing values. For normal values representing averages, such as temperature, a month was not used if more than three consecutive days or more than a total of five days were missing.

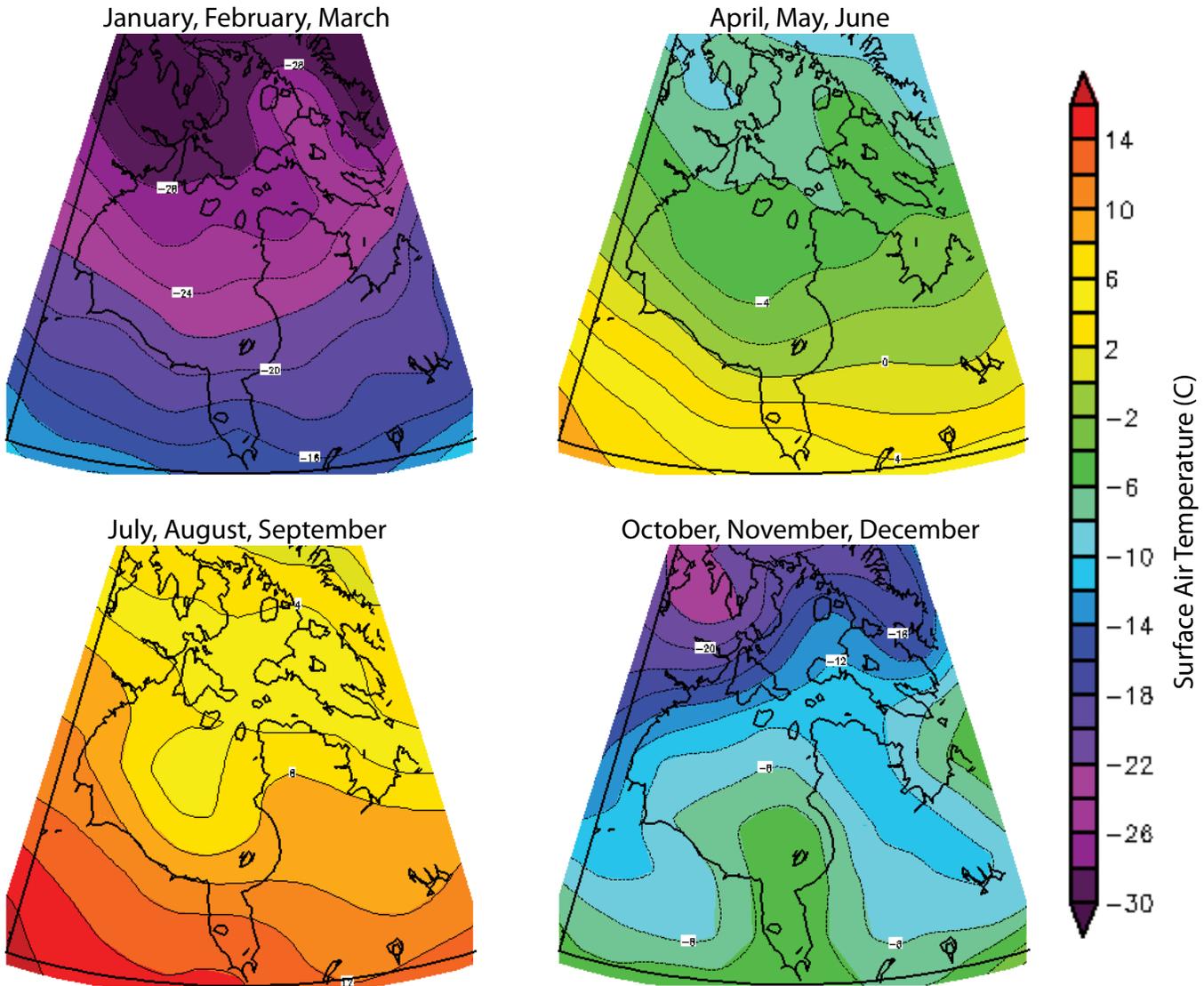
Precipitation is difficult to measure. The measurement of solid precipitation, such as snow and hail, is particularly difficult as measurements are subject to many systematic errors (Goodison et al. 1997). It is even more challenging in Arctic and sub-Arctic areas where the winter precipitation regime is characterized by frequent trace events and high wind speeds. The measurement of precipitation over 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 region.

Winds (u and v components) and air temperatures considered in this chapter were obtained from the NCEP North American Regional Reanalysis (NARR) dataset

(<http://www.esrl.noaa.gov/psd/cgi-bin/data/narr/>), with a spatial resolution of 32 km at the lowest latitude and a three-hour sampling interval (Mesinger et al. 2006). An extension to the NCEP global reanalysis project, the NARR model uses the Regional Data Assimilation System and very high-resolution Eta model combined, and covers 1979 to the present. Seasonal means and anomaly plots for winds were generated using the online analysis tools provided by the NOAA/ESRL Physical Science Division, Boulder, Colorado (<http://www.esrl.noaa.gov/psd/>). Monthly averages of winds were computed over the 1981-2010 period with anomalies from 2011-2018 computed with respect to the climatological mean.

### 3. Air temperature observations and trends

There are no thorough and consistent historical datasets for air temperatures over the marine area of the Hudson Bay Region. However, it is possible to get a sense for these temperatures



**FIGURE 1.** Average seasonal surface air temperatures for the Hudson Bay Region between 1979 and 2018 according to NCEP reanalysis data. The seasons are defined as follows: Winter – January, February, and March; Spring – April, May, and June; Summer – July, August, and September; and Fall – October, November, and December. This figure is produced from <https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl>

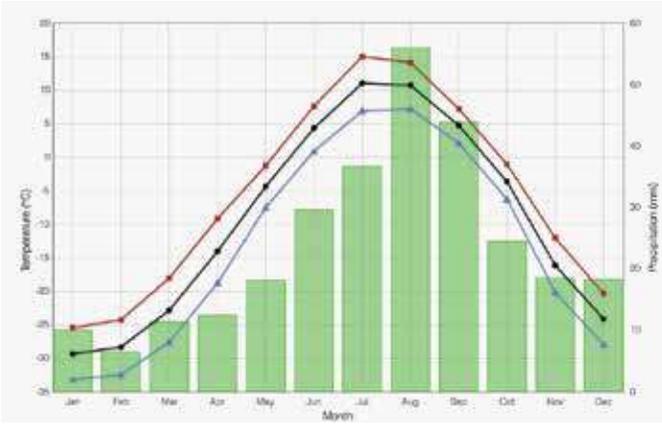
using reanalysis datasets. Figure 1 shows the 40 year seasonal average or climatology, for 1979-2018, of surface air temperatures over the Hudson Bay Region from NCEP reanalysis data.

The average seasonal temperatures shown in Figure 1 show warmer temperatures in the southwest of the Hudson Bay Region and colder temperatures in the north with the exception of fall (October, November, December), when warmer temperatures lie over James Bay and south-central Hudson Bay. Air temperatures over northern Hudson Bay and Hudson Strait are similar while those over Foxe Basin are colder.

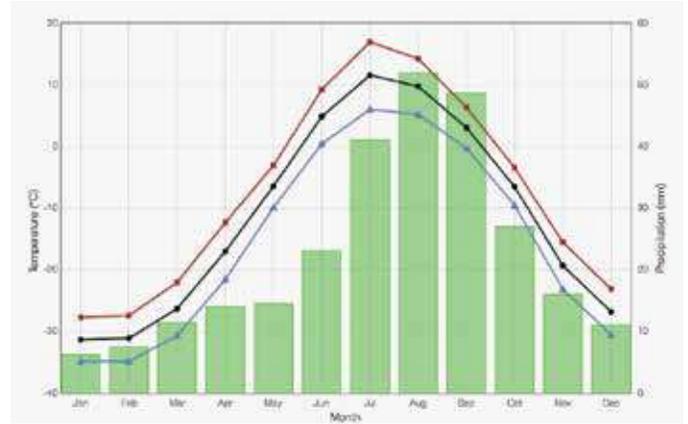
Figure 1 also shows the large seasonal variation in temperature in the Hudson Bay Region, with average temperatures over the marine environment ranging between 2 and 12°C in the summer and more than 20 degrees lower (between -16 and -30°C) in the winter.

Figure 2 shows the climate normals for 1981 to 2010 for six weather stations distributed around the region (Arviat, Baker Lake, Churchill, and Rankin Inlet in the west, Kuujjuarapik in the southeast, and Moosonee in western James Bay). Similar to Figure 1, Figure 2 shows that stations in the south of the Region

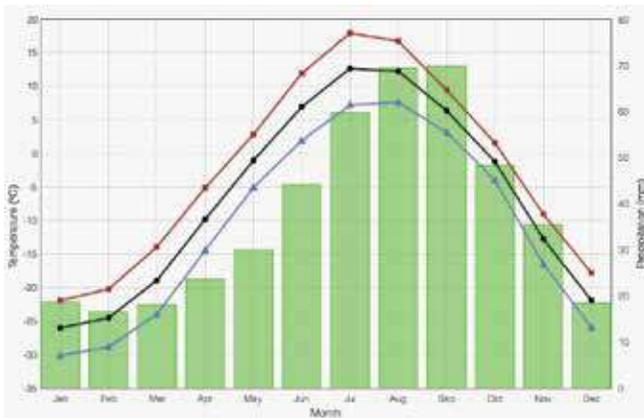
Arviat



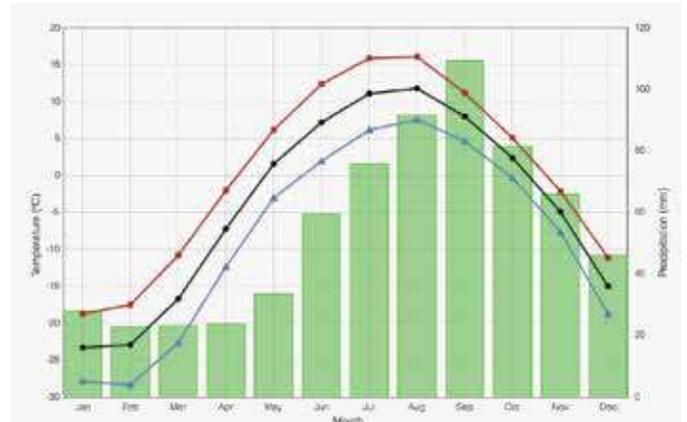
Baker Lake



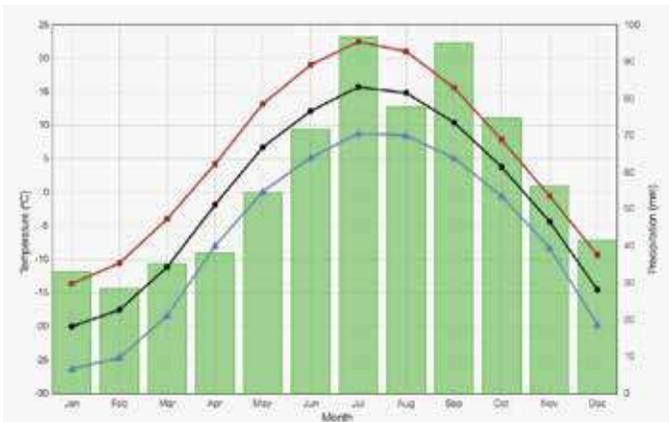
Churchill



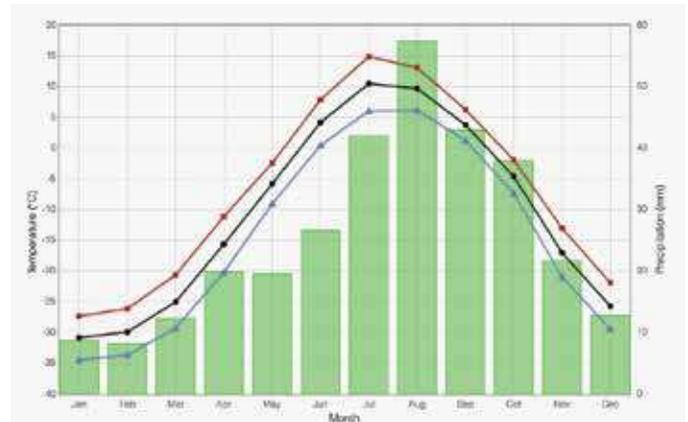
Kuujjuarapik



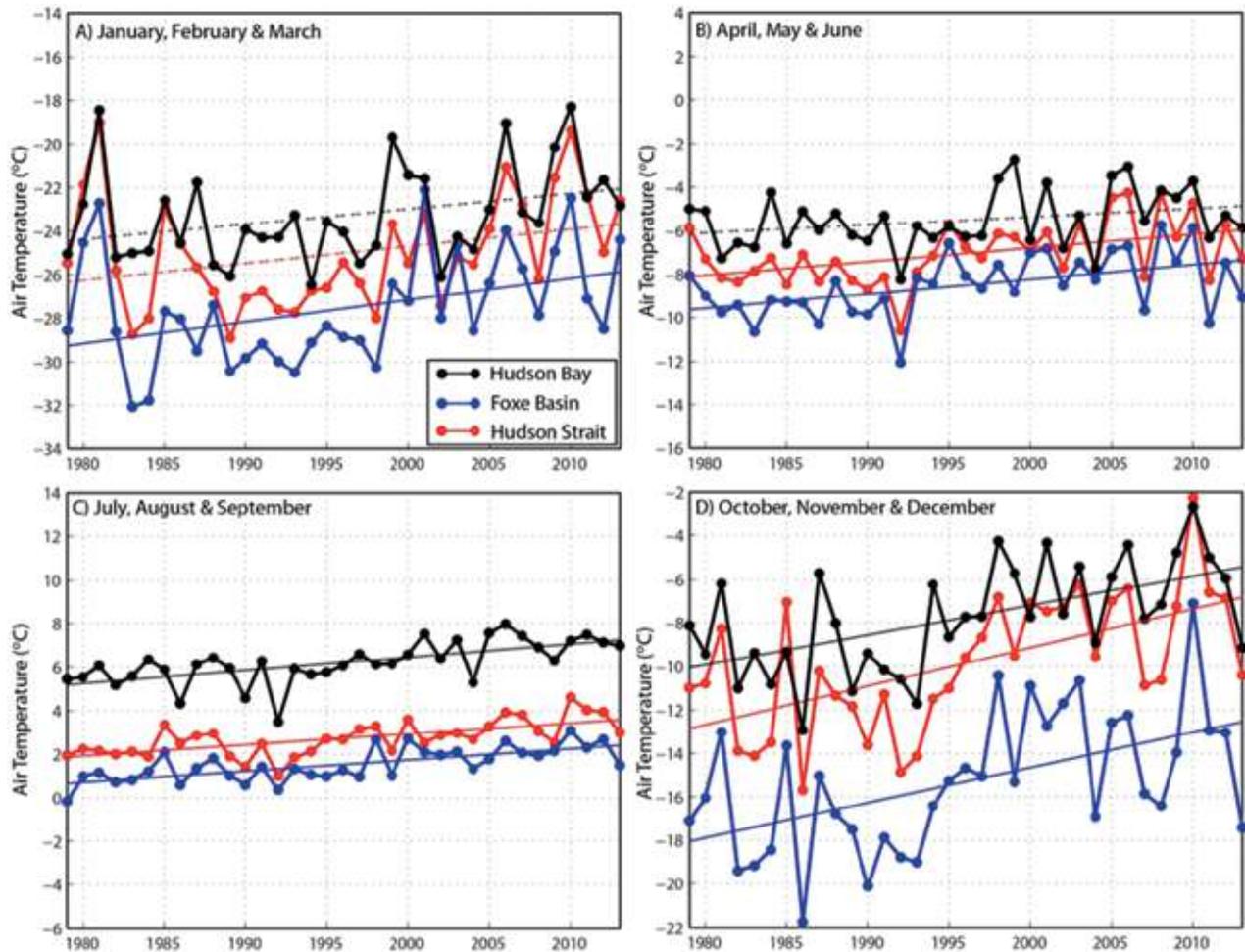
Moosonee



Rankin Inlet



**FIGURE 2.** Climate normals for Arviat, Baker Lake, Churchill, Kuujjuarapik, Moosonee and Rankin Inlet. Daily Maximum Temperature (°C) is shown with a red square, Daily Average Temperature (°C) is shown with a black circle, Daily Minimum Temperature (°C) is shown with a blue triangle and Precipitation (mm) is shown in green. The figure is from Digital Archive of Canadian Climatological Data [http://climate.weather.gc.ca/climate\\_normals/index\\_e.html](http://climate.weather.gc.ca/climate_normals/index_e.html)



**FIGURE 3.** The seasonal surface air temperatures for Hudson Bay (black), Foxe Basin (blue), and Hudson Strait (red), for 1979 to 2013. Trends are indicated with a solid or dotted line, where solid lines indicate significant trends ( $p < 0.05$ ). From Andrews et al. (2016).

(Moosonee and Churchill) have warmer summers, with the warmest month typically being July. Rankin Inlet, Baker Lake and Arviat show the coldest temperatures during winter.

The trends for surface air temperatures in the Region for the period of 1979 to 2013 were produced using NCEP Reanalysis 1 data. The Region was subdivided into Hudson Bay (including James Bay), Foxe Basin and Hudson Strait (including Ungava Bay) and the analysis considered the same four seasons as Figure 1 above. Figure 3 shows that the average surface air temperatures in all three sub-regions have positive trends during 1979-2013, meaning that the temperatures have increased during this time. The seasonal trends are summarized in Table 1 (Andrews et al. 2016). All regions displayed significant warming trends during summer and fall, and Foxe Basin underwent significant warming in all seasons. Warming was most rapid in each region during fall. Significant positive trends vary

from 0.05 to 0.18°C/year, which over the 34 year study period (1979 to 2013) corresponds to a total warming of 1.7 to 6.1°C. For example, analysis of NCEP Reanalysis data suggests that a total warming of 6.1°C took place in average fall temperatures for Hudson Strait between 1979 and 2013.

A study completed by Hochheim and Barber (2014) examined temperature and sea ice trends in the Greater Hudson Bay Region. The authors looked at terrestrial surface air temperatures. Temperature trends and anomalies were computed using monthly temperature records from 1950 to 2010, obtained from environment Canada's CANGRD data set (Hochheim and Barber 2014). The analysis found that terrestrial surface air temperatures increased throughout the entire Hudson Bay Region when temperatures from 1996-2010 were compared with those from 1980-1995. During the fall season, the mean regional warming trend between 1980 and 2010 was roughly 0.8°C per

**TABLE 1.** Seasonal surface air temperature trends (°C decade) for the period of 1979 to 2013 over the Hudson Bay Region from NCEP reanalysis data. Significant trends, computed with 95% confidence levels, are indicated with an asterisk (\*).

	Winter (JFM)	Spring (AMJ)	Summer (JAS)	Fall (OND)
Hudson Bay and James Bay	0.7	0.4	0.6*	1.4*
Hudson Strait and Ungava Bay	0.8	0.6*	0.5*	1.8*
Foxe Basin	1.0*	0.7*	0.5*	1.6*

decade for Hudson Bay, 1.5°C per decade for Hudson Strait, and 0.9°C per decade for Foxe Basin. During spring, the average air temperature warmed roughly 0.8°C per decade for Hudson Strait and 0.5°C for Foxe Basin between 1980 and 2010. Hudson Bay showed high inter-annual variability and no clear trend between 1980 and 2010 (Hochheim and Barber 2014).

Air temperature trends and permafrost thaw in Nunavik are discussed in detail in the climate variability and change chapter of the ArcticNet IRIS for Nunavik-Nunatsiavut (Brown et al 2012). The later period of the 20<sup>th</sup> Century was characterized by a rapid warming of about 2 degrees Celsius that is present in all seasons. Temperature exhibits large inter-annual variability in all seasons except summer. The summer air temperature increase is associated with a warming of permafrost by about 2 degrees Celsius, which has resulted in a dramatic increase in the number of thermokarst lakes and active layer detachments in Nunavik (Brown et al 2012).

#### 4. Rainfall and snowfall observations and trends

Figure 4 shows the monthly average rainfall for the period of 1981 to 2010 for seven weather stations distributed around the Hudson Bay Region (including the six stations described above). Kuujjuarapik and Moosonee have the greatest rainfall and the stations in northwest Hudson Bay (Arviat, Rankin Inlet, Baker Lake) have the lowest rainfall. August and September are the wettest months with the exception of Moosonee, which receives the most rainfall in July.

Rainfall trends have been examined only for a few specific areas. Using meteorological data (1943-2009) collected from the station at the Churchill MB airport, Macrae et al. (2014) documented that annual precipitation, primarily summer rainfall, has increased. The likely explanation for this trend is the longer ice-free period in Hudson Bay, which leads to more water vapour being supplied to adjacent areas (Macrae et al. 2014; Gagnon

and Gough, 2005; Hochheim and Barber 2010). For Nunavik, Brown et al. (2012) reported a 17% increase in rainfall over the 1950-2001 period. This increase was interpreted as being part of a longer-term trend in view of evidence for increasing lake levels in the region since the 17<sup>th</sup> Century (Begin and Payette 1988).

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. 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 Region over the 1981-2010 period. Figure 5 shows the monthly average snowfall for seven communities. Snowfall amounts are lowest in the northern part of the Region with Rankin Inlet, Baker Lake and Arviat having lower monthly average snowfalls than the other stations. The largest snowfall amounts occur in November and December.

Snowfall trends for Nunavik were analyzed by Brown et al. (2012). They estimated regionally averaged total annual snowfall with respect to a 1971-2000 reference period for climate stations with at least 40 years of data in the period since 1950 in the rehabilitated monthly precipitation data set of Mekis and Hogg (1999; updated to 2008) that includes corrections for data homogeneity and regional differences in average snowfall density (Mekis and Brown 2010). The regional average was based on four Nunavik stations, of which three were along the coast (Inukjuaq, Kuujjuaq, Kuujjuarapik). They report that over the 1950-2001 period, annual snowfall amount increased 23% for Nunavik stations. There were insufficient stations to compute a regional average for Nunavik after 2001.



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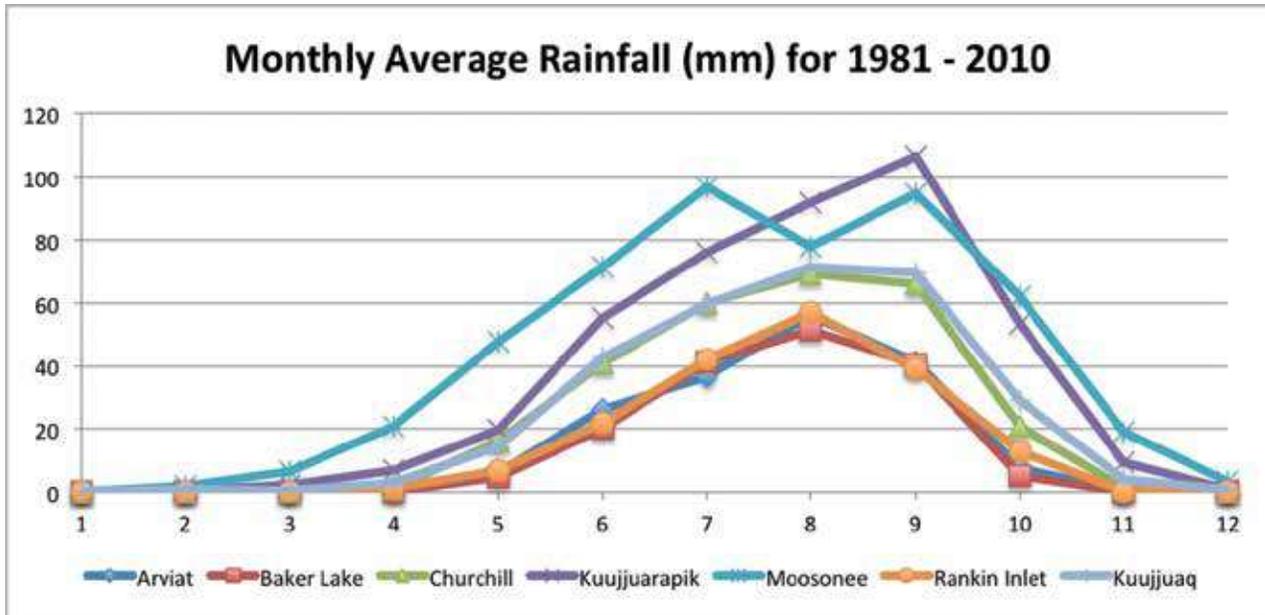


FIGURE 4. Monthly average rainfall in millimeters for Arviat, Baker Lake, Churchill, Kuujjuarapik, Moosonee, Rankin Inlet and Kuujjuaq. Numbers 1-12 correspond to January through December. The data was downloaded from the Digital Archive of Canadian Climatological Data [http://climate.weather.gc.ca/climate\\_normals/index\\_e.html](http://climate.weather.gc.ca/climate_normals/index_e.html)

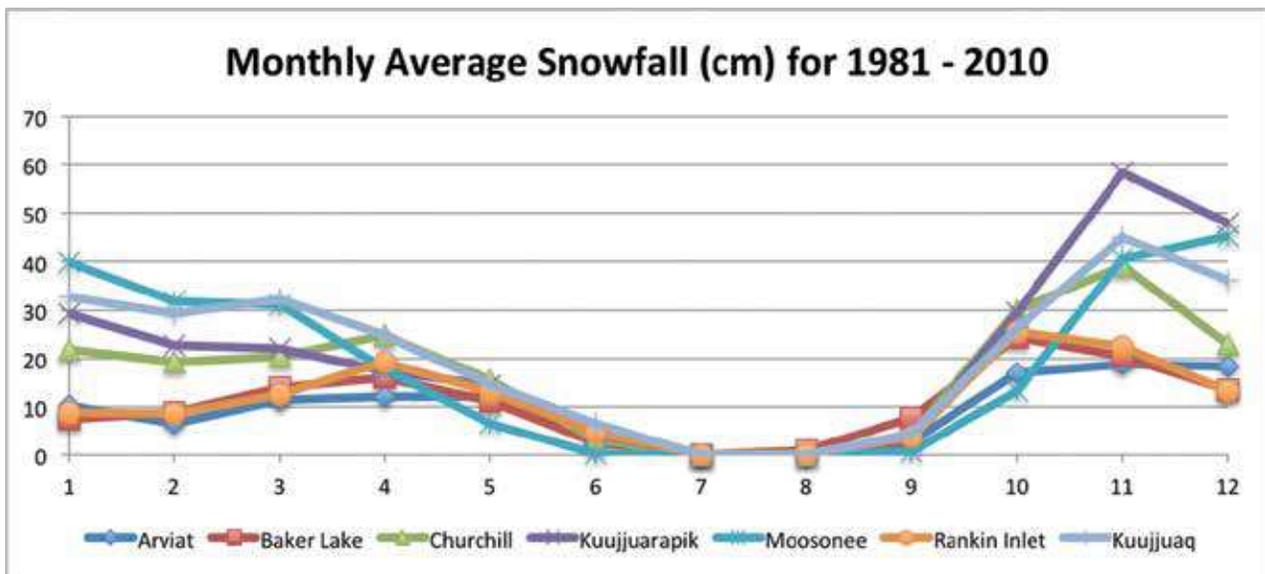


FIGURE 5. Monthly average snowfall in centimeters for Arviat, Baker Lake, Churchill, Kuujjuarapik, Moosonee and Rankin Inlet. The data was downloaded from the Digital Archive of Canadian Climatological Data [http://climate.weather.gc.ca/climate\\_normals/index\\_e.html](http://climate.weather.gc.ca/climate_normals/index_e.html).

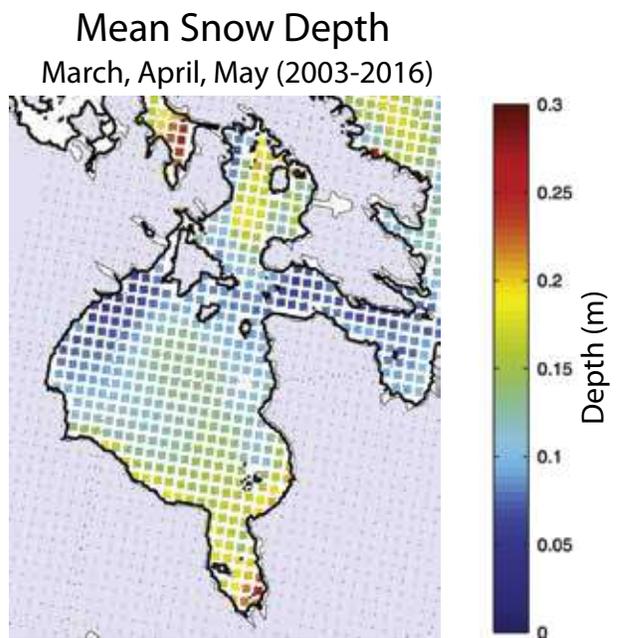
The accumulation of snow on sea ice can play an important role in ice growth as well as ice melt (Thomas and Dieckmann 2010). The presence of snow will slow the growth of sea ice by insulating it from the overlying cold air. The presence of snow on the sea ice in spring will slow the melt of the sea ice by maintaining high surface albedo (i.e., reflecting incoming light). On the other hand, if, in the spring, there is a rainfall event, the altered wet snow/saturated surface may have the opposite effect and advance the rate of melt of the sea ice by lowering the surface albedo. 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 albedo of sea ice and particularly snow sustains both cold Arctic air temperatures during sunlit seasons as well as the equator-to-pole temperature gradient that governs hemispheric-scale heat circulation.

The presence of snow on sea ice is significant for northerners in that it affects travel by snow-machine and is also significant for shaping habitat characteristics (e.g., for ringed seals). Generally, sea ice that is older than a few days will have accumulated snow on it (Thomas and Dieckmann 2010). Deeper snow will generally be found on older 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 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 for loose snow (Budd et al. 1966; Schmidt 1982).

Landy et al. (2017) used brightness temperatures (DMSP/SSM/I-SSMIS brightness temperatures) from satellite data and applied an algorithm developed by Markus and Cavalieri (1998) to create a 14 year (2003–2016) dataset for snow depth on sea ice in the eastern Canadian Arctic, including the Greater Hudson Bay Marine Region. The average snow depth during March-April-May over the Region is shown in Figure 6. Snow depth is greatest (>0.2 m) in southern James Bay, southeastern Hudson Bay and Foxe Basin. The thicker snow depths may be due to more precipitation in southern/southeastern areas and older ice being present in Foxe Basin. The recurring polynya along the northwest part of Hudson Bay and recurring open water in Hudson Strait may give rise to the low snow depth values in these areas.



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**FIGURE 6.** The average snow depth in March-April-May for 2003-2016 as obtained from DMSP/SSMIS brightness temperatures. Adapted from Landy et al. (2017).



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## 5. Observations and trends in winds

Generally, monthly mean wind speeds over the Hudson Bay Region vary from 5 to 16 km/h (1.5-4.5 m/s), peaking during late fall and early winter after a spring and summer minimum. Figure 7 shows the monthly average wind speeds and direction from 1979-2018 over the Greater Hudson Bay Marine Region. Throughout winter, western Hudson Bay and the eastern end of Hudson Strait including Ungava Bay have the highest wind speeds. There is also a west-east decrease in wind speeds across Foxe Basin in winter.

Figure 8 shows the monthly wind speed at five stations averaged from 1981-2010. A sufficient number of wind speed measurements were only available from five weather stations for this timeframe. Figure 8 shows similar results to the work by Gachon et al. (2011) with minimum wind speeds during July and maximum wind speeds during the fall from October to December. It is interesting to note that stronger winds are recorded at the weather stations (12-24 km/hr; Figure 8) than was derived from the NOAA NARR reanalysis dataset (5 to 16 km/h

or 1.5-4.5 m/s; Figure 7). This could be due to the different time periods that were averaged to produce Figure 7 versus Figure 8, or due to a regional bias in the reanalysis dataset.

Evidence for recent changes in regional wind patterns can be examined by comparing the patterns from 2011-2018 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, assuming the 1981-2010 period reflects the long-term average conditions. These calculated anomalies are illustrated in Figure 9. Although there was some regional and temporal variation, overall the wind anomalies from 2011 to 2018 relative to the 1981-2010 period indicate stronger winds throughout the Hudson Bay Region (i.e., all the anomalies are positive). The strongest changes (shown in yellow, orange and red) appear to be during April, June and October in Hudson Bay. In Hudson Strait and Ungava Bay, the strongest changes appear to be during July, August, September and December.

Wind speed observations from seven Environment Canada weather stations were examined in a recent report (Andrews

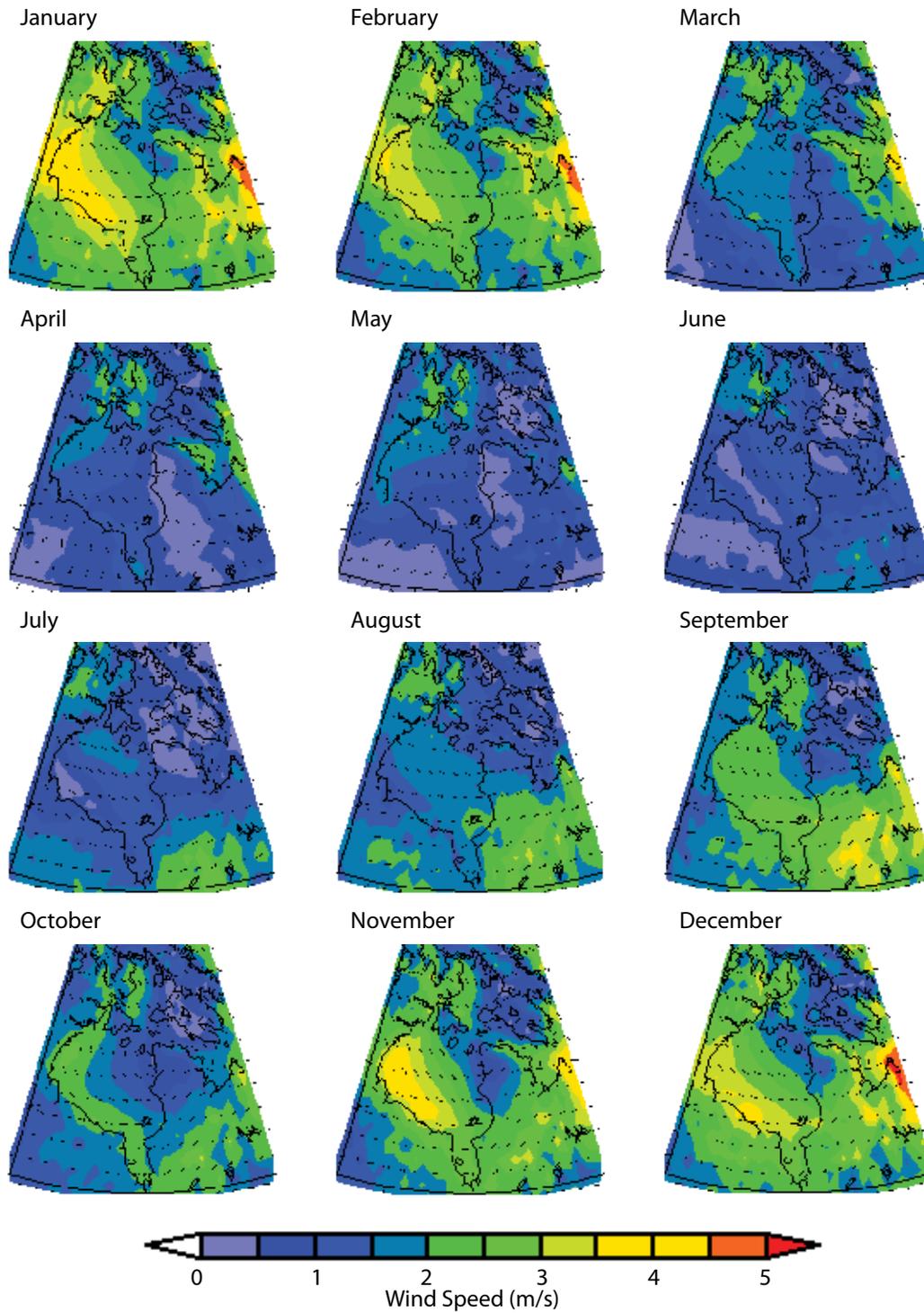


FIGURE 7. Monthly average wind speeds (m/s) for the Hudson Bay Region. Data from the NOAA NARR reanalysis dataset averaged over the years of 1979 to 2018. This figure is produced from <http://www.esrl.noaa.gov/psd/cgi-bin/data/narr/plotmonth.pl>

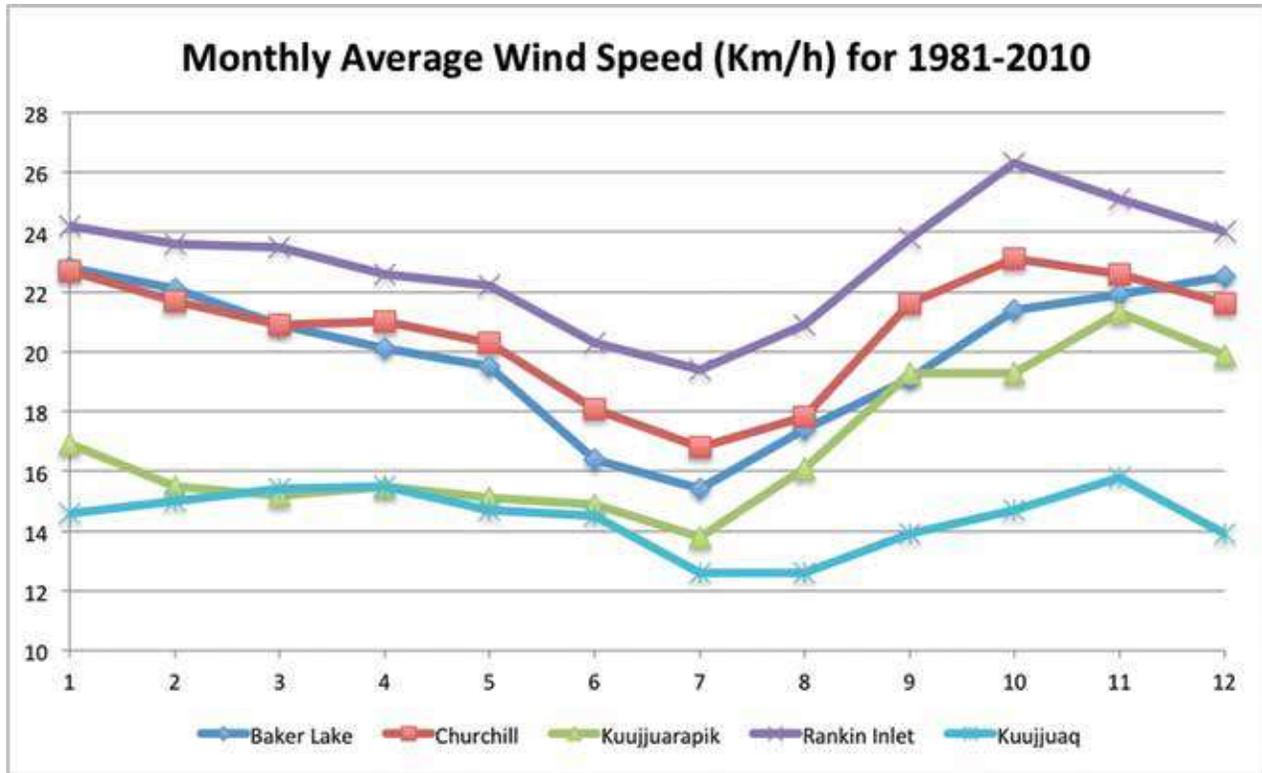


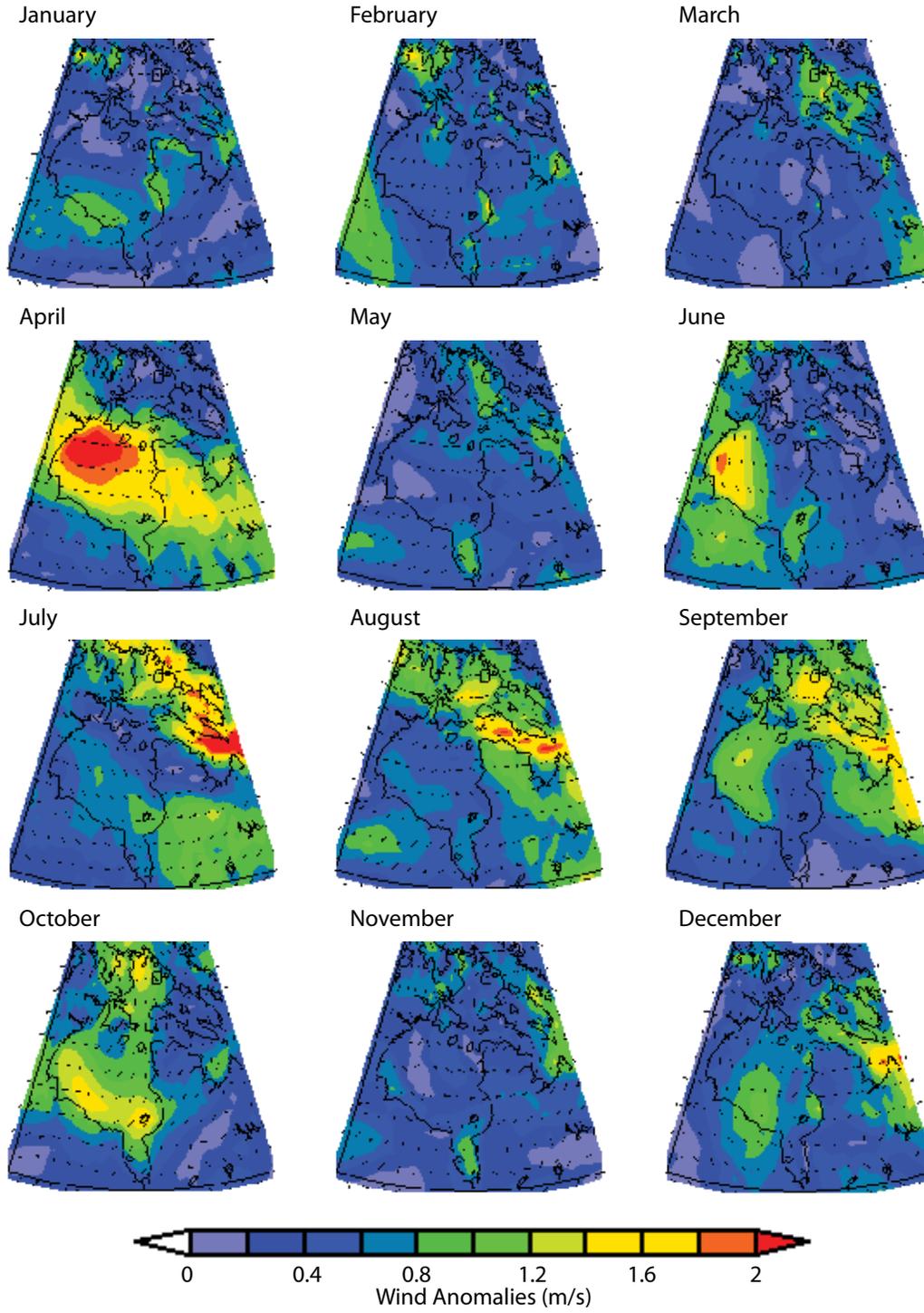
FIGURE 8. Monthly average wind speeds in km/h for Baker Lake, Churchill, Kuujjuarapik, Rankin Inlet and Kuujjuaq. The data was downloaded from the Digital Archive of Canadian Climatological Data [http://climate.weather.gc.ca/climate\\_normals/index\\_e.html](http://climate.weather.gc.ca/climate_normals/index_e.html)

TABLE 2. Average monthly and annual wind speeds (km/h) between 2001 and 2011. (+) indicate locations and time frames with significant positive trends between 1970 and 2011. Significance was determined using  $p < 0.05$  at the 95% confidence level. Data from Environment Canada (2013b).

	July	August	September	October	November	Annual
Baker Lake	13.6	15.9 (+)	17.5	19.3	20.5	18.1
Churchill	17.8	19.3	21.3	24.0	22.7	21.2 (+)
Coral Harbour	14.6	16.2	15.4	16.7	18.5	17.2
Hall Beach	14.7 (+)	15.5	16.6	18.6	20.1 (+)	21.0 (+)
Iqaluit	17.3	19.1	22.1	23.6	26.1	17.0
Kuujjuaq	13.8	13.5	16.6	18.4	20.5	13.4
Kuujjuarapik	11.9	11.1	14.0	13.6	14.8	17.5

et al. 2016), with focus on the open-water season (July to November). Monthly averages calculated from 2001 to 2011 show that wind speeds peak towards the end of the open water season, during September, October, and November (Table 2). Monthly average wind speeds during the open water season are greatest in Churchill and lowest in Kuujjuarapik and Coral Harbour. Analyzing the 41 year (1970-2011) wind-speed record at each station shows only three instances of significant positive

trends during the open water season: Hall Beach during July (0.860 km/h per decade) and November (1.0 km/h per decade) and Baker Lake during August (0.690 km/h per decade). Annual average wind speeds (2001-2011) are greatest in Churchill and Hall Beach, both of which have also experienced significant positive trends in annual wind speeds since 1970 of 0.290 and 0.592 km/h per decade, respectively. No significant trends indicating decreasing wind speeds were observed.



**FIGURE 9.** Anomalous wind patterns from 2011-2018 compared to the average wind patterns in the same area between 1981 and 2010. This figure is produced from <https://www.esrl.noaa.gov/psd/cgi-bin/data/narr/plotmonth.pl>

## 6. Adverse weather

Adverse weather usually refers to storms and blizzards, fog, freezing precipitation, blowing snow, freezing spray, and high winds. Currently, there is very little published research discussing the frequency of adverse weather in the Hudson Bay Region. Andrews et al. (2016) prepared the following summary of adverse weather.

### 6.1. Storms and blizzards

Many studies of Arctic weather comment on the likelihood of increasing storminess in the future and scientists appear quite confident in predicting a rise in Arctic storm frequency (e.g., Hanesiak et al. 2010). However, few studies look specifically at the trends in the Greater Hudson Bay Marine Region.

In an examination of cyclone frequency throughout the Arctic basin north of 68°N (which is the northern part of Foxe Basin), Sepp and Jaagus (2011) found that cyclonic activity increased significantly between 1948 and 2002. This increase reflected changes in the number of cyclones entering the arctic basin and the number of cyclones developing in the arctic

basin (Sepp and Jaagus 2011). In addition, Vermaire et al. (2013) also expect increased susceptibility to storm surges in low lying areas of the Arctic, particularly when climate-induced changes in sea ice are considered.

### Storms

Storms are influenced by both large- and regional-scale atmospheric processes. Large-scale processes include the behaviour and location of the polar front, while important regional-scale processes include sea ice extent and the temperature gradients between ocean, land, and atmosphere (Savard et al. 2014). With respect to these regional-scale influences, Savard et al. (2014) identify three distinct periods, in the Hudson Bay Region:

- Period 1, January to mid-May: The Region is generally ice covered, with little contrast between the sea surface temperature and air temperature over the surrounding land.
- Period 2, May to early September: These months include the melting (May-July) and early open water time periods (July-early September). During this time the temperature of the ocean in the Hudson Bay Region is colder than the temperature of the nearby landmasses, resulting in a thermal gradient between land and sea. The ocean acts as a heat sink for the atmosphere.
- Period 3, September to December: The temperature difference between the ocean and the landmasses reverses and strengthens, and the ocean waters of the Hudson Bay Region become a heat source for the atmosphere. The flux of heat and humidity from the ocean waters to the atmosphere strengthens such that it favours the formation, intensification, and regeneration of atmospheric depressions in the region.

With respect to larger-scale processes, the summer and fall are most prone to storms. This is because the frontal zone between the cold Arctic air and the warmer temperate air moves north towards northern Hudson Bay in the summer; this frontal zone supports the formation of atmospheric depressions and storms (Savard et al. 2014).

Storm activity in the Hudson Bay Region is greatest during the months of August to December, because both the regional- and larger-scale atmospheric conditions are at their most favourable for supporting atmospheric depressions (Savard et al. 2014). On the regional scale, the flux of heat and humidity from ocean to atmosphere creates and strengthens atmospheric depressions and causes a slowing of the movement of these depressions, resulting in longer residence times in the Bay for these weather systems (Savard et al. 2014). On a larger scale, the frontal zone is in its northern position over Hudson Bay. As a result, the August to December time period is sometimes referred to as the “storm season”, and this



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so-called storm season peaks in October and November (Savard et al. 2014).

A more quantitative description of storms in the Hudson Bay Region was provided in a 2011 non-peer-reviewed workshop presentation led by Environment Canada meteorologist Phillipe Gachon (Gachon et al. 2011). Using three different reanalysis data sets running from 1979 to either 2004 or 2009, Gachon et al. (2011) were able to present the monthly frequencies for several characteristics of storm tracks in the Hudson Bay area. Highlights of these findings are as follows:

- Storm frequency: Generally, storms occur most often during spring and fall, when the thermal contrast is greatest between the land and sea, and occur less often during winter and summer, when the thermal gradient is weaker. Storm frequency is greatest from August to December and peaks in October. (Note that this finding agrees with the results of Savard et al. 2014).
  - Fall months (September, October and November) average 2.5 storms per month or slightly more, while winter or early summer months (e.g., February or July) average closer to 2 storms per month.
- Storm intensity: Intense storms are most frequent in fall and spring and are relatively infrequent in summer.
  - There is roughly 1 intense storm per month in October, November, and March; other fall and spring months are just below 1. The frequency of intense storms is also relatively high in winter (just under one per month) but is very low in summer (roughly 0.2 per month).
- Average storm intensity is highest in fall, although all months are quite similar.
- Average storm length is between 3 and 4 days for all months, though storms average slightly longer from late spring through to early fall. These results agree with the observation by Savard et al. (2014) that storm tracks are slowed during the “storm season”.

### **Storm surges**

Savard et al. (2016) used hydrodynamic modelling to produce a series of daily water level measurements (with a tidal component, a non-tidal residual and total water level) for the period 1979 to 2013. The data was modelled for 23 coastal points around James Bay, Hudson Bay and Hudson Strait. The objective of this study was to look at the impact of climate change on storm surges, specifically during the open-water season, when any ice dampening, from the seasonal sea ice cover, would not be incorporated into the modelled data. The results of this study suggested that not all storms will produce storm surges and if they do it may only be in certain locations. An



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example given is that a storm may have no effect in Churchill but may produce a 2 m surge in Rupert Bay, Stag Island in James Bay. Their modeled data showed that climate change has modified the seasonality and frequency of the storm surges in the study area. They also determined that the changes in water levels associated with storm surges was largely caused by the winds that developed as part of the storms, particularly in southern Hudson Bay and James Bay. With the lengthening of the open water season (see Theme I. Chapter ii.) in the Greater Hudson Bay Marine Region, storm surges are now occurring more frequently in early winter (December and January) (Savard et al. 2016). With the changing seasonality and frequency of storm surges there is a need for more in-situ water level data. Theme I. Chapter iii. further describes the projections of storm surges from Savard et al. (2016).

### Blizzards

In an examination of hazardous weather in the Canadian Arctic, Ricketts and Hudson (2001) of the Meteorological Service of Canada reported the average number of blizzard events per year for several locations within the Hudson Bay Region. The authors defined blizzards as “visibility of 1 km or less in blowing snow and/or snow, winds of 40 km h<sup>-1</sup> or more and temperature below freezing; conditions lasting for at least 6 hours” (Ricketts and Hudson 2001). The number of blizzards per year reported by Ricketts and Hudson (2001) for various locations within the Hudson Bay Region vary from 3.5 in Cape Dorset (western Hudson Strait), 5.5 in Churchill, 10.4 in Hall Beach (northern Foxe Basin), 11.7 in Coral Harbour (Southampton Island, northern Hudson Bay), and 16.9 in Rankin Inlet (western Hudson Bay). These values are the average values per year between 1980-1999, with the exception of Rankin Inlet (1982-1999) and Cape Dorset (1985-1999).

### 6.2. Fog, freezing precipitation, and blowing snow

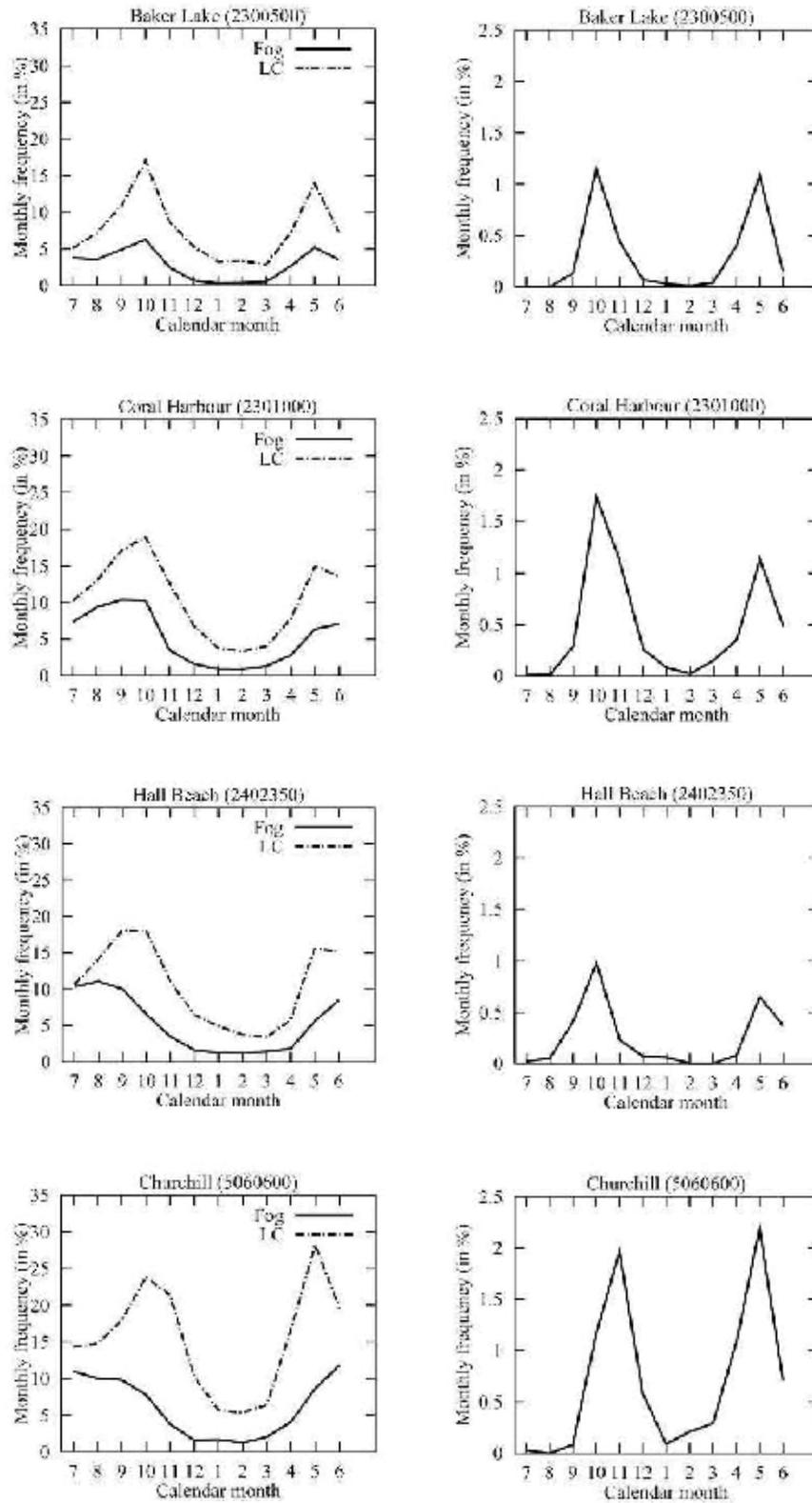
Hanesiak and Wang (2005) examined trends in the frequency of “adverse weather” (including fog, freezing precipitation, blowing snow, and low cloud ceiling) using data collected at 15 weather stations across the Canadian Arctic between 1953 and 2004. This analysis included four weather stations in the Hudson Bay Region: Baker Lake, Hall Beach, Coral Harbour and

Churchill. The average monthly frequencies of fog, low ceiling, and freezing precipitation between the mid-1950s and 2004 for these three locations are presented in Figure 10.

Hanesiak and Wang (2005) also examined the longer-term trends in these adverse weather conditions between the mid 1950s and 2004. When considering all 15 climate stations, they found that the Canadian Arctic experienced a significant increase in the incidence of freezing precipitation between the 1950s and 2004. However, there was much regional variation. Churchill did not experience any significant change in freezing precipitation, nor did Coral Harbour and Hall Beach when all months are considered together. But when considered seasonally, freezing precipitation in both locations increased significantly in spring and fall, and declined significantly in winter. In terms of fog events, which were defined as occasions when fog cover “extends to at least 2 m above ground level and reduces visibility to less than 5/8 mile (ie., 1 km..)” (Hanesiak and Wang 2005), the frequency was found to have increased at the western Arctic stations and decreased at the eastern stations during the time frame (Hanesiak and Wang 2005). However, there was no significant change in the frequency of fog events at any of the three Hudson Bay Region stations with the exception of a significant decline in fog frequency at Churchill in the fall. In terms of blowing snow, which the authors defined as “snow particles raised by the wind to sufficient heights above



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**FIGURE 10.** The average monthly frequency (% of days) with fog and low ceiling (LC) (left column), or freezing precipitation (right column) in Baker Lake, Coral Harbour, Hall Beach, and Churchill. Analysis extends from 1962 to 2004 for Baker Lake, 1955 to 2004 for Coral Harbour and from 1953 to 2004 for Hall Beach and Churchill. Adapted from Hanesiak and Wang (2005). © American Meteorological Society. Used with permission.



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the ground to reduce the horizontal visibility at eye level (1.8 m) to 6 miles or less." (Hanesiak and Wang 2005), the trend was primarily negative when all 15 stations are considered and was negative at Churchill, Coral Harbour, and Hall Beach when all 12 months are considered. There was no significant change in blowing snow at any one season at these stations.

### 6.3. Freezing spray

Fog, freezing precipitation, rain, and wet snow can all cause ice to form on vessels operating in Arctic waters. This superstructure icing can be quite hazardous to shipping. The most common cause of superstructure icing in the Hudson Bay Region is freezing spray, which occurs when air temperatures fall below the freezing temperatures of sea water and sea surface temperatures are below 6°C (Canadian Coast Guard 2012). Ice accretion rates from freezing spray can exceed 2 centimetres per hour and can lead to ice build-up of 25 cm or more. Spray icing is most frequently encountered in October and November in the Hudson Bay Region, due to the combination of cold air temperatures and remnant warm surface waters from the summer (Canadian Coast Guard 2012). No research discussing trends in the frequency of freezing spray in the Hudson Bay Region could be found to inform this analysis.

## 7. Conclusions and recommendations

There are many studies, mostly global or hemispheric in nature, suggesting that there is significant climate change occurring in the Greater Hudson Bay Marine Region including

warming, increases in precipitation and increases in snowfall. However, there has been little research specifically on these climate parameters in the Region, in part because stations with sufficient data are scarce. There is thus a mismatch between air temperature, precipitation, and snowfall research results and the information needs of the Inuit and Cree that live in the Region, who are experiencing these changes first-hand. Inuit and Cree in the Region are reporting increases in extreme events, such as rain on snow, less predictable weather, and an increase in the intensity of storms. There are few scientific studies looking at the changes in adverse weather and storms in the Greater Hudson Bay Marine Region, which is an important research gap considering the potential for impacts on safe travel and infrastructure.

The ability to monitor climate change at a regional level is strongly dependent on the availability, distribution and effectiveness of climate stations. In the Greater Hudson Bay Marine Region, relevant stations for the gathering of meteorological and related climate data are too few in number and unevenly distributed. There are also major hydrographic regions for which reliable precipitation data and water level data are scarce or non-existent, which limits analysis of changing precipitation, runoff and water level statistics. The lack of long-term climate monitoring stations reduces the ability to evaluate output from regional climate models and to determine regional climate trends. There should be an increase in long-term meteorological and hydrological monitoring including both an increase in the number of stations and improvement in the spatial distribution. It will be important also to utilize data generated by unofficial stations, for example, long-term community-based monitoring programs and incorporate these data into trend analyses and regional models where possible.

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I.ii

# Characteristics of the Seasonal Sea Ice Cover

## AUTHORS

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## Summary

Sea ice is a defining element of the Arctic environment, and while it may only be seasonally present within the Greater Hudson Bay Marine Region it exerts an influence on all facets of the Bay. The ice cover represents a habitat for marine animals, a barrier to shipping, and an important part of the Inuit culture that forms a travel route and extends hunting grounds. Sea ice typically begins to form in Foxe Basin and northwestern Hudson Bay during late October and covers the entire marine region by the end of December. The complete ice cover remains intact until May when it begins to melt, with all sea ice typically melting out by late July or early August. While the ice cover is intact the extent, thickness and type of sea ice varies both in terms of space and time as the ice cover is a dynamic feature that is continually evolving and changing. A majority of the ice cover is mobile, leading to the dynamic formation of ridges and rubble fields. However there is a narrow band of landfast ice that forms around the periphery of the Bay and provides a stable platform for over-ice travel. Variability in the timing, motion and thickness of the ice cover arise due to variability and long-term changes in the temperature and wind in the atmosphere, and temperature, salinity, tides and currents in the underlying water column. Overall there are significant trends towards delayed ice formation and earlier breakup that is prolonging the open water season, however the ice cover is highly dynamic and quite variable.

## Key Messages

- **The timing of freeze-up and breakup has been changing, with earlier spring breakup and later fall freeze-up. The length of open water season has increased between 3 and 5 weeks over the past 30 years.**
- **Sea ice thickness is important to estimate the volume of the Arctic sea ice cover and estimate the freshwater flux entering the ocean following summer melt and downstream effects of this flux on oceans at lower latitudes. Ice thickness is also important for marine mammal habitat and forecasting marine transportation (shipping or cruise) routes. There are no clear trends in sea ice thickness however the thickness is linked to the freeze-up and breakup dates. There are numerous reports of ice that is not thick or strong enough to travel on which is causing concerns for safety in many communities.**

- **Sea ice thickness is not well documented, however newly emerging technology and community based monitoring programs are now available and will need to be incorporated into future studies of trend analysis.**

## 1. Introduction

The ice cover within Hudson Bay is comprised of both landfast and mobile pack ice. Landfast sea ice forms along the coast and remains relatively stable throughout winter as it is either anchored to shore or the seafloor. The mobile ice pack is exactly that, it is a mobile ice cover that forms outside of the coastal zones and drifts around the Bay according to winds, currents, tides, and interactions between ice floes. In terms of ice thickness, cold temperatures promote ice growth by removing heat from the surface waters until the thin band of surface water in contact with the ice reaches its freezing point and freezes onto the bottom of the existing ice cover. Beyond just temperature driven ice growth, the ice cover can grow thicker through ridging and rafting of ice floes that are compressed against each other. This dynamic form of ice growth occurs continuously within the mobile ice cover where ice floes are continually interacting with each other, but within



**FIGURE 1.** The locations of recurring polynyas and coastal leads in the Hudson Bay Marine Region (Modified from Canadian Coast Guard 2012).

the landfast ice, dynamic activity is limited to the ice edge where the mobile ice compresses against the landfast ice and creates a very thick band of deformed ice called *stamukhi*. Within the ice cover, areas of open water called polynyas can exist throughout winter and provide an important biological hotspot for wildlife. Polynyas can exist as a result of either upwelling of warm water to the surface, known as a sensible heat polynya, or offshore winds that force the mobile ice cover away from the landfast ice edge, known as a latent heat polynya. Due to its geography and large coastal area, polynyas are an important part of the seasonal ice cover in Hudson Bay and form within many coastal areas of Hudson Bay (Figure 1). Within the mobile ice cover areas of open water separating floes are known as leads and form as ice floes diverge from each other. New ice formation occurs within leads and polynyas throughout winter, promoting increased sea ice volume and continued brine rejection into the underlying water column as salt is rejected from the growing ice cover.

## 2. Historical timing of sea ice freeze and melt

The Hudson Bay Marine Region undergoes a complete freeze and thaw cycle every year that is best characterized by the dates of freeze-up and breakup. Based on weekly ice charts produced between 1981 and 2010, the Canadian Ice Service presented the typical pattern and timing of freeze-up and breakup within the region (Figure 2). Typically, sea ice first forms in Foxe Basin during mid-late September. In early October, sea ice forms along the northwest coast of Hudson Bay and subsequently advances southward along the coast during October before advancing southeastward across the Bay during November. Typically by early December a majority of Hudson Strait, Hudson Bay and James Bay are ice covered, though the eastern boundaries of all three regions may still be ice-free by mid-December. Dropping air temperatures ultimately drives the cooling of the sea surface and timing of freeze-up, however the surface salinity, wind forcing and solar radiation all influence the precise timing of sea ice formation. Once the ice cover has formed it grows thicker through both thermodynamic and dynamic processes (ridging and rafting of ice floes), while also presenting a platform for the accumulation of snow. Snow acts to insulate the ice and thereby reduces thermodynamic sea ice growth.

In terms of breakup, the Canadian Ice Service (2013) presented the typical pattern and timing of sea ice breakup in the Hudson Bay Marine Region (Figure 2). Historically the ice cover has begun to breakup in coastal areas during early June, when rising air temperatures and solar heating of areas

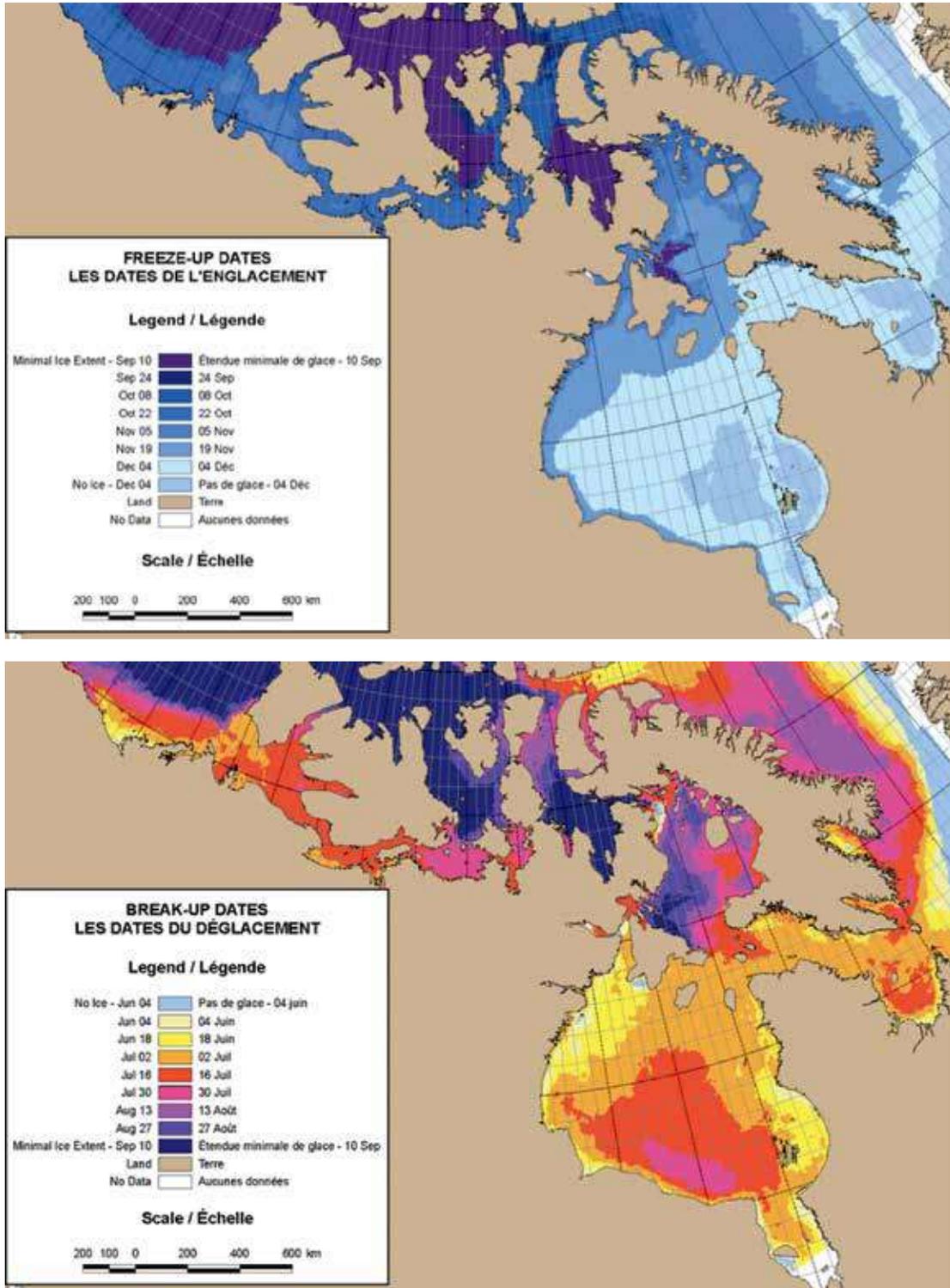
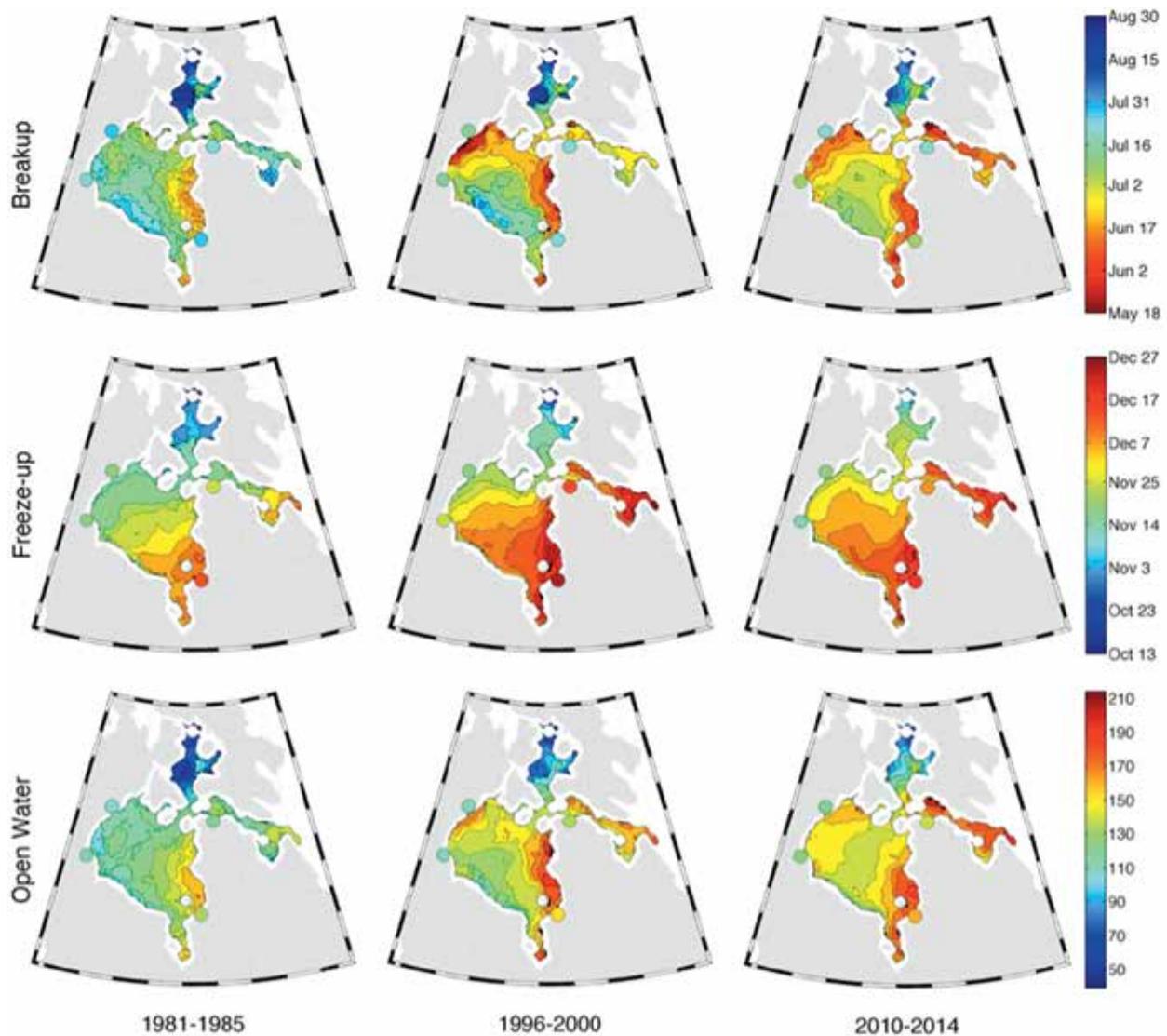


FIGURE 2. Average freeze-up and breakup dates between 1981 and 2010 in the Hudson Bay System. The different colours indicate where sea ice exists at the corresponding date. The edge of each colour indicates the location where the median value of ice concentration falls below 1/10 (CIS 2013).

of open water prevent the formation of new ice within the coastal polynyas. Breakup progresses from the northwest and eastern coasts of Hudson Bay towards the centre of the Bay where sea ice remains until late July or early August. Further north within Foxe Basin the ice cover doesn't typically breakup until late August or early September. Of course air temperatures, winds, solar radiation, cloud cover, snow depth and ice thickness will all influence the timing of sea ice breakup which can vary spatially and temporally (Gagnon and Gough 2005). The timing of breakup dictates the onset of the open water shipping season that is used to re-supply communities and mines throughout the Bay (see Theme III. Chapter ii. for more

information on community re-supply and shipping), but is also critical to the biological food web within Hudson Bay (see Theme II. Chapters iii. - vi. for more information on the biological food web), specifically forcing polar bears back to shore as the sea ice no longer presents a stable hunting platform.

In a more recent analysis Andrews et al. (2018) presented the median timing of freeze-up and breakup, and duration of the open water season throughout the Hudson Bay Marine Region based on daily sea ice observations from satellites (Figure 3). The analysis focused on three separate five-year periods and once again highlighted the spatial variability in the timing of freeze-up and breakup and in turn highlight

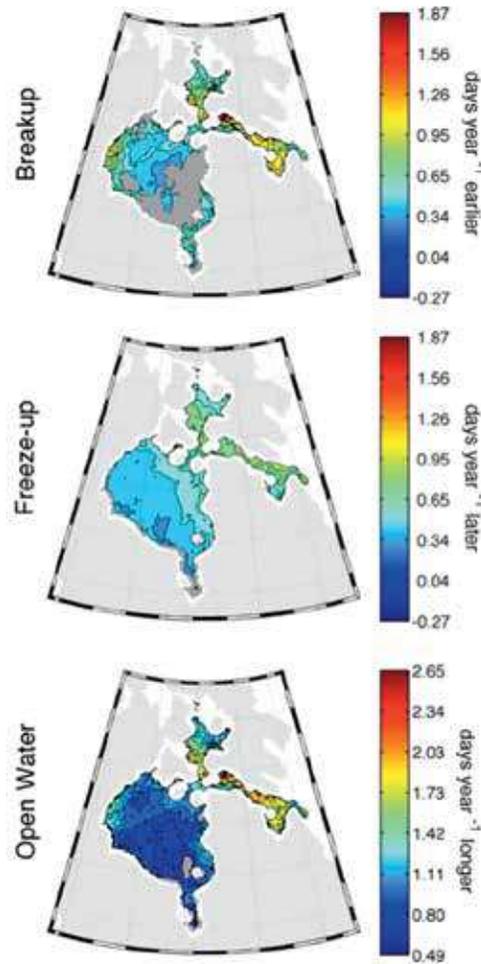


**FIGURE 3.** The timing of breakup and freeze-up, and the length of the open water season in the offshore waters of the Hudson Bay Marine Region during three five year-long periods. (Andrews et al. 2018).

the variability in the open water season within the region. Furthermore the maps highlight how these three variables changed between the three periods. In the early 1980s breakup began in eastern Hudson Bay, around mid-June and ended in Foxe Basin at the end of August. More recently breakup has begun in both eastern and northwestern Hudson Bay between late-May and early-June. Within Hudson Bay breakup still progresses towards the southern region, though the timing of this has moved forward as well, with southern Hudson Bay now breaking up in early to mid-June compared to mid-late July during the early 1980s. Foxe Basin continues to be the last area to breakup within the region, and now occurs in early-August compared to late-August during the early 1980s. In terms of freeze-up the northwest to southeast pattern is still present, however the timing has shifted towards later freeze-up with the greatest change occurring between the early 1980s and late 1990s. In the early 1980's freeze-up began in late-October to early November and was complete by early-December. More recently between 2010 and 2014, freeze-up began in mid to late-November and was complete around late-December. Generally breakup is occurring earlier and freeze-up is occurring later, and collectively these two factors have considerably increased the duration of open water throughout the Hudson Bay Marine Region.

### 2.1. Trends in freeze-up and breakup dates

Both Hochheim and Barber (2014) and Andrews et al. (2018) used satellite-based observations of ice sea ice concentration to assess the changes in the timing of breakup and freeze-up within the Hudson Bay Marine Region since 1980. Both studies found that sea ice is breaking up earlier during spring and forming later during fall. Collectively these two changes are fostering a longer open water season, though there is considerable spatial variability in the trends of all three variables (Figure 4). There is a significant trend towards earlier breakup throughout a majority of the region with trends varying from 2.9 to 17.9 days per decade, with the greatest changes taking place in Hudson Strait and Foxe Basin. Within Hudson Bay there are significant trends towards earlier breakup throughout the northwest and the coastal waters of southeast. However, a large portion of south-eastern Hudson Bay, beyond the coastal waters near the Belcher Islands, did not exhibit significant trends in breakup. Conversely, the entire Hudson Bay Marine Region exhibited significant trends towards delayed freeze-up. Trends were greatest in Hudson Strait and Foxe Basin where freeze-up has been significantly delayed at a rate of 10 days per decade. Within Hudson Bay the change in freeze-up increases from the southwest to northeast, where freeze-up has been delayed at a rate of 5 days per decade. Subsequently the entire region has exhibited a significant lengthening of the open



**FIGURE 4.** Trends in breakup, freeze-up, and open water timing. 1980-2014 trends (days per year) in offshore ice timing from linear regression. Pixels with significant trends ( $p < 0.05$ ) are shown in colour, all other pixels are shown in dark gray. (Andrews et al. 2018)

water season, with trends from 5 to 15 days per decade within Hudson Bay, and the greatest changes taking place in Hudson Strait and southern Foxe Basin where trends are as great as 23 days per decade.

To highlight the changes in the ice cover of the Hudson Bay Marine Region, Hochheim and Barber (2014) compared the timing of breakup and freeze-up, and open water duration from 1996-2010 against the 1980-1995 period (Table 1). In terms of the duration of open water, it increased by 3.1 weeks in Hudson Bay, 3.5 weeks in Foxe Basin and 4.9 weeks in Hudson Strait. Approximately half of these changes were due to delayed freeze-up while changes in breakup accounted for the other half. Delayed freeze-up manifests itself as a considerable

**TABLE 1.** Some results from an examination of sea ice extent (SIE) and surface air temperature (SAT) trends for the Hudson Bay System (Hochheim and Barber 2014).

	Hudson Bay James Bay	Foxe Basin	Hudson Strait Ungava Bay
A. Average change in open water season for 1996-2010 vs. 1980-1995 (weeks)	+3.1	+3.5	+4.9
B. Average change in freeze-up date for 1996-2010 vs. 1980-1995 (weeks later)	1.6	2	2.4
C. Mean change in breakup date for 1996-2010 vs. 1980-1995 (weeks earlier)	1.5	1.5	2.5
D. Change in fall air temperature corresponding to B. and C.**	+1.5°C	+1.9°C	+2.9°C
E. Relationship between fall air temperature and freeze-up date	Increase of 1°C delays freeze-up by 0.71 weeks	Increase of 1°C delays freeze-up by 0.88 weeks	Increase of 1°C delays freeze-up by 0.67 weeks
F. Relationship between fall SAT and late-fall SIE	Increase of 1°C relates to 14.4% reduction in SIE	Increase of 1°C relates to 14.4% reduction in SIE	Increase of 1°C relates to 15% reduction in SIE

\* sea ice extent data from different weeks were used for the three locations: Hudson Bay - November 19th to December 5th, Foxe Basin - October 29th to November 18th, Hudson Strait - November 26th to December 16th.

\*\* Freeze-up dates and late-fall sea ice extent were correlated to seasonal temperatures from September to November (Sep-Oct-Nov) for Hudson Bay and Foxe Basin, and October to December (Oct-Nov-Dec) for Hudson Strait.

reduction in sea ice extent, which Hochheim and Barber (2014) ascribe to increasing fall air temperatures. Overall the authors found that fall air temperatures and fall sea ice were highly correlated ( $R^2 = 0.79-0.82$ ) and that for every 1°C increase in the fall air temperature, the fall sea ice extent decreased by 14%, and freeze-up was delayed by 0.7 to 0.9 weeks. In terms of spring breakup, spring sea ice extent and breakup dates were correlated with both fall and spring air temperatures, as well as with surface winds. This highlights the relationship between freeze-up (fall air temperatures) and breakup, but also highlights the dynamic component (winds) of the breakup of the ice cover.

Beyond satellite detection of changes to the ice cover in the Hudson Bay Marine Region, the communities in the region have also reported changes:

*“The land used to be covered in snow, prior to the sea-ice freezing over. Now, the land is barely covered with snow prior to the sea-ice freezing and the sea-ice no longer freezes around October. Now it freezes around the middle of December. It seems to be later and later every year, the land fast ice around Rankin Inlet.”*

Rankin Inlet (Elder’s Conference on Climate Change, Jerome Tattuinee, pg 12)

*“The ice around our island used to form around late October, but in the recent past, this has not occurred until December. It now varies between the middle to late December and the ice is a lot thinner than before. Whereas it used to be about six feet thick, it now averages about three feet or less.”*

Sanikiluaq (Elder’s Conference on Climate Change, Zach Novalinga, pg 7)

*“We used to have spring camps. If we left in May and we started going ice fishing in the middle of May, we would be able to camp for 2 or 3 weeks at a time in springtime because the ice was solid. But now from what I am seeing, we are only able to stay out a week if not little over a week because we have to go home right away because the ice is melting rapidly”*

Sanikiluaq (Community Environmental Monitoring Systems Workshop Report, Sarah Kittosuk, pg 8)



S. SCHEMBRI

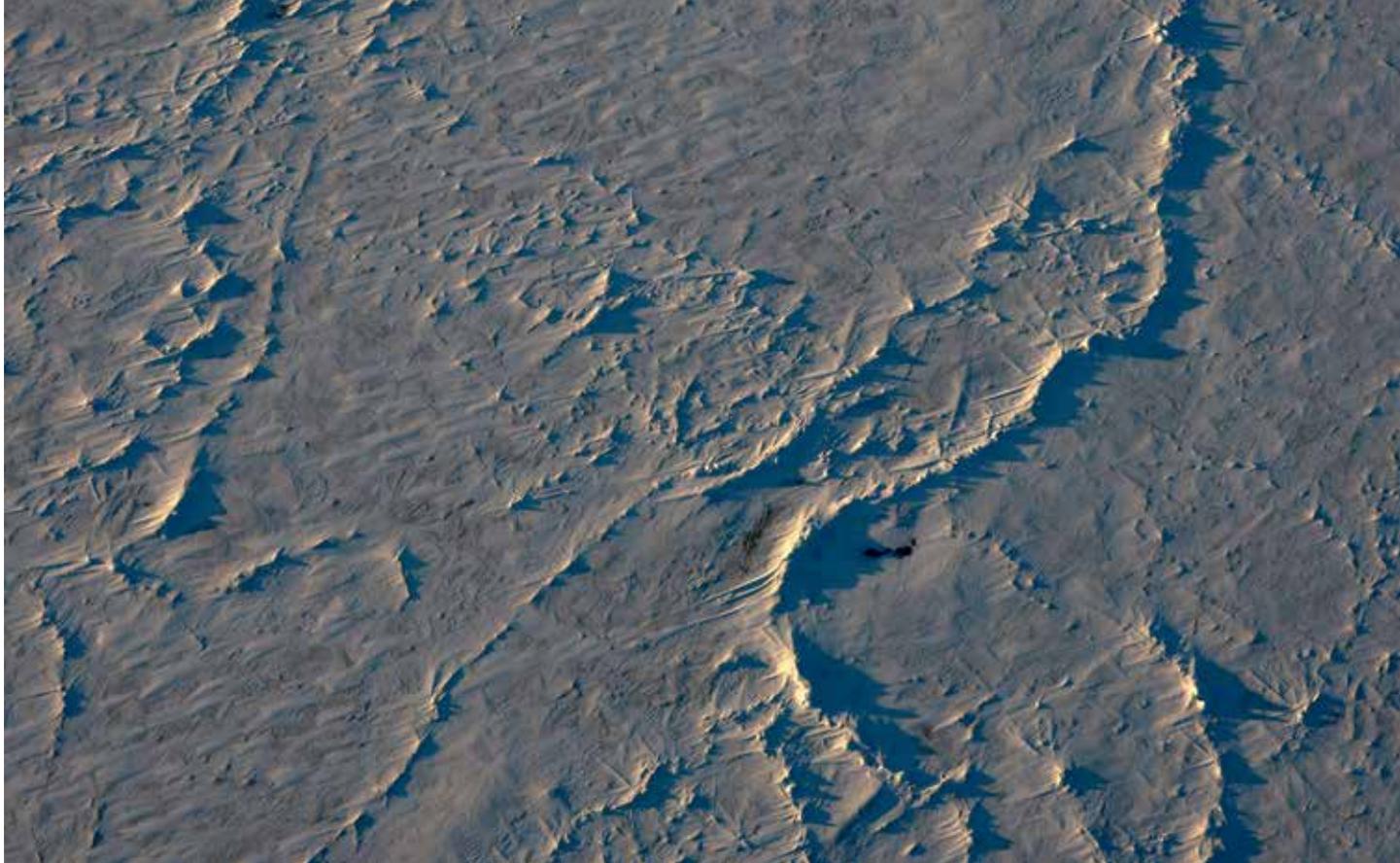
*“For example, this fall I went out hunting for 3 days while the ice was freezing. Thinking that it was solid, on the third day I tried to go on top with a hunter in front of me. I couldn’t follow him anymore because it was very unstable ice. There were actually waves.”*

Inukjuak (Community Environmental Monitoring Systems Workshop Report, Daniel Kasudluak, pg 9)

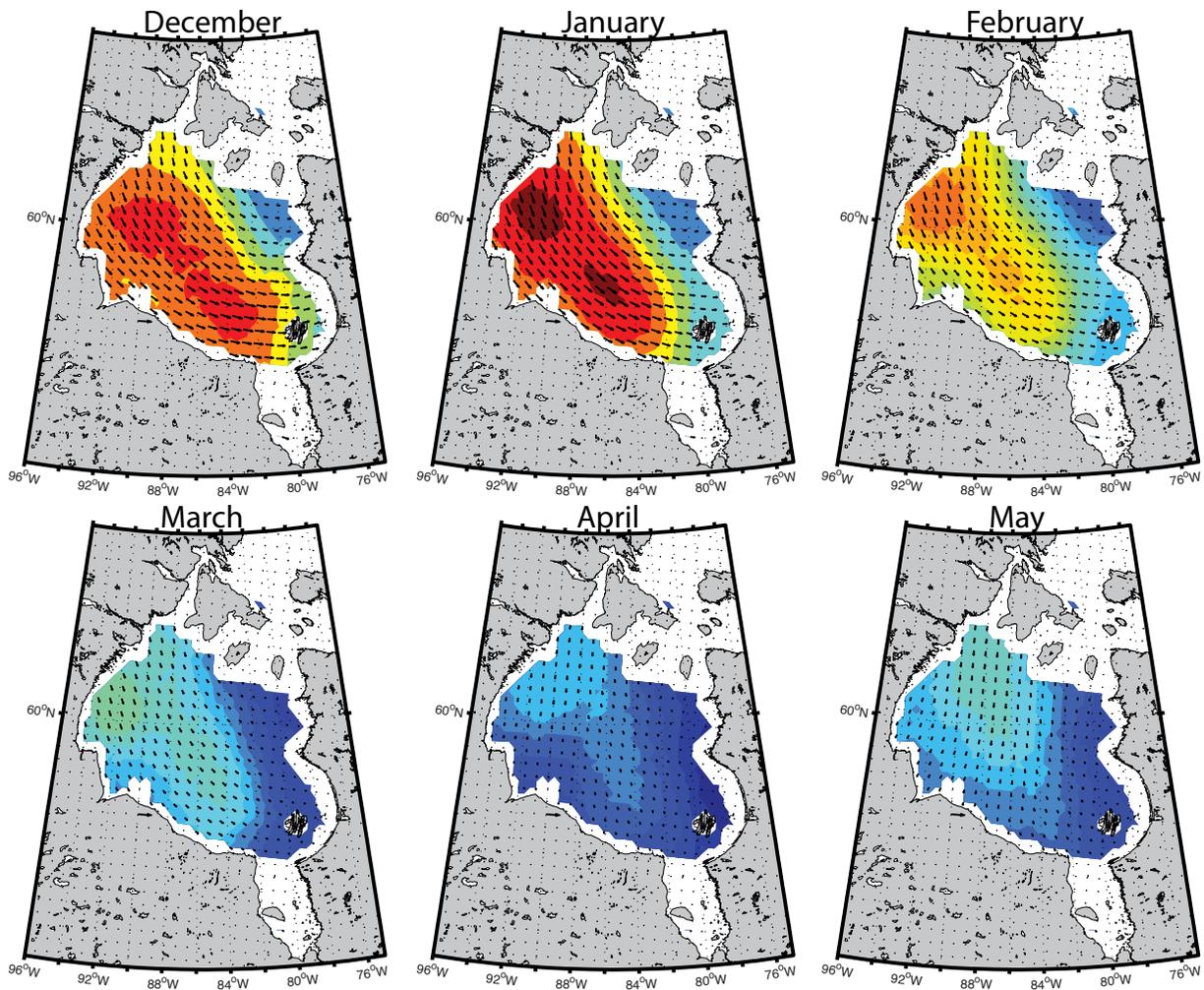
Personal observations such as these from communities are important, in addition to confirming changes noted from satellites and models they can also provide a much more detailed set of observations. Furthermore they draw attention to the impacts that these changes are having on the people who rely on the sea ice and treat it as a part of their identity. Community-based monitoring and research projects are described in more detail in the concluding chapter: Perspectives on the Future of Research in the Greater Hudson Bay Marine Region.

### 3. Sea ice motion

From the first aggregation of ice crystals during freeze-up to the last remnant piece of ice to melt out during spring breakup, the ice cover of the Greater Hudson Bay Marine Region is a dynamic feature. The coastal band of landfast sea ice becomes anchored to either the shore or seafloor and moves vertically with the tides, but beyond the landfast ice the mobile ice cover is in near constant motion. Ice floes within the mobile pack ice drift under the forcing of winds, currents, tides, the geostrophic force and oppositional forces from the interactions of ice floes. Under the prevailing westerly winds the mobile ice pack within the region is typically advected from the northwest to the southeast across the Bay. From the 1979-2016 monthly means it is clear that ice drift speeds are greatest in the northwest portion of Hudson Bay during all months (Figure 5). In terms of timing, ice drift speeds are greatest during December and January (up to 4 km/day), when the ice cover is comprised of new, thin sea ice. But as the ice grows thicker throughout winter the ice drift speeds gradually slow down to monthly mean speeds of <1.5 km/day during April, May and June.



L. CANDLISH



**FIGURE 5.** Monthly mean fields of sea ice drift in Hudson Bay from 1979 to 2016 (data from Tschudi et al. 2016 - NSIDC Polar Pathfinder 25 km resolution)

Between March and April there is a slight shift in the ice drift pattern from a south-eastward heading to more of a southward heading, which is the reason why southern Hudson Bay is typically the last area to become ice free. Note that the Polar Pathfinder ice drift dataset produced by the NSIDC (Tschudi et al. 2016) has a coarse resolution of 25 km, therefore it doesn't provide ice drift data in small areas like Foxe Basin or James Bay, or in relatively narrow channels like Hudson Strait.

Westerly winds and the resultant south-eastward ice drift within Hudson Bay lead to the frequent formation of polynyas in areas downwind from the coastal landfast sea ice. The largest polynya forms in the northwestern region of Hudson Bay (Gough et al. 2004) and is an extension of the Roes Welcome Sound polynya that forms further north between the mainland and Southampton Island (Barber and Massom 2004). As an

example, MODIS imagery shows a narrow band of open water in northwestern Hudson Bay on February 27, 2010, but after a week of strong northwesterly winds the mobile ice was forced offshore and created a polynya that covered 6,800 km<sup>2</sup> (Gunn 2014). In this situation strong northwesterly winds advected the existing ice cover offshore and exposed a vast area of open water, which would have subsequently refroze. This process leads to enhanced production of sea ice in northwestern Hudson Bay, as well as along the western coasts of Foxe Basin, James Bay, Ungava Bay and a few sporadic locations in Hudson Strait (Figure 7). Beyond the polynya in northwestern Hudson Bay, there are several polynyas that form within the Belcher Islands and around Akimiski Island in James Bay. Additionally, the large tides within the Greater Hudson Bay Marine Region drive an extensive coastal flaw lead system that exposes areas

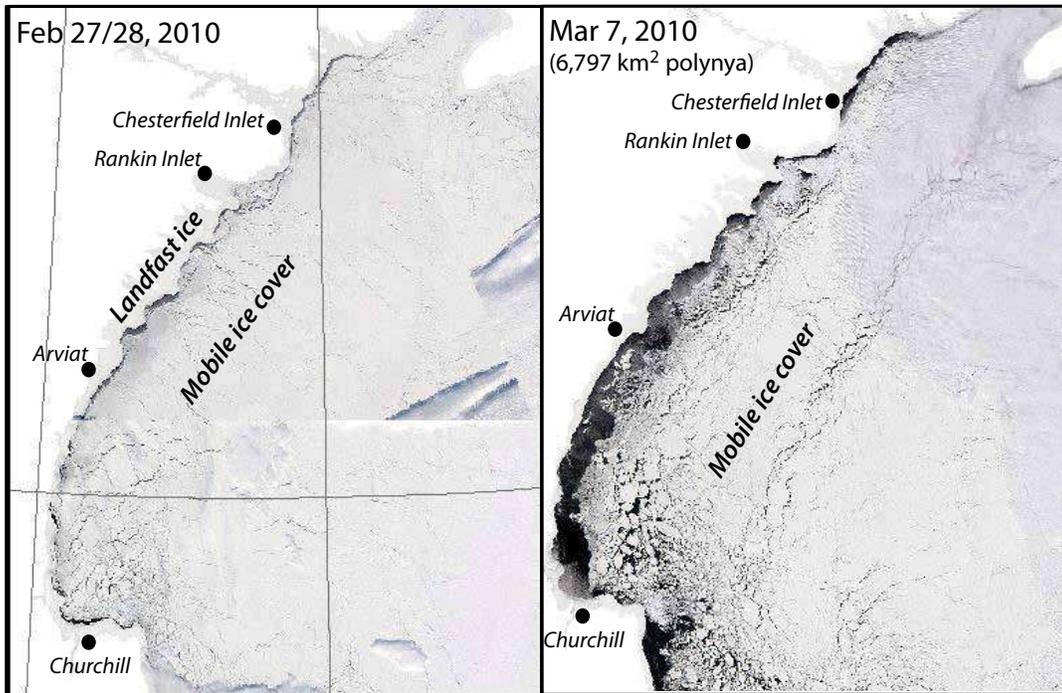


FIGURE 6. MODIS images over northwestern Hudson Bay before and after strong northwesterly winds opened the polynya in early March 2010 (Adapted from Gunn 2014)

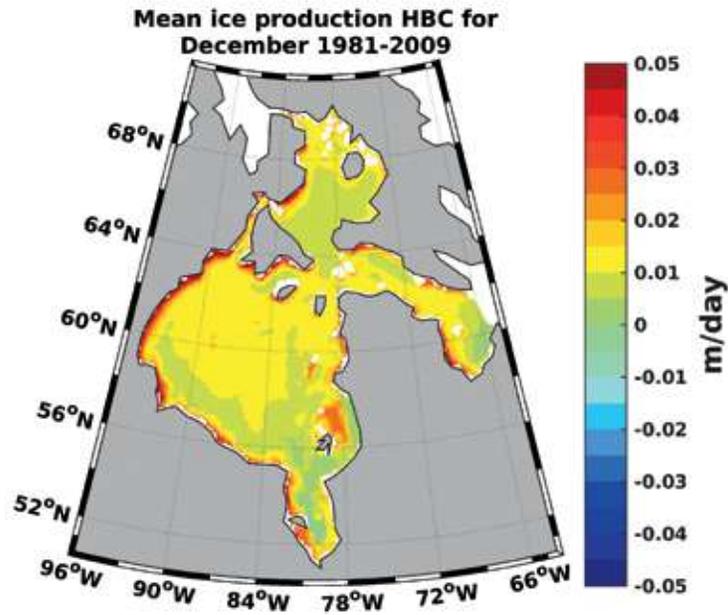
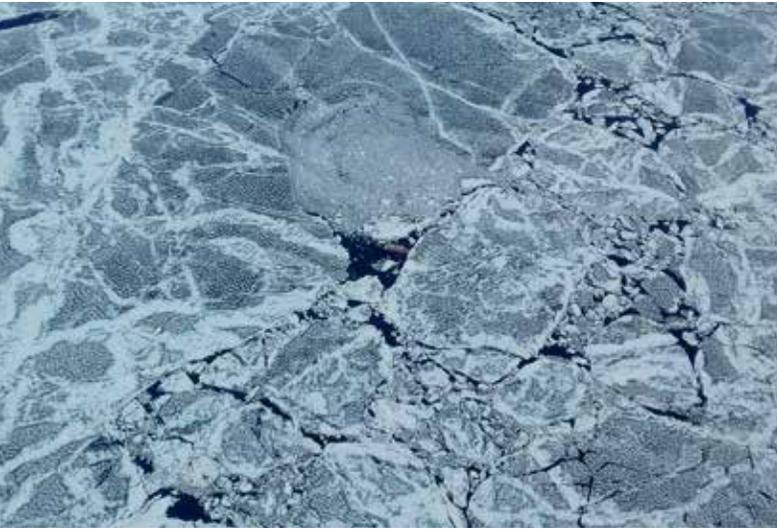


FIGURE 7. 1981 – 2009 average monthly sea ice production for December (Adapted from the NEMO model).



S. KIRILLOV

of open water along the landfast ice edge semi-diurnally. The difference between the coastal flaw lead and a polynya is that the flaw lead closes during the next high tide, whereas a polynya persists beyond the tidal cycle.

#### 4. Sea ice thickness

While understanding the spatial extent and timing of sea ice is important, the third dimension of sea ice, its thickness, provides further insight into the ice cover of an area. Following the initial formation of sea ice, it is the thickness of this ice that determines whether it is suitable for human travel or wildlife migration. The thickness of sea ice dictates what class of ship can operate within the ice cover, and influences the timing of breakup as thicker ice is going to take longer to melt out. Furthermore ice thickness dictates the volume of sea ice that represents a freshwater reservoir that is transported and redistributed around the Bay (See Theme I. Chapter v). As we previously discussed, sea ice grows thicker through two separate processes; 1) Thermodynamic growth is the result of cold air temperatures and cold surface waters that are near their freezing point, and 2) Dynamic deformation of the ice cover through ridging and rafting of ice as a result of convergent ice motion.

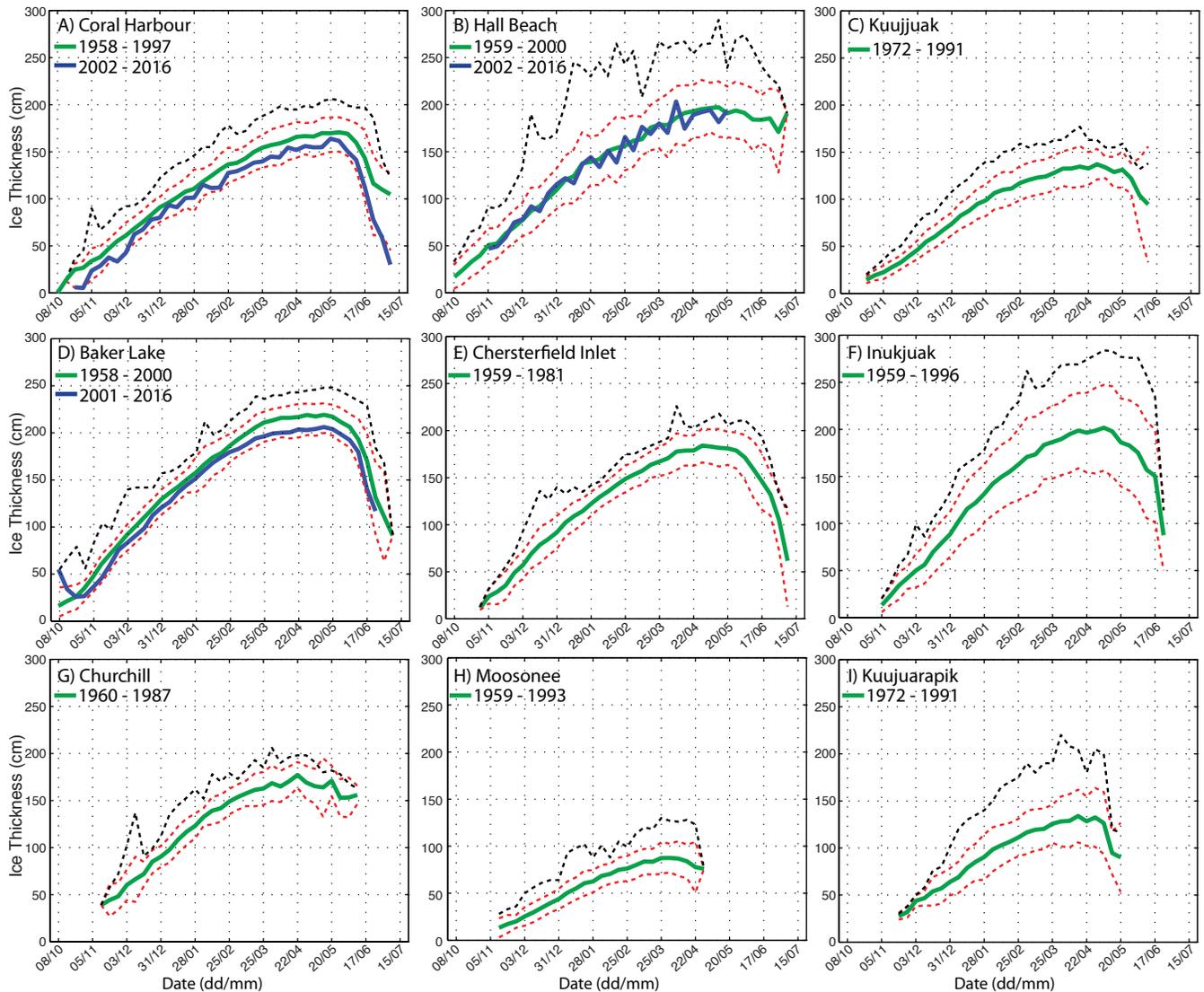
Historically observations of ice thickness were limited to manual measurements, meaning that observations were limited to the landfast ice. Between 1958 and 2000 the Canadian Ice Service collected weekly observations of landfast ice thickness at nine communities (Chesterfield Inlet, Baker Lake, Churchill, Coral Harbour, Hall Beach, Inukjuak, Kuujjuak, Kuujjuarapik and Moosonee; data analysed within Gagnon and

Gough 2006; and within this work, Figure 8). This initial program revealed that maximum ice thickness within the region occurred between mid April and late May, and varied from 0.9 m in Moosonee, where there is the shortest sea ice season, to above 2 m in Baker Lake, Inukjuak and Hall Beach (Figure 8; Gagnon and Gough 2006). The authors observed a thickening trend in western Hudson Bay compared to a slight thinning trend in Eastern Hudson Bay, which they ascribed to the variability in air temperature, snow depth and dates of freeze-up and breakup. While the initial program ended in 2000 it was brought back in 2002 but only within three communities within the region (Coral Harbour, Hall Beach and Baker Lake). Focusing on these two periods we can see that the average weekly ice thickness is lower in Coral Harbour and Baker Lake, while mean ice thickness remained relatively stable in Hall Beach. While these observations help ensure the safety of over ice travel and provide a long-term dataset, they are limited in their application because they only represent the growth of landfast sea ice.

With the operation of NASA's ICESat mission (Ice, Cloud and land Elevation Satellite) from 2003 to 2008, and the European Space Agencies Cryosat-2 mission from 2010 to present, satellite altimetry has become the preeminent technique for measuring sea ice thickness at high temporal and spatial scales. Satellite altimetry can typically measure ice thickness with an uncertainty below 0.5 m (Ricker et al. 2014), though snow depth, snow density and sea ice density must be estimated or parameterized to estimate ice thickness. While these data had been used within several studies to assess ice thickness in the Arctic (Kwok and Rothrock 2009; Maslanik et al. 2007; Tilling et al. 2015; Ricker et al. 2014), the method was not applied to sea ice in Hudson Bay until the work of Landy et al. (2017). From ICESat and Cryosat-2 the authors derived the first spatially complete fields of ice thickness within the region



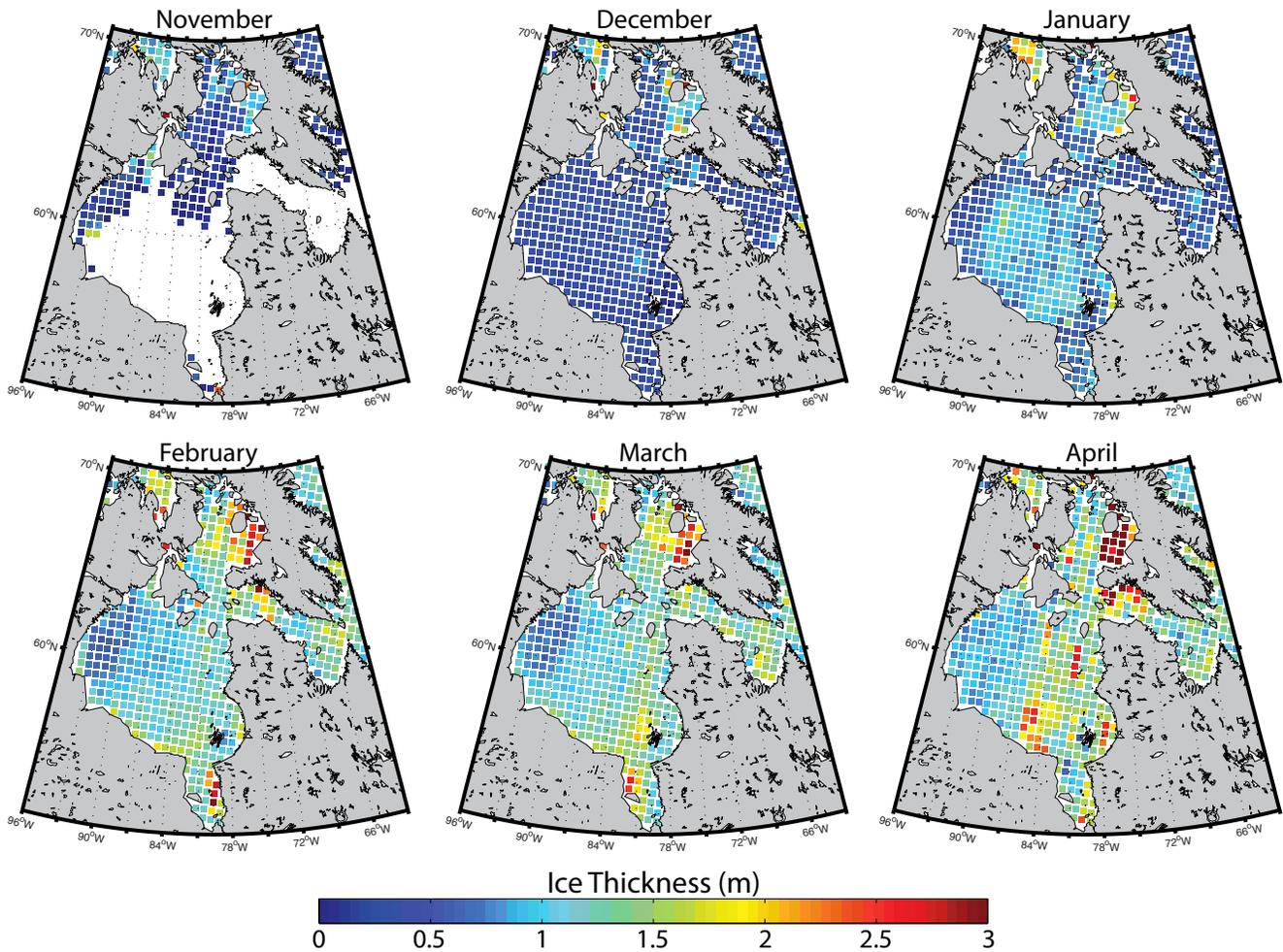
L. DALMAN



**FIGURE 8.** The weekly mean thickness of landfast sea ice (cm) near nine communities. Green lines denote the mean from the initial 1959-2000 program, Blue lines denote the mean from the follow-on 2001-2016 program, red dashed lines denote +/- 1 standard deviation of the full time series mean and the black dashed line denotes the maximum weekly ice thickness from the entire time period. Data was collected through weekly manual measurements as part of the Canadian Ice Service ice thickness program.

(Figure 9). Following the onset of freeze-up in November, thin sea ice is present in Foxe Basin and northwestern Hudson Bay, and covers the entire region by the end of December. The ice cover thickens through January, February, March and April when the onset of melt prevents the use of satellite altimetry to measure ice thickness into spring. Generally the thickest sea ice is present in Foxe Basin, while from January onwards there is a clear asymmetrical pattern in ice thickness within Hudson Bay with thicker ice in the east compared to the west. The prevailing patterns of westerly winds and eastward ice

drift regularly opens the polynya in northwestern Hudson Bay, leading to continued formation of new ice that is thinner than the surrounding ice that had formed previously. The ice that is advected eastward across the Bay is confined by the east coast, causing the ice cover to converge and leading to the dynamic formation of ridges and rafted pieces of ice that comprise the very thick sea ice within this region. While the ice cover within the region is seasonal, it is important to note that within the stamukhi of the landfast ice edge and within the ridges of the mobile ice cover, there are very thick pieces of ice present.

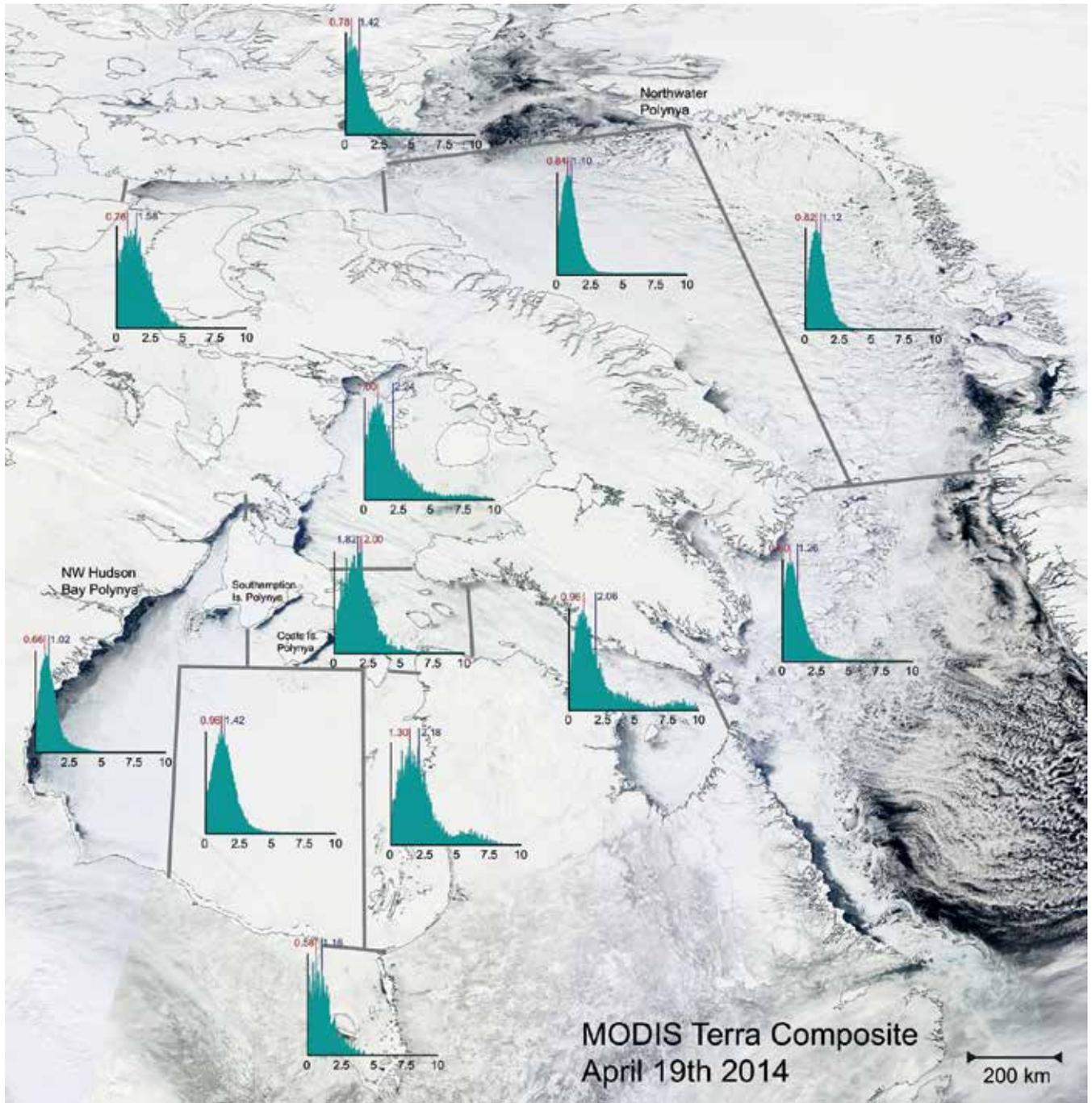


**FIGURE 9.** Monthly average sea ice thickness in the HBMR as observed by ICESat GLAS, Cryosat-2 and SMOS, for 2003–2016. (Adapted from Landy et al. 2017)

These results are similar to those of previous modelling studies that identified the process of sea ice volume redistribution within the Hudson Bay Marine Region (Saucier et al. 2004; Gagnon and Gough 2006; Joly et al. 2011).

Beyond the spatial pattern of ice thickness we can also look at the distribution of ice thickness throughout the region or in smaller sub-regions that were previously defined by the Canadian Ice Service. An ice thickness distribution presents the proportion of observations from within an area that correspond to a particular ice thickness. From this we can not only present the mean ice thickness, but also the mode, while highlighting the presence of very thick or very thin ice types. An example of the sub-regional ice thickness distributions from April 2014 is presented in Figure 10. The MODIS image within Figure 10 shows the polynya in northwestern Hudson Bay that is associated with the thinner ice thickness distribution for that region.

Within the region the mean ice thickness varies from 0.58 m in James Bay to 2.00 m in the Narrows, while the modal ice thickness varies from 1.02 m in northwestern Hudson Bay to 2.24 m in Foxe Basin. Northwestern Hudson Bay is characterized by a unimodal distribution, indicating a relatively homogeneous, thin ice cover. Comparatively, eastern Hudson Bay is characterized by a bimodal distribution around a modal thickness of 1.30 m and a secondary modal thickness around 6 m which reflects the presence of dynamically thickened sea ice. The ice thickness distributions in eastern Hudson Bay, Foxe Basin and Hudson Strait all display a long right tail, which indicates the presence of dynamically deformed sea ice in these three sub-regions. Comparatively there is a very shallow right tail to the ice thickness distribution in northwestern Hudson Bay where ice is exported before it can aggregate into thicker pieces.



**FIGURE 10.** Sub-regional ice thickness distributions from April 2014 in the Greater Hudson Bay Marine Region. Ice thickness distributions have a bin spacing of 5 cm. The mean and mode ice thickness are presented in red and purple, respectively. From Landy et al. (2017).



D.V. BARBER

#### 4.1. Trends in sea ice thickness

Between 1958 and 2003, two of the seven communities within the Greater Hudson Bay Marine Region that measured landfast ice thickness in partnership with the CIS (described in the above section) displayed a non-significant negative trend in maximum ice thickness (Inukjuak and Kuujuarapik), while the five other communities measured a positive trend in maximum ice thickness, with three of the five trends being significant ( $p > 0.10$ ; Chesterfield Inlet, Coral Harbour and Moosonee; Gagnon and Gough 2006). Meanwhile six of the seven communities showed a trend towards the earlier occurrence of maximum ice thickness, with three communities displaying a significant trend ( $p > 0.10$ ; Gagnon and Gough 2006). Overall Gagnon and Gough (2006) concluded that there was a significant positive trend in maximum ice thickness in western Hudson Bay, while there was a non-significant negative trend in eastern Hudson Bay. The positive trend in western Hudson Bay was ascribed to a negative trend in snow depth, although decreasing fall air temperatures and earlier freeze-up were also cited as contributing factors. While these trends are noteworthy, it must be reaffirmed that most of these trends are non-significant, and come from only seven landfast ice locations within the Hudson Bay Marine Region.

The spatially and temporally more complete analysis of Landy et al. (2017) does not cover a sufficiently long enough period to determine trends in ice thickness and volume. Though the 12 years of data does provide evidence of the considerable interannual variability in ice thickness within Hudson Bay, that following Gagnon and Gough (2006) can be ascribed to a variety of physical factors that determine the timing of freeze-up, the thermodynamic growth of sea ice, the dynamic thickening of the existing ice cover and of course the

duration of the ice growth season prior to the onset of ice melt. With the launch of ICESat-2 the record of satellite derived ice thickness throughout the polar regions and within the Greater Hudson Bay Marine Region will continue to grow and allow for more thorough analysis of the trends that underlay the interannual variability.

## 5. Regional sea ice summaries

Below are sub-regional summaries of the timing, motion and thickness of the ice cover within the Greater Hudson Bay Marine Region.

### 5.1. Hudson Bay

Within Hudson Bay, sea ice formation begins in the northwest and advances to the southeast across the Bay. Historically sea ice formation began in early-mid-November with the ice cover being complete by early-mid-December. However since the 1980s freeze-up has been significantly delayed throughout the Hudson Bay at a 5 days/decade. Subsequently freeze-up now begins in late November with a complete ice cover in place by late December. The ice cover of Hudson Bay is comprised of a 10-15 km wide band of landfast ice along the coast and a mobile ice cover that exists in the offshore area of Hudson Bay. Landfast ice grows thermodynamically throughout winter to average maximum thicknesses of 2.0 m (Inukjuak), 1.9 m (Chesterfield Inlet), 1.7 m (Coral Harbour), 1.7 m (Churchill), and 1.4 m (Kuujuarapik). Within the mobile ice cover, sea ice grows thermodynamically, but also grows thicker through dynamic deformation of the ice cover through convergence of ice floes. The prevailing westerly winds drive eastward ice drift and create an asymmetry in ice thickness with thinner, newly formed sea ice located in the northwest and thicker, heavily deformed sea ice in eastern Hudson Bay. The cross-Bay advection of the ice cover leads to the frequent formation of a large polynya in northwestern Hudson Bay that drives the formation of new ice throughout winter.

The ice cover in Hudson Bay historically began to breakup in the east around mid-June with the last ice breaking up in southern Hudson Bay around mid- to late-July. Significant trends towards earlier breakup are present throughout northwestern Hudson Bay, while the timing has not significantly changed within eastern and southern Hudson Bay. This contrast of trends in breakup has led to similar timing in breakup during recent years between northwestern and eastern Hudson Bay, with breakup in southern Hudson Bay occurring slightly earlier in early to mid-July in recent years. Collectively these changes have fostered a significant lengthening of the open water season throughout Hudson Bay by 5 to 15 days/decade since 1980.

## 5.2. Foxe Basin

As the furthest north region of the Greater Hudson Bay Marine Region, Foxe Basin is where sea ice first forms, is the last to breakup, has the thickest landfast ice, the thickest mobile ice and the shortest open water season. Significant trends towards delayed freeze-up (5 – 9 days/decade) and earlier breakup (4 to 12 days/decade) are present throughout Foxe Basin and have considerably changed the timing of sea ice. Historically freeze-up began in late-October to early-November, however more recently freeze-up hasn't begun until mid- to late-November. Breakup historically occurred in mid-late August, but again more recently breakup is occurring around late-July to early August. Historically some ice was able to persist through summer and evolve into second year ice, however this is no longer the case as the area becomes entirely ice free during summer (CIS 2013).

Although the duration of the ice season is decreasing in Foxe Basin it remains the longest ice growth season within the Marine Region. As a result, landfast sea ice near Hall Beach grows to an average maximum thickness of 2.0 m, while the mobile ice cover in Foxe Basin is the thickest within the Greater Hudson Bay Marine Region. Dynamically deformed thick pieces of sea ice are present within eastern Foxe Basin and on average exceed 3 m in thickness. Due to limitations in the resolution of satellite derived fields of ice motion there are no observations of ice drift from Foxe Basin.

## 5.3. Hudson Strait and Ungava Bay

Hudson Strait and Ungava Bay display the greatest trends in open water season duration with a maximum trend of 25 days/decade in the northwest portion of Hudson Strait. Throughout much of this region the open water season has increased in duration at a rate of 17-20 days/decade. While this trend is due to both earlier breakup and later freeze-up, the trends in breakup are much greater than the trends in freeze-up. From 1981-1985 sea ice in the area broke up over the course of July, whereas from 2010-2014 the area broke up between mid-May to mid-June. In terms of freeze-up, historically sea ice in Hudson Strait formed from the northwest to southeast, mimicking the freeze-up pattern in the rest of the Marine Region. More recently though, freeze-up has progressed from north to south across the strait. The ice cover breaks up from the northwestern portion of Hudson Strait to the south end of Ungava Bay, where winds compress the remaining sea ice during the end of the melt season.

Once again due to the limitations in spatial resolution of satellite derived fields of ice motion there are no observations of ice drift in Hudson Strait and Ungava Bay. However the ice thickness data reveals dynamically deformed sea ice is present in the area, specifically in northwestern Hudson Strait near

Salisbury, Nottingham and Mill Island. Furthermore, winter shipping activity through Hudson Strait to the Port at Deception Bay is subject to a highly compressed ice pack that under certain wind conditions can immobilize ships within ridges for several days at a time (Mussels et al. 2017).

## 5.4. James Bay

As the furthest south region in the Greater Hudson Bay Marine Region, James Bay is subject to a shorter sea ice season that leads to reduced ice growth. Landfast ice thickness at Moosonee is the lowest of all 9 communities measured within the Marine Region and reaches an average maximum thickness of 0.9 m in early April before the onset of melt and subsequent breakup of the ice cover. Historically breakup within James Bay began in the south around mid-June and lasted until mid-July when the northwest portion of James Bay broke-up. More recently breakup began throughout James Bay in late-May to early June and finished in the northwest around late June. Since 1980 there have been significant trends towards earlier breakup and delayed freeze-up throughout most of James Bay that are driving a prolonged open water season, however this region is subject to high year to year variability. Satellite derived estimates of ice thickness reveal a thin ice cover, though certain areas of dynamically deformed, thick sea ice are present within James Bay and reveal a dynamic component to ice growth. Though there are no observations of ice drift from within James Bay we can infer a dynamic mobile ice pack that likely behaves in a manner similar to the of Hudson Bay, with westerly winds forming leads and polynyas in the west, specifically around Akimiski Island, and driving sea ice convergence in the east. Sea ice in James Bay is relatively fresh due to the high input of riverine water into the area, and is also typically discoloured due to the high concentrations of sediment and re-suspended mud within the water column (CIS 2013).

## 6. Conclusions and recommendations

Sea ice is a defining component of the Greater Hudson Bay Marine Region that influences biogeochemical processes and dictates the open water shipping season, but most importantly it is a part of Inuit culture and provides seasonal access to travelling routes and hunting areas. From local and satellite based observations we know that the ice cover is changing, specifically it is forming later and breaking up earlier. These changes prolong the open water shipping season. On one hand this is increasing the potential for re-supply to communities and mine sites throughout the region, but on the other hand it is limiting the period when locals can safely travel over the ice. Recently, advances in satellite observing systems have increased our



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understanding of sea ice thickness within Hudson Bay, highlighting the west-east asymmetry that is created by the cross Bay transport of sea ice under westerly winds and the resultant dynamic deformation of the ice cover. These winds drive the recurrent formation of a large polynya in northwestern Hudson Bay, though there are several other recurrent polynyas located around Hudson Bay. Beyond polynyas, open water is frequently present within the vast coastal flaw lead system that exists at the landfast ice edge around the periphery of the region. Coastal flaw leads and polynyas are biologically active areas of open water that promote air-sea interactions and lead to continuous formation of new ice that leads to continuous brine rejections into the underlying water column. While a majority of the observations of sea ice within Hudson Bay come from satellites, Inuit and Cree who hunt, fish and travel on the coastal waters and sea ice have observed significant changes in recent decades such as unprecedented rapid freezing of the biologically-important flaw leads and polynyas in the Belcher

Islands area of southeast Hudson Bay. (For additional examples of changes observed by communities see *Voices from the Bay 1997*, *CEMS 2008 Report* and *ICC's 2008 report: The Sea Ice is Our Highway*). Overall, there have been few in-situ scientific studies looking at sea ice in Hudson Bay and the coastal processes associated with ice; however results from the Hudson Bay System Study (BaySys Project) should significantly advance our understanding of sea ice in the Greater Hudson Bay Marine Region and its interactions with other components of the marine system.

Due to the changing and ever dynamic ice conditions communities face potentially dangerous conditions in the already extreme environment of the Greater Hudson Bay Marine Region when travelling on sea ice. While satellites and models provide useful observations and information, they may not be available in real time, in an easily interpretable format, or simply in too large of a file to be accessible to the community. Tools like Siku (SIKU.org) are working towards integrating

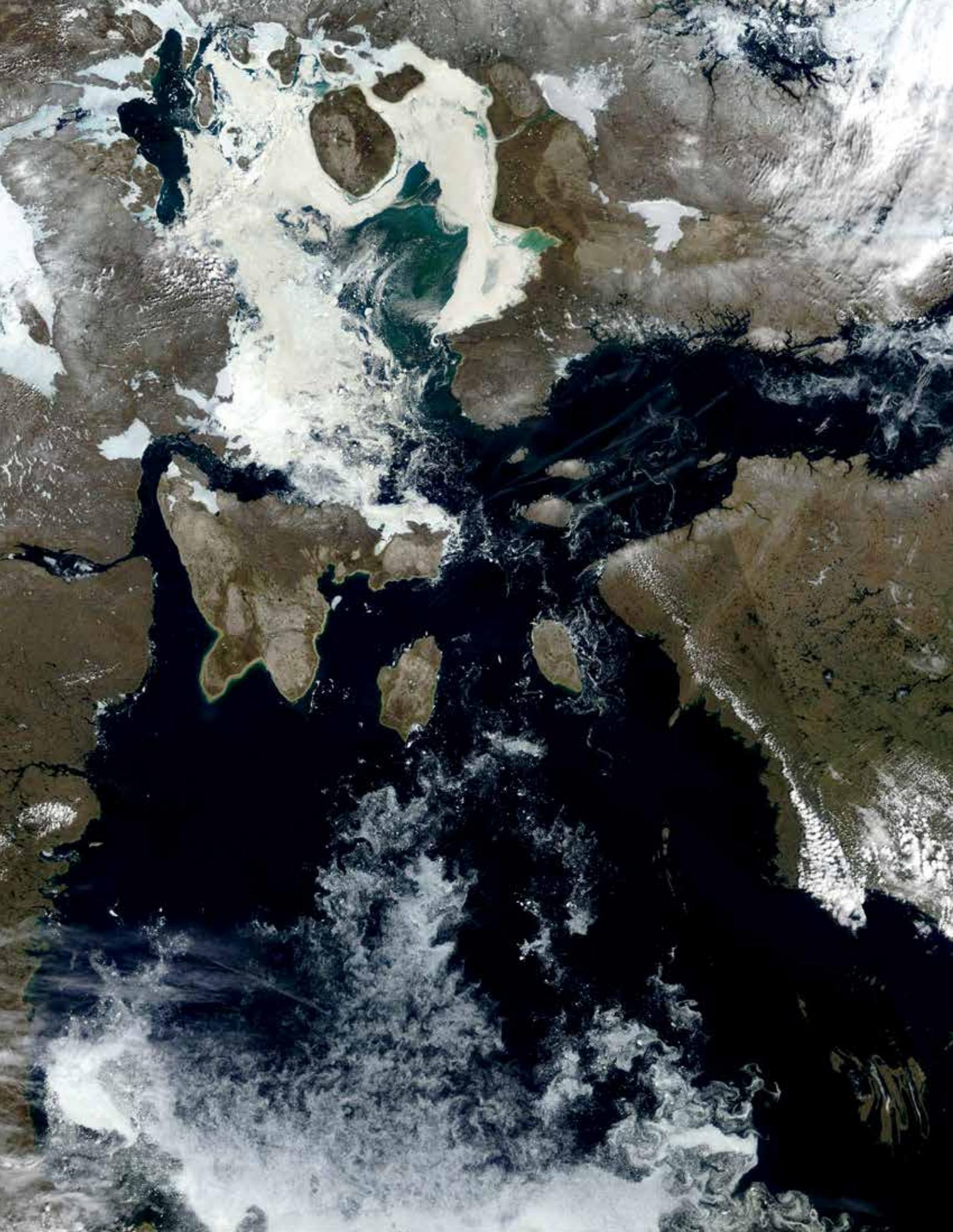
near real-time satellite data with community based observations, but this is not an immediate fix and takes time, energy and support to build a platform that can help merge local and scientific knowledge. Having access to accurate information on the local sea ice and weather conditions are important for community members; *“reliable knowledge of the ice can be a matter of life and death”* (ICC 2008). Community-based monitoring programs and long-term federally funded monitoring programs, such as the one run by the Canadian Ice Service for sea ice thickness, are invaluable and should be expanded to include more locations.

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I.iii

# Climate Change Projections

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## Key Messages

**P**rojections of future climate change in the Greater Hudson Bay Marine Region, while uncertain in rates and details, are all in agreement that it will continue to get warmer, in some regions it will become wetter, and there will be a longer open water season and higher maximum sea surface temperatures. Detailed wind patterns or extreme events cannot be projected accurately with current models.

Surface air temperatures were projected to increase as follows:

- **Steiner et al. (2013) projected 1°C per decade, corresponding to a temperature rise of roughly 4.7°C when comparing between 2012-2061 and 1961-2005.**
- **Joly et al. (2011) projected an annual mean temperature increase of 3.9°C when comparing 2041-2070 and 1961-1990.**
- **Diaconescu et al. (2017) projected an increase of 2-8°C during winter months and 1-3°C during summer months when comparing 2040- 2064 and 1980-2004.**

Winds speeds were projected to increase as follows:

- **Steiner et al. (2013) projected an increase in annual mean wind speeds throughout the Hudson Bay Region from 1961 to 2100.**

Precipitation rates were projected to increase as follows:

- **Steiner et al. (2013) projected an increase in precipitation of 0.05-0.06 mm/day/decade when comparing 2012-2066 and 1961-2005.**
- **Diaconescu et al. (2017) projected a regional increase of 0.0-0.4 mm/day when comparing 2040-2064 and 1980-2004. The largest trends were in Eastern Hudson Bay and Foxe Basin.**

Sea ice was projected to change as follows:

- **Joly et al. (2011) projected freeze-up to be delayed by 25-31 days and breakup to occur 22-24 days earlier when comparing 2041-2070 and 1961-1990.**
- **Lavoie et al. (2013) projected freeze-up to be delayed by one month and breakup to occur one to two months earlier when comparing 2046-2065 and 1986-2005.**

## 1. An introduction to climate models and uncertainties

Climate projections rely on highly complex mathematical models. These models use equations that are designed to simulate the physical, chemical and biological processes and their interactions. Models require guidance (forcings) from input data in order to run their simulations. One of the major inputs into models is the concentration of carbon dioxide in the atmosphere. Projections from models need to be used with an understanding that many factors can influence the projections and changes and a 'cascade of uncertainty' can occur (Jones 2000). A cascade of uncertainty is related to input data such as greenhouse gas emission, greenhouse gas cycle, radiative (solar energy) forcing and climate sensitivity. Other sources of uncertainty include the very formulation of Global Climate Models, the natural variation of the climate system and the ability of Regional Climate Models to downscale global projections to smaller scales (Rowell 2006). For a more in-depth explanation of uncertainties in models see studies done by de Elia et al. (2008) and Rowell (2006).

The main point to keep in mind when using model projections is that outputs from models are based on future scenarios, actual future conditions cannot be known. A scenario is a reasonable description of how the future may develop based on a set of assumptions about key driving forces such as rate of

technological change, future socio-economic developments and relationships. Most published projections will use projections obtained from model ensembles, which are different scenarios run with different models. Model ensembles will help give an idea of the uncertainties that arise. Different models will have different particular strengths and weaknesses and by using model ensembles, any really anomalous projections due to weaknesses or bias in a particular model will be apparent.

Appendix A describes more details about the models and scenarios discussed in this chapter.

## 2. Atmospheric projections

### 2.1. Air temperature

#### **IPCC 2013 temperature projections for 2016-2035**

Using forcing scenario RCP 4.5 (see Appendix A for a description of RCP 4.5), the IPCC produced a set of very broad resolution projections for the increase in temperature for 2016-2035 relative to 1986-2005 (Kirtman et al. 2013). These projections were provided on a global scale and without specifying projections for the Greater Hudson Bay Region. However, the large-scale projections for the area containing the Greater Hudson Bay Region indicate surface air temperature increases of roughly 4°C for winter and 2°C for summer for 2016-2035 relative to 1986-2005 (Kirtman et al. 2013).

### **Box 1. If you cannot predict the weather next month, how can you predict the climate in the next 30 years?**

**IPCC (2013) addresses this question** by using the following example:

*"An ability to predict future climate without the need to accurately predict weather is more commonplace than it might first seem. For example, at the end of spring, it can be accurately predicted that the average air temperature over the coming summer in Melbourne (for example) will very likely be higher than the average temperature during the most recent spring—even though the day-to-day weather during the coming summer cannot be predicted with accuracy beyond a week or so. This simple example illustrates that factors exist—in this case the seasonal cycle in solar radiation reaching the Southern Hemisphere—that can underpin skill in predicting changes in climate over a coming period that does not depend on accuracy in predicting weather over the same period."*

The statistics of weather conditions used to define climate include long-term averages of air temperature and rainfall, as well as statistics of their variability, such as the standard deviation of year-to-year rainfall variability from the long-term average, or the frequency of days below 5°C. Averages of climate variables over long periods of time are called climatological averages. They can apply to individual months, seasons or the year as a whole.

A climate projection might provide an answer to the question: 'What is the probability that temperature in Hudson Bay averaged over the next ten years will exceed the temperature in Hudson Bay averaged over the past 30 years?'

Climate projections do not provide forecasts of the detailed day-to-day evolution of future weather. Instead, they provide probabilities of long-term changes to the statistics of future climatic variables.



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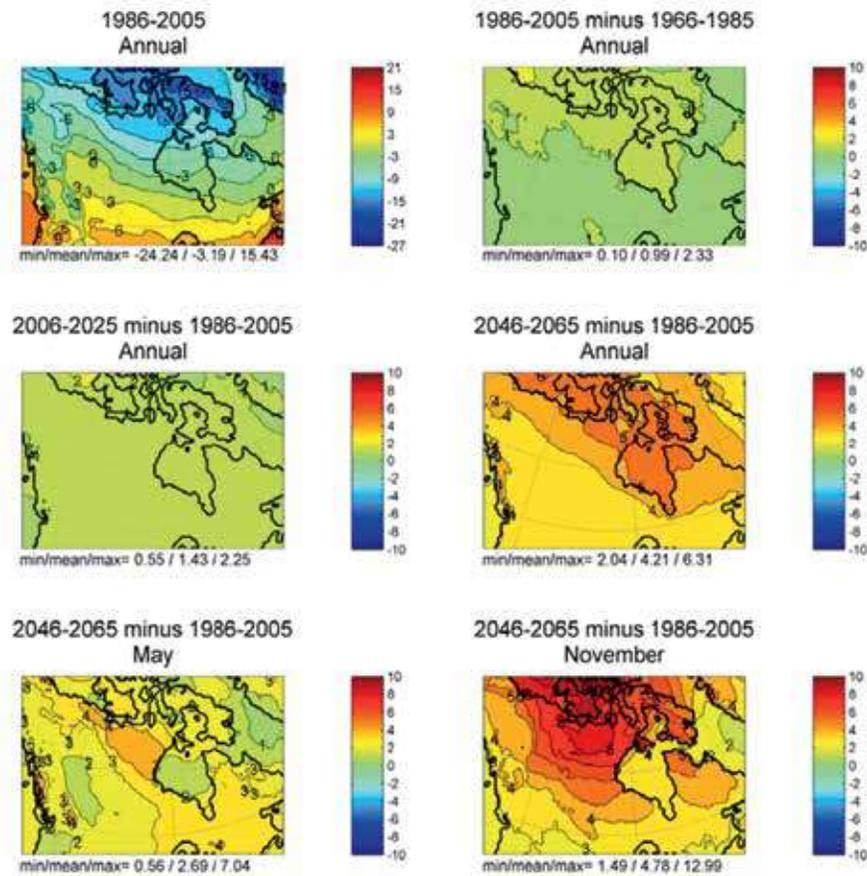
**The Canadian Regional Climate Model 4 (CRCM4) projections for 2005 to 2100**

The Canadian Centre for Climate Modelling and Analysis (CCCma), a division of the Climate Research Branch of Environment Canada, maintains a number of climate models. One of these models is the Canadian Regional Climate Model (CRCM). CRCM4 was recently run and produced hindcasts back to 1961 and future projections to 2065 for air temperatures in Hudson Bay. The future projections were made using the IPCC RCP 4.5 and 8.5 scenarios (see Appendix A for a description of the scenarios) (Steiner et al. 2013).

Hindcasts from 1961 to 2005 produced using CRCM4 show a range in annual average temperature in the Greater Hudson Bay Region, with values near 3°C in the south and -9°C in the north. CRCM4 predicts temperatures to rise more rapidly in the north. This difference is representative of a general trend towards greater warming at higher latitudes. For example, CRCM4 predicts an increase of 5-6°C in the annual average temperature between 2005 and 2065 in Hudson Bay, while the

**TABLE 1.** The historical trends and future projections for annual average surface air temperature in the Hudson Bay Region produced using CRCM4 (from Steiner et al. 2013). Temperature projections used the IPCC’s 2013 scenarios RCP 4.5 and RCP 8.5. Trends were multiplied with the length of the two time periods to obtain the corresponding temperature changes.

Historical Trend (1961-2005) = +0.48°C per decade			
Projected trends and corresponding temperature change		2012-2061	1961-2100
RCP 4.5	Trend (°C per decade)	+0.94	+0.64
	Temperature Change (°C)	+4.7	+8.96
RCP 8.5	Trend (°C per decade)	+0.90	+0.93
	Temperature Change (°C)	+4.5	+13.02



**FIGURE 1.** CRCM4 projections for surface air temperature in the Greater Hudson Bay Region, created using the IPCC's RCP 8.5 scenario. From Steiner et al. (2013).

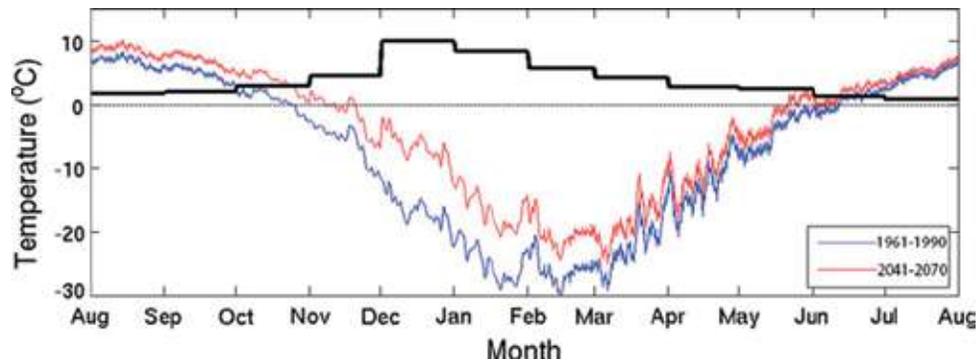
rest of North America averages a predicted increase of 3–6°C (Steiner et al. 2013).

Simulations using CRCM4 estimate a historical warming trend of 0.48°C per decade in the annual average temperature of the Hudson Bay Region between 1961 and 2005. The model projected that this trend would increase under both the RCP 4.5 and RCP 8.5 scenarios, rising to 0.94°C per decade (RCP 4.5) and 0.9°C per decade (RCP 8.5) for the time period between 2012–2061. It is somewhat surprising that RCP 4.5 produces a stronger warming trend for Hudson Bay during this time period, however RCP 8.5 does show a stronger warming trend when the timeframe is extended to 2100 (Steiner et al. 2013).

RCP 4.5 is a “medium-low” scenario, which is projecting a rise of 4.7°C in annual average temperature in the Greater Hudson Bay Marine Region for 2061. Further temperature projections by CRCM4 using the RCP 8.5 scenario, a relatively high scenario, are shown in Figure 1 (Steiner et al. 2013). The first panel in Figure 1 (top left) shows a hindcast of the average annual temperature for the years 1986–2005. The second panel

in Figure 1 (top right) shows the temperature anomalies (i.e., differences) when comparing the two time periods 1986–2005 minus 1966–1985. The third panel in Figure 1 (middle left) shows projected increases of 0–2°C for the Hudson Bay Region for the annual average temperatures when comparing 2006–2025 vs. 1986–2005. Similarly, the fourth panel in Figure 1 (middle right) shows an increase of 3–8°C for the Hudson Bay Region in the annual average temperatures of 2046–2065 minus 1986–2005. The fifth and sixth panels in Figure 1 (bottom left and right) shows the increases in the average monthly temperatures of 0–4°C in May and 2–8°C in November for the time period of 2046–2065 compared to 1986–2005.

For both scenarios RCP 4.5 and 8.5, the CRCM4 model projects the most rapid warming to take place in the winter months of January, February, and March in the Greater Hudson Bay Region (Steiner et al. 2013).



**FIGURE 2.** A comparison of the CRCM4 temperature estimates for the periods 1961-1990 and 2041-2070 in the Greater Hudson Bay Region. Data consists of temperature values at 12 hour time intervals. The blue line represents the estimates for 1961-1990 while the red line represents 2041-2070. The black line displays the average difference between the two for each month (Joly et al. 2011).

### **Canadian Regional Climate Model (CRCM) projections for 2041-2070**

Joly et al. (2011) used the Canadian Regional Climate Model 4 (CRCM4), forced the model with the IPCC SRES A2 scenario (a “high” forcing scenario), to develop projections of air temperatures in the Greater Hudson Bay Region. The study developed projections for the years 2041-2070, during which time the SRES A2 scenario called for a CO<sub>2</sub> concentration of 707-950 ppm or roughly a doubling of the present-day ~400 ppm CO<sub>2</sub> concentration (Joly et al. 2011).

Joly et al. (2011) compared the CRCM4 hindcast results for the period 1961-1990 with the projections for 2041-2070 for temperatures at 2 m elevation in the Hudson Bay Region. The projected changes in temperature between the two time periods varied significantly amongst seasons, ranging from a rise of 0.8°C for July to an increase of 10°C for December, with a mean annual warming of 3.9°C. In general, the colder months displayed a much larger and more rapid increase in temperature than the warm months (Joly et al. 2011). This result is in agreement with the CRCM4 projections produced by Steiner et al. (2013) when the model was forced with the RCP scenarios. Figure 2 shows a comparison of the temperatures for the two 30-year time frames as estimated by CRCM4.

### **2.2. Wind speed**

The study by Steiner et al. (2013) (described in section 2.1) looked at the CRCM4 model projections for wind speed squared ( $m^2s^{-2}$ ), a predictive metric related to wind speed. Wind speed squared, although not as intuitive as simply wind speed, is more relevant from the perspective of climate change impacts and extreme events. CRCM4 projected an increase of 0.17  $m^2s^{-2}$  per decade between 1961 and 2100 under the RCP 8.5 scenario and an increase of 0.08  $m^2s^{-2}$  under RCP 4.5 for

the same time frame; both trends were statistically significant (Steiner et al. 2013). For the RCP 8.5 scenario, these increases were fairly uniform throughout the Hudson Bay Region, although wind speeds in the eastern part of Hudson Strait were projected to increase more rapidly than other areas. In general, according to Steiner et al. (2013), wind speeds were projected to increase throughout the Hudson Bay Region from 1961 to 2100.

### **2.3. Storms**

A study by Savard et al. (2014) looked at projections for storm characteristics in the Greater Hudson Bay Region for 2041-2070 vs. 1961-2000 using eight different model simulations based on the IPCC’s SRES A2 scenario. The study projected no discernible change in the average number of cyclonic centres (centres of low pressure systems) over a full year in the Hudson Bay Region. However, the models projected a 25% increase in the number of cyclonic centres during December and January. No significant change was projected for any other months. They also projected an increase in the number of cyclone trajectories moving through the Hudson Bay Region in December and January and an increased residence time for storms above Hudson Bay during December and January.

The authors suggested that the projected increases in cyclone centres, trajectories, and residence times for the months of December and January are a product of open water, and thus storm-supporting conditions, persisting later into the year (Savard et al. 2014). In effect, the storm season is projected to lengthen in response to an extension of the open water season.

Savard et al. (2014) suggested that the projected changes in the storm regime of 2041-2070 compared to 1961-2000 for December and January could have a significant impact on coastal erosion in their study area of Nunavik and more



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generally on coastal infrastructure throughout the Hudson Bay Region. They suggested that, with the extension of the open water season and projected extension of the storm season, there could be an increase in the energy of waves reaching the eastern coast of Hudson Bay in December and January (see section 4.1 for a discussion on storm surges).

#### 2.4. Precipitation

The study by Steiner et al. (2013) summarized the precipitation trends for the Hudson Bay Region using a model ensemble described in section 2.1. They found that during the period of 1961 to 2005, the precipitation trend was 0.03 mm/day/decade, which increased to 0.05-0.06 mm/day/decade under RCP 8.5 and RCP 4.5 forcing for the period of 2012 to 2066. The trends under RCP 8.5 were consistently 0.05 mm/day/decade or greater, whereas the RCP 4.5 trends ranged from 0.00 to 0.06 mm/day/decade. The long-term trend from 1961-2100 indicates that precipitation increases more under the RCP 8.5 forcing than RCP 4.5.

#### 2.5. Regional summary of temperature and precipitation projections

Table 2 gives a regional summary of climate projections run by the Ouranos modelling group. Projections were compiled using data from seven RCM runs from the North American Coordinated Regional Climate Downscaling Experiment (CORDEX) and seven runs from the Arctic CORDEX interpolated to a common grid at 0.25° of spatial resolution for RCP 4.5. The future climate period is 2040-2064 and projected rates of change are computed in regards to the reference period 1980-2004. Note that these changes are projected only over land and not the marine environment. The scenarios and modelling efforts are further described in Diaconescu et al. (2017).

Consistent with the previously described projections, the CORDEX results indicate greater winter warming compared to summer. They suggest increases in annual and winter mean precipitation in all sub-regions but strongest in Eastern Hudson Bay and James Bay. Weak negative trends in annual mean solid precipitation and snow depth are possible for James Bay (Table 2).

**TABLE 2.** A summary of spatially averaged projected changes in the Greater Hudson Bay Marine Region. The values indicate the median (spatially averaged) projected changes for the period 2040 to 2064. The changes are computed using seven RCM simulation runs from the CORDEX experiment for the reference period 1980-2004. The bolded values represent the spatially averaged median value and in brackets are the lower and upper bounds. Winter is defined as December, January, February and summer is defined as June, July and August.

	Western Hudson Bay	Eastern Hudson Bay	James Bay	Hudson Strait & Ungava Bay	Foxe Basin
Mean annual air T (°C)	<b>3.7</b> (2.3 : 4.2)	<b>4.0</b> (2.1 : 4.56)	<b>3.7</b> (1.5 : 4.0)	<b>4.2</b> (2.2 : 4.6)	<b>4.0</b> (2.52 : 4.6)
Mean winter air T (°C)	<b>5.6</b> (2.9 : 7.1)	<b>6.9</b> (3.2 : 8.3)	<b>5.4</b> (1.8 : 6.6)	<b>7.2</b> (3.6 : 8.5)	<b>6.7</b> (3.7 : 8.0)
Mean summer air T (°C)	<b>2.6</b> (1.2 : 3.2)	<b>2.6</b> (1.1 : 3.2)	<b>2.5</b> (1.1 : 3.1)	<b>2.4</b> (1.2 : 3.0)	<b>2.6</b> (1.1 : 3.3)
Winter thawing events (days)	<b>0.0</b> (-2.0 : 2.9)	<b>0.2</b> (-1.6 : 1.6)	<b>-1.3</b> (-4.5 : 1.7)	<b>0.7</b> (-1.2 : 2.1)	<b>0.1</b> (-1.5 : 1.3)
Annual mean precip. (mm/day)	<b>0.1</b> (0.0 : 0.3)	<b>0.3</b> (0.2 : 0.4)	<b>0.2</b> (0.1 : 0.4)	<b>0.2</b> (0.1 : 0.4)	<b>0.3</b> (0.0 : 0.3)
Winter mean precip. (mm/day)	<b>0.2</b> (0.0 : 0.5)	<b>0.4</b> (0.1 : 0.5)	<b>0.4</b> (0.1 : 0.5)	<b>0.3</b> (0.1 : 0.5)	<b>0.2</b> (0.0 : 0.3)
Summer mean precip. (mm/day)	<b>0.1</b> (-0.2 : 0.4)	<b>0.3</b> (-0.1 : 0.5)	<b>0.1</b> (-0.2 : 0.6)	<b>0.3</b> (0 : 0.6)	<b>0.2</b> (-0.1 : 0.4)
Annual mean solid precip. (mm/day)	<b>0.0</b> (-0.05 : 0.04)	<b>0.0</b> (-0.03 : 0.05)	<b>-0.1</b> (-0.08 : -0.02)	<b>0.0</b> (-0.04 : 0.08)	<b>0.0</b> (-0.05 : 0.05)
Maximum snow depth (m)	<b>0.0</b> (-0.05 : 0.06)	<b>0.0</b> (-0.04 : 0.03)	<b>-0.1</b> (-0.12 : -0.01)	<b>0.0</b> (-0.03 : 0.07)	<b>0.0</b> (-0.09 : 0.08)

### 3. Sea ice projections

Joly et al. (2011) also modelled the effect of a warmer climate (described in section 2.1) on the ice-ocean system of the Greater Hudson Bay Marine Region. They included only the direct effects of increased air temperatures, not any indirect effects of warming such as altered precipitation etc. The difference between the 2041-2070 and 1961-1990 temperature estimates from CRCM4 with the SRES A2 scenario were used to run the ocean model. The analysis by Joly et al. (2011) projected a significant reduction in the length of the sea ice season (and conversely a significant increase in the length of the open water season) in Hudson Bay, Foxe Basin and James Bay. Table 3 summarizes the change in freeze-up and breakup dates for Hudson Bay, Foxe Basin and James Bay.

The projected changes in sea ice thickness by Joly et al. (2011) merit some examination. Joly et al. (2011) projected a decline in sea ice thickness throughout the Hudson Bay Region for 2041-2070 vs. 1961-1990, with the greatest reductions occurring in Hudson Strait and south-eastern Hudson Bay (Figure 3). However, the trends observed by Gagnon and Gough (2006) (described in Theme I, Chapter ii), show a significant increase in landfast sea ice thickness in western Hudson Bay between 1958 and 2003. The two findings are not necessarily incompatible. Landfast sea ice and mobile sea ice are quite different and may be shaped by different environmental influences or respond differently to the same influences. It is possible that landfast sea ice and mobile sea ice thicknesses could exhibit different trends during the same timeframe.

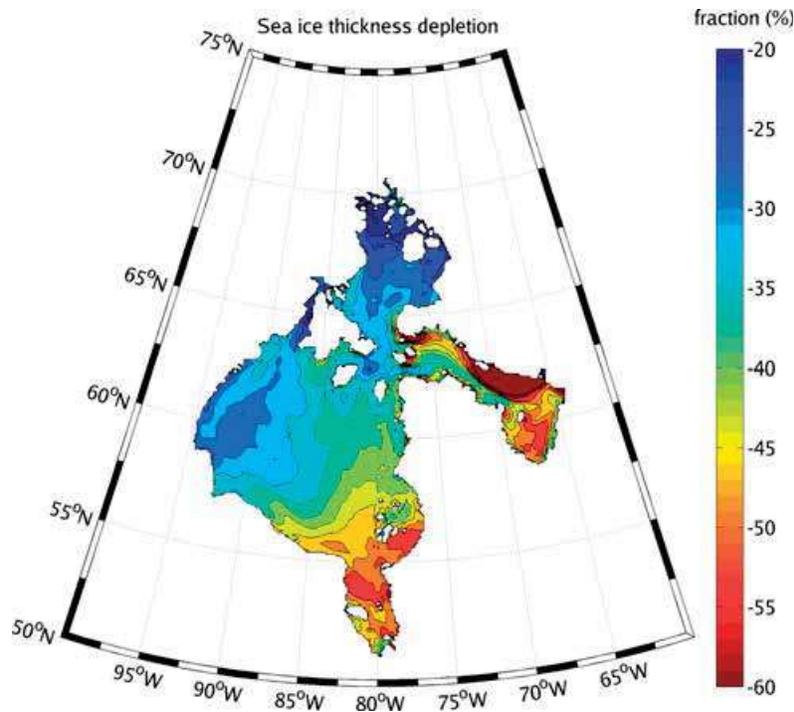
A study of sea ice projections by Lavoie et al. (2013) used the CMIP5 multi-model ensemble (CanESM2, GFDL, HadGEM2, IPSL, and MPI) with scenarios RCPs 4.5 and 8.5 for the Greater



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**TABLE 3.** Change in the average timing of freeze-up and breakup date between the historical 1961-1990 and 2041-2070 climate scenarios from Joly et al. (2011).

	Freeze-up		Breakup	
	1961-1990	2041-2070	1961-1990	2041-2070
Hudson Bay	Dec. 4 <sup>th</sup>	+25 days	July 8 <sup>th</sup>	-24 days
Foxe Basin	Nov. 4 <sup>th</sup>	+31 days	July 13 <sup>th</sup>	-22 days
James Bay	Dec. 18 <sup>th</sup>	+26 days	June 22 <sup>nd</sup>	-39 days



**FIGURE 3.** The average change in sea ice thickness between 2041-2070 and 1961-1990 for the ice-covered months of January, February, March, and April in the Hudson Bay Region. From Joly et al. (2011).

Hudson Bay Region. Each of the five model projections for 2046 – 2065, showed a reduction of sea ice thickness compared 1986-2005. The mean sea ice thicknesses in April for 2046-2065 were 34, 56, 85, 110, and 133 cm GFDL, CanESM2, IPSL, MPI, and HadGEM2, respectively, for RCP 4.5. With the RCP 8.5 scenario, the corresponding sea ice thicknesses were 22, 52, 70, 93, and 117 cm. The reduction in sea ice thickness, compared to 1986-2005, from the multi-model ensemble mean shows trends

of -6.2 cm/decade for RCP 4.5 and -8.3 cm/decade for RCP 8.5. Lavoie et al. (2013) also projected that the sea ice will form later in the fall (by up to one month with RCP 8.5) and melt earlier in spring (by one to two months with RCP 4.5 and RCP 8.5, respectively).

## 4. Ocean projections

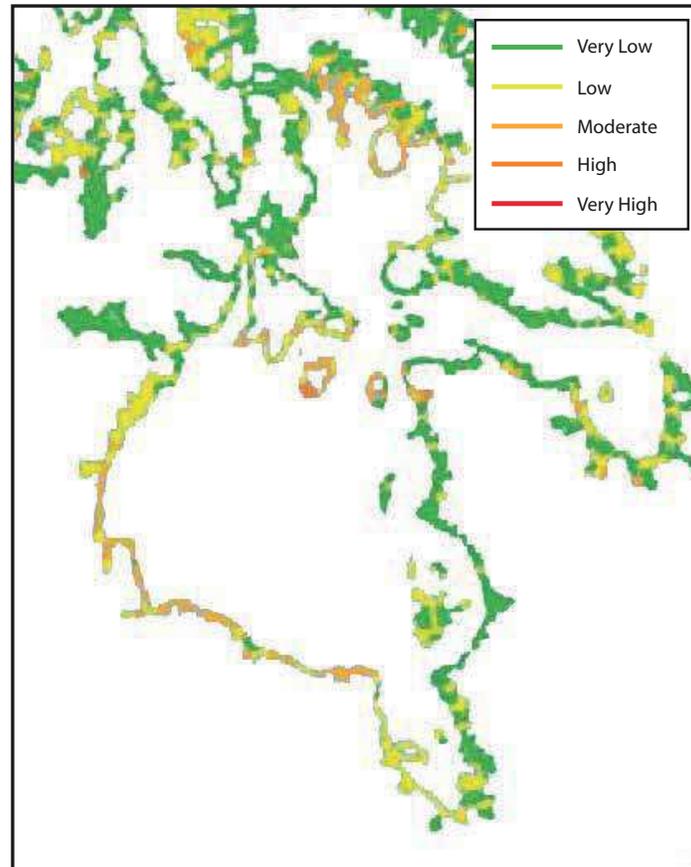
### 4.1. Sea level and storm surges

An analysis by Smith et al. (2013) looked at the sensitivity of the Canadian coastline to sea level rise. This method looks at several contributing factors of coastal erosion including relief, rock type, sea level tendency, tidal range and wave height. Figure 4 shows the sensitivity of the Greater Hudson Bay Region to coastal erosion based on projected sea level rise. The sensitivity of the coastline to erosion throughout the Greater Hudson Bay Marine Region is mostly very low or low, except for the coastline of Manitoba and Ontario in Western Hudson Bay and some parts of Foxe Basin.

A major factor is the ongoing rate of land uplift (isostatic rebound) and associated falling relative sea level in the region. Particularly around the southern part of the Region, uplift



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**FIGURE 4.** Sensitivity to coastal erosion based on sea level rise and other factors including rates of land uplift (isostatic rebound), relief, rock type, sea level tendency, tidal range and wave height (adapted from Smith et al. 2013).

remains in the order of 0.75-1 cm/yr (Sella 2007). Where the current eustatic rise of sea level and local uplift have been measured at the same place (Kuujuaq), the eustatic sea level rise is slower than the rate of uplift. The net effects on the coastline depend on future changes in sea level. However, it is predicted that the accelerating rate of sea level rise will not exceed the land uplift over the next 100 years (Gough and Robinson 2000).

A study by Savard et al. (2014) (described in section 3.3 and in Theme I, Chapter i.) suggest that there will be an increase in the frequency of extremely high water levels along the eastern coast of Hudson Bay, in James Bay, and in Hudson Strait due to changes in storm characteristics. They also predict a more frequent co-occurrence of high water levels and strong waves leading to storm surges in these locations. In addition, Savard (2016) predicted an increase in the frequency of storm surges for Nunavik during the months of December and January.

#### 4.2. Sea surface temperature

A study by Lavoie et al. (2013) used the CMIP5 multi-model ensemble (CanESM2, GFDL, HadGEM2, IPSL, and MPI) RCPs 4.5 and 8.5 for the Hudson Bay Region to explore effects of warming on sea surface (water) temperature. Each of the five model projections for 2012 – 2062 showed an increase in the annual mean sea surface temperature in Hudson Bay ranging from 0.16 and +0.36°C per decade for RCP 4.5 and +0.2 and +0.38°C per decade for RCP 8.5. The multi-model ensemble average for sea surface temperature showed an increase of  $0.22 \pm 0.08^\circ\text{C}$  per decade for RCP 4.5 and  $0.31 \pm 0.07^\circ\text{C}$  per decade for RCP 8.5 across the Region.

The existing evidence supports the notion that sea surface temperatures in the region are responsive to climate change and shortening of the ice cover season. Galbraith and Larouche (2011) analyzed sea surface weekly average temperatures derived from NOAA–AVHRR remote sensing data for the



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period 1985–2009 and related them to air temperature and ice breakup patterns. They found that the past co-variability of sea surface temperature and ice breakup dates was consistent overall with the climate change modeling results of Joly et al. (2010). Specifically, the satellite data analysis provided evidence for an increase in sea surface temperature of  $\sim 0.13$  °C per day of ice-breakup advance, which is equivalent to 3.1°C sea surface temperature increase for an ice-breakup advance of 24 days. Longer term sea surface temperature trends (1920–2011) near Churchill MB were examined using oxygen and carbon isotopic records in shell calcite of brachiopods (Brand et al. 2014). The results suggested that climate-forced change contributed to an average increase of about 0.1°C in sea surface water temperature of Hudson Bay during 1920–1970 and an average increase of about 3.6 °C during 1971–2011. The total (3.7°C) estimated warming of Hudson Bay surface waters over the  $\sim 90$  year period represents about six times the 0.67 °C increase observed during the past 100 years in global ocean sea surface temperature and about double the projected average increase of  $\sim 2$ °C in sea surface temperature for polar regions.

### 4.3. Sea surface salinity

Sea surface Salinity was projected for 2012 – 2062 in the model study by Lavoie et al. (2013) (described in section 4.2). The results from Lavoie et al. (2013) showed no clear trends. Only three models out of five showed a freshening of the sea surface with the RCP 4.5 scenario. However, the RCP 8.5 scenario showed a decrease over time of sea surface salinities with CanESM2. The multi-model ensemble mean trends showed no clear trend due to the variable trends in RCP scenarios and standard deviation higher than the mean.

Increases in the freshwater content of Arctic Ocean waters at both basin-scale and regional-scale (see Alkire et al. 2017) suggest that freshening may be observed also in downstream areas including the Greater Hudson Bay Marine Region. However, historical trends in sea surface salinity in the region have received little investigation to date. Brand et al. (2014) observed changes in oxygen isotope ratios of brachiopod shell calcite near Churchill MB consistent with freshening of surface waters but lacked sufficient information on natural variability to draw conclusions on trends.

## 5. Future work

The Greater Hudson Bay Marine Region has seen some modelling efforts aimed at projecting future atmosphere, ice and ocean conditions, which all show that warmer and more ice-free waters should be expected during the next century. However, ongoing efforts may be expected to significantly improve projections during the coming decade. One of these efforts is a large-scale study examining the effects of climate warming and river regulation on the Hudson Bay system. This Hudson Bay System Study (BaySys) is underway but was not completed prior to publication of this IRIS report. BaySys is a collaborative project led by the University of Manitoba and Manitoba Hydro, which aims to understand the relative contributions of climate change and river regulation to freshwater-marine interactions in the Hudson Bay system. This project takes a multidisciplinary approach, including retrospective analysis, fieldwork, and modeling efforts. Watershed models are coupled to physical- and biogeochemical models

of the marine environment, which are informed by field observations, and used to project conditions for the 2030s and 2050s. The models are forced with scenarios of both climate change and regulation, allowing for the separation of those two impacts on the Hudson Bay system. This modelling effort is a collaboration utilizing models run through the University of Manitoba, University of Alberta, Manitoba Hydro, Ouranos and Université Laval.

The BaySys project uses an Arctic configuration of the Nucleus for European Modelling of the Ocean (NEMO) general ocean circulation model coupled with the LIM2 sea ice model, and a biogeochemical model, with input river discharge data from the HYPE model (described in Theme I. Chapter iv.) and forced with atmospheric data from CMIP5 scenarios run by Ouranos. Results from BaySys have begun to be published (see Theme I. Chapter iv.) and are expected to continue in 2019 and 2020.

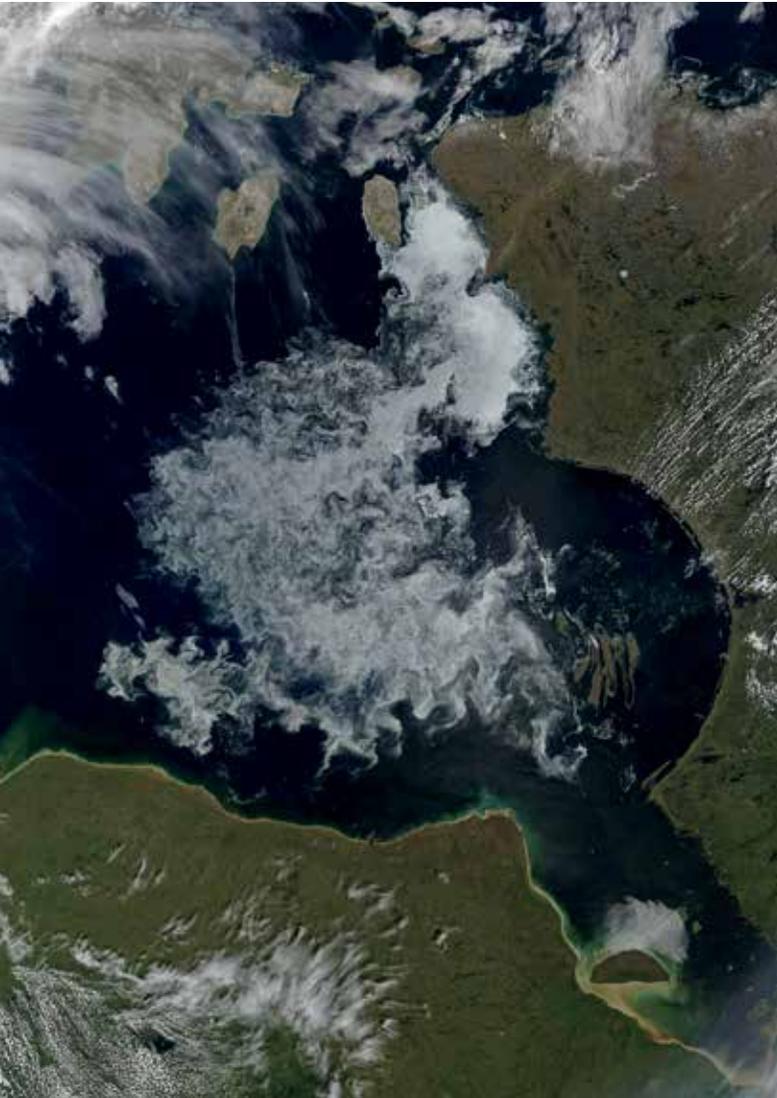
## 6. Summary and conclusions

Studies such as those done by Joly et al. (2011), Lavoie et al. 2013, Steiner et al. (2013), Savard et al. (2014) and Diaconescu et al. (2017) give modelled trends and projections for the Greater Hudson Bay Marine Region. Although these studies utilize different models, different scenarios and different time periods there are some clear trends in the projections for the coming decades. Table 4 gives a general summary of the projections from these modelling studies for the Greater Hudson Bay Marine Region. The projected changes described in this chapter and summarized in Table 4 will likely have major



**TABLE 4.** A general summary of atmospheric, ocean and sea ice projections for the Greater Hudson Bay Marine Region from studies done by Joly et al. (2011), Lavoie et al. (2013), Steiner et al. (2013), Savard et al. (2014) and Diaconescu et al. (2017).

Variables	Projections over the next 20 to 50 years
<b>Surface Air Temperature</b>	Very likely increase in air temperatures by 1–3°C in summer and 2–8°C in winter. Greatest changes projected to occur in Foxe Basin, Hudson Strait, Ungava Bay and Eastern Hudson Bay. High inter-annual variability also is to be expected.
<b>Precipitation</b>	Likely a slight increase in precipitation in over the whole Region with larger increases projected to occur in Foxe Basin, Hudson Strait, Ungava Bay and Eastern Hudson Bay.
<b>Winds and Storms</b>	Likely an increase in storm intensities during the fall months with increased potential for storm surges in Eastern Hudson Bay, and Hudson Strait. Projections indicate an increase in wind speeds throughout the Region, with Hudson Strait showing the largest changes.
<b>Sea Level</b>	Within the Greater Hudson Bay Marine Region it is predicted that the rate of sea level rise will not exceed the land uplift over the next 100 years.
<b>Sea Ice</b>	Very likely a longer open water season throughout the Region. The sea ice is projected to breakup one to two months earlier and freeze-up one month later.
<b>Ocean Surface Temperature and Salinity</b>	Very likely increased average annual sea surface temperatures (0.5 – 2°C) throughout the Hudson Bay Marine Region. Projections for sea surface salinity are uncertain.



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implications on the ecosystem and wildlife and on industries such as shipping. Further discussions of these implications are provided in the chapters under Themes II and III.

The physical environment within the Greater Hudson Bay Marine Region, at the southern margin of the Arctic, is rapidly changing with projections following similar trends. Traditional knowledge also describes recent changes in weather patterns and climate, including the shortening of winters and lengthening of summers; shifting of dominant wind regimes; and increased occurrence of stronger wind events with potentially dangerous consequences (Voices from the Bay 1997; Elders Report on Climate Change 2001). Inuit and Cree living in the region need better information in order to adapt to the changing climate.

*“The world’s environment evolves daily. There are changes which occur everyday. If somebody could keep up with this world, we would know every detail of it.”*

Johnny Epoo, Inukjuak (Voices from the Bay 1997)

*“We cannot make predictions anymore. We don’t know if the water is going to freeze or not. We used to know what was going to happen at certain seasons but, with all the changes in the climate and the different qualities of water, we can’t make these predictions anymore.”*

Helen Atkinson, Chisasibi (Voices from the Bay 1997)

While this chapter attempts to summarize the available information for the Greater Hudson Bay Marine Region, it is by no means conclusive. Although not discussed in this chapter important early work was done by Gagnon and Gough (2005) and Saucier et al. (2004) and Gough and Wolfe (2001), which provided much of the groundwork for the models and projections cited above. The current studies that are being done by Ouranos, BaySys and other groups aim to provide higher resolution regional modelling for the atmosphere, sea ice and ocean environments specific to the Greater Hudson Bay Marine Region.

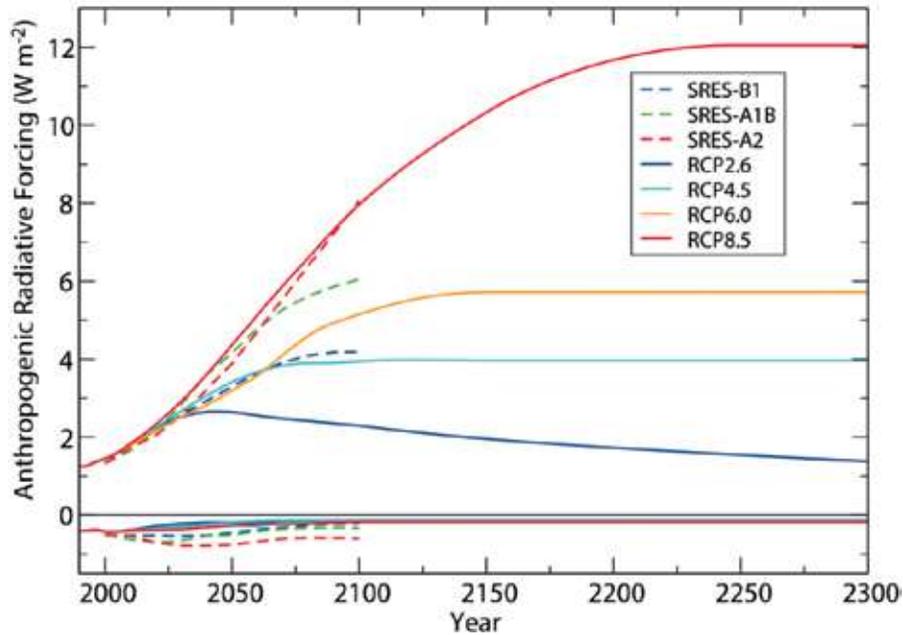
## Acknowledgements

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**FIGURE A1.** The change in atmospheric forcing ( $W m^{-2}$ ) between 2000 and 2300 under various IPCC forcing scenarios. “SRES” scenarios were in use from 2000–2012, RCP scenarios were finalized for the 2013 IPCC Report (Cubasch et al. 2013). From Collins et al. (2013).

## APPENDIX A

### IPCC Forcing scenarios

#### A.1. IPCC 2013: Representative Concentration Pathway (RCP) Scenario 4.5

The RCP 4.5 scenario is considered a “medium-low” forcing pathway, which involves stabilization of atmospheric forcing at  $4.5 W m^{-2}$  near the year 2100 (Cubasch et al. 2013). In this scenario, the atmospheric concentration of  $CO_2$  rises from 389.1 parts per million (ppm) in 2010 to 538.4 ppm in 2100; this rise in concentration is rapid at first but declines to near zero by the end of the 21<sup>st</sup> century (IPCC 2013). The “ $CO_2$  equivalent” concentration ( $CO_{2e}$  ppm), which incorporates

**TABLE A1.** The change in  $CO_2$  and  $CO_2$  equivalent concentrations between 2000 and 2100 under the RCP 4.5 Scenario (IPCC 2013; Cubasch et al. 2013).

RCP 4.5 Scenario	$CO_2$ (ppm)	$CO_2$ equivalent ( $CO_{2e}$ ppm)
Year 2000	368.9	~400
Year 2050	486.5	~510
Year 2100	538.4	~595

the concentrations of all greenhouse gases (Methane, Nitrous Oxide, etc) by converting them into the  $CO_2$  concentration that would have an “equivalent” forcing effect, rises from roughly  $400 CO_{2e}$  ppm in 2000 to just under  $600 CO_{2e}$  ppm by 2100 (Cubasch et al. 2013).

#### A.2. IPCC 2013: Representative Concentration Pathway (RCP) Scenario 8.5

The RCP 8.5 scenario is the highest of the IPCC’s 2013 scenarios. In the RCP 8.5 scenario, forcing reaches  $8.3 W m^{-2}$  by the year 2100 and is still rising rapidly at this point (Collins et al. 2013). The scenario’s projections for future atmospheric concentrations of  $CO_2$  and  $CO_2$  equivalent are listed in the table below:

**TABLE A2.** The change in  $CO_2$  and  $CO_2$  equivalent concentrations between 2000 and 2100 under the RCP 8.5 Scenario (IPCC 2013; Cubasch et al. 2013).

RCP 8.5 Scenario	$CO_2$ (ppm)	$CO_2$ equivalent ( $CO_{2e}$ ppm)
Year 2000	368.9	~400
Year 2050	540.5	~700
Year 2100	935.9	~1100

### A.3. IPCC 2000: Special Report on Emissions Scenarios (SRES) A2 (“high”) and B1 (“low”)

The IPCC SRES were used in IPCC reports until the most recent IPCC series of reports began to be published in 2013. Until quite recently the SRES were used to force climate models and as a result these scenarios are an integral part of many recent scientific publications.

**TABLE A3.** The change in CO<sub>2</sub> and CO<sub>2</sub> equivalent concentrations between 2000 and 2100 under two IPCC SRES scenarios (IPCC 2013; Cubasch et al. 2013).

SRES A2 “high”	CO <sub>2</sub> (ppm)	CO <sub>2</sub> equivalent (CO <sub>2e</sub> ppm)
Year 2000	368	~400
Year 2050	527	~500
Year 2100	846	~950
SRES B1 “low”	CO <sub>2</sub> (ppm)	CO <sub>2</sub> equivalent (CO <sub>2e</sub> ppm)
Year 2000	368	~400
Year 2050	485	~480
Year 2100	544	~590

## References

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I.iv

# The Freshwater System

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## Summary

In recent decades, the Hudson Bay drainage basin has been undergoing significant change to both climate (temperature and precipitation) and development of hydroelectric complexes, consequently affecting the freshwater regime. In the future, temperatures are expected to continue to increase. As air temperatures warm, the atmosphere can hold more moisture, resulting in increases in precipitation. Previous studies and our own findings are in agreement that river discharge to the Hudson Bay drainage basin is expected to continue to increase but at a faster rate than during the recent historic period. Increasing trends in river discharge exist across all seasons and are most prominent in fall and winter, but more moderate during summer when higher temperatures and evapotranspiration may offset increasing precipitation. Runoff across the Hudson Bay drainage basin is also generally increasing along a longitudinal (east to west) gradient with the largest increases along the northern and eastern portions of the Bay, and the smallest increases across the western Hudson Bay region in some of the Canadian Prairie basins. Based on the projected changes to temperature and precipitation, historical development of regulation in the Hudson Bay drainage basin, and increasing political will toward greener energy sources, development of hydroelectric facilities within the Hudson Bay drainage basin is anticipated to continue in the decades to come – and will continue to also influence the seasonality of river discharge in regulated rivers. The interface between the freshwater and marine system will undoubtedly be impacted by such projected increases to river discharge and the degradation of spring runoff peaks relative to seasonal low flows.

This chapter provides an in-depth review of the drainage basin of the Greater Hudson Bay Marine Region. The impacts of climate change and hydroelectric development are presented and future projections under stressors from climate and hydroelectric development are presented.

## Key Messages

- **Over the past four decades, freshwater discharge into Hudson Bay has increased due to strong increasing winter flows.**
- **In the future (2021-2070), freshwater discharge is expected to continue to increase by up to 20% in some regions of the HBDB.**
- **Increases in freshwater discharge are most certain for the eastern portion of the HBDB, but are highly uncertain for parts of the western HBDB owing to disagreement in projected climate scenarios.**

## 1. Introduction

For millions of years, the Hudson Bay system has been evolving through geologic change, glaciation, and flooding. Yet in recent decades, the system has become increasingly more vulnerable to rapid change resulting from human-driven influence (i.e., regulation of freshwater systems, development and climate change). As one of the largest continental shelves in the world, Hudson Bay depends on annual fluxes of freshwater, with seasonal fluxes impacting the formation, breakup and melt of sea ice. Timing, duration and magnitude of freshwater flux has a major influence on the marine properties, ecological drivers, circulation patterns, and the dynamics of sea ice; with ice-free seasons elongating under climate change (Hochheim and Barber, 2014). With freshwater discharge into Hudson Bay reported to be on the decline from 1964 to 1990, increasing in recent decades (Déry et al. 2005; 2011), increasing winter discharge (Déry et al. 2011), and projected increases in precipitation across the Nelson (McCullough et al. 2012; Clair et al. 1998) and northern Québec watersheds (Sottile et al. 2010); there is much uncertainty around future freshwater discharge. With many of the key physical, biological and biogeochemical processes occurring in Hudson Bay highly dependent on the large freshwater delivery system, improved understanding of the factors influencing historic trends and projected futures of the freshwater regime are crucial to our understanding of the Hudson Bay system, including its entire drainage basin, and their vulnerabilities.

This chapter begins with a description of the Hudson Bay Drainage Basin (HBDB), or landmass, including the major rivers delivering freshwater into the marine system and the

human influences (regulation) affecting the timing and delivery of freshwater. Factors affecting the freshwater system such as underlying geology, permafrost, ecological units, and climatology will be discussed. Since climate warming is now occurring at unprecedented rates in the Canadian sub-arctic (Bhury et al. 2011), understanding the potential impacts on the freshwater system and resources for Hudson Bay are of particular concern. Projected changes (2021-2070) in river discharge will be framed in the context of historic trends (1964-2013), discussed for 21 of the 42 rivers discharging into the HBDB that have observed streamflow records. Climate-related changes to runoff and discharge resulting from changing temperature and precipitation patterns will be explored using state-of-the-art hydrologic modelling coupled to global climate model (GCM) output. We end the chapter with a brief summary of our state of knowledge for the Hudson Bay freshwater system, and possible future impacts to the system.

## 2. The watershed

Draining surface water from nearly one third of the Canadian landmass into Hudson Bay, the Hudson Bay Drainage Basin (HBDB) is sandwiched between two continental divides (i.e., lines of high elevation): The Laurentian (to the south) and Arctic (to the north). Freshwater enters Hudson Bay through a network of 42 large rivers with outlets into Hudson, James, and Ungava Bays (Figure 1). Water is collected from the Canadian provinces of Alberta (AB), Saskatchewan (SK), Manitoba (MB), Ontario (ON) and Québec (QC); the Northwest Territories and Nunavut (NU); and four American States (Montana (MT), North Dakota (ND), South Dakota (SD), and Minnesota (MN)), eventually finding its way to Hudson Bay. The landscape spans 26° of latitude, 54° of longitude and eleven ecozones, and rises to more than 3,200 m in the western Rocky Mountain Range. With more than half the basin underlain by isolated to continuous permafrost, and a portion of the basin with non-contributing drainage area (i.e., Assiniboine and Saskatchewan River basins, tributaries of the Nelson River), the watershed is large, remote, and complex in terms of hydrology and climate. Capturing a total of 30% of water runoff in Canada, and its rivers contributing 20% of the Arctic Ocean's freshwater supply (Canadian Geographic 2016), Hudson Bay is a large freshwater 'bathtub' for Canada and the Canadian Arctic.

The gross drainage area, or area that contributes water based on elevation (i.e., topography), of the HBDB is ~3.8 million km<sup>2</sup>. The basin ranges in elevation from 3,200 m at the western headwaters in the Rocky Mountain Ranges (Nelson River headwaters) to 0 m (sea level) at the estuaries and river outlets of Hudson Bay.



M. FORTIER/ARCTICNET



FIGURE 1. Map of the Hudson Bay Drainage Basin (HBDB), and its regional watersheds.

## 2.1. Regional watersheds

Hudson Bay is fed by several large (and many small) rivers forming regional watersheds that drain water from the surrounding land area. From west to east, the major, hydro-metrically monitored rivers flowing into the system include the Thelon, Churchill, Nelson, Hayes and Seal from the west; Winisk and Severn in the southwest; the Ekwan, Attawapiskat, Albany, Abitibi, Moose, and Nottaway along western and southern James Bay; the Rupert, Eastmain, and La Grande Rivière along eastern James Bay; and Grande Rivière de la Baleine, Petite Rivière de la Baleine, and Nastapoca from the east. Combined, these rivers equate to a mean freshwater discharge of  $\sim 950 \text{ km}^3$  per year, or about one fifth of the total annual river runoff to the Arctic (Déry et al. 2004; Shiklomanov et al. 2000).

Table 1 lists 42 gauged rivers discharging into Hudson Bay (22 of 42), James Bay (13) and Ungava Bay (7); their size, mean annual discharge, and ranks (by size and mean annual

discharge). For each drainage region of the HBC, thirty-year mean annual discharge is shown (Figure 2), and summarized in Table 2 using a combination of gauged rivers and modelled ungauged areas.

Of the 42 rivers, some play more significant roles in the freshwater-marine coupling of Hudson Bay, and are described in more detail.

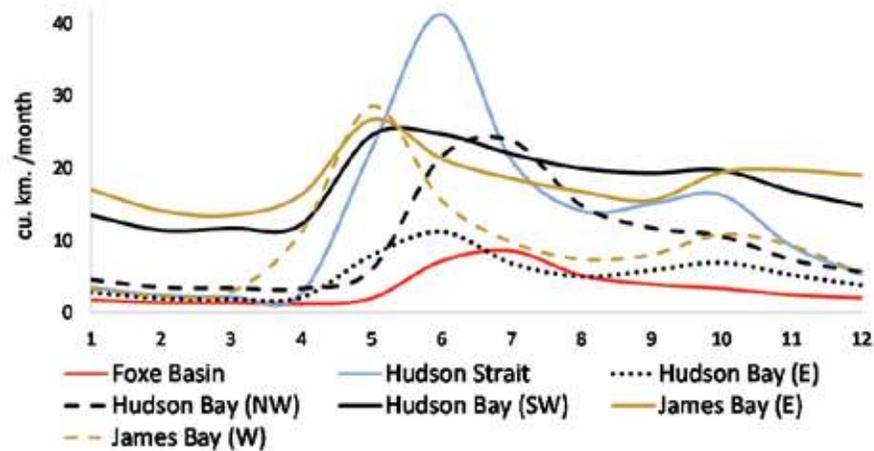
**TABLE 1.** Summary of the 42 gauged rivers draining into Hudson Bay, James Bay and Ungava Bay, ordered regionally from west to east along the perimeter of Hudson Bay. Outlet locations refer to HB-Hudson Bay, JB-James Bay, or UB-Ungava Bay, and Province/Territory refers to the location of the outlet (NU-Nunavut, MB-Manitoba, ON-Ontario, QC-Québec).

River	Outlet	Province/ Territory	Drainage Area, DA (km <sup>2</sup> )	Rank (DA)	Mean annual discharge, Q (km <sup>3</sup> )	Rank (Q)
Kirchoffer	HB	NU	3,160	38	0.84*†	40
Brown	HB	NU	2,040	40	0.52*†	42
Lorillard	HB	NU	11,000	31	2.64*†	35
Chesterfield Inlet	HB	NU	259,979	3	41.3‡	4
Diana	HB	NU	1,460	41	0.30*†	37
Ferguson	HB	NU	12,400	27	2.59*†	36
Tha-anne	HB	NU	29,400	21	6.17*†	27
Thlewiaza	HB	NU	27,000	23	6.82‡	26
Seal	HB	MB	48,100	12	11.5‡	21
Churchill	HB	MB	288,880	2	18.9‡	13
Nelson	HB	MB	1,125,520	1	102.7‡	1
Hayes	HB	MB	103,000	6	19.7‡	11
Severn	HB	ON	94,300	9	21.9‡	10
Winisk	HB	ON	54,710	11	15.2‡	18
Ekwan	JB	ON	10,400	32	2.8‡	34
Attawapiskat	JB	ON	36,000	18	11.4‡	22
Albany	JB	ON	118,000	4	31.8‡	7
Moose	JB	ON	98,530	7	39.0‡	5
Harricana	JB	QC	21,200	24	7.8‡	25
Nottaway	JB	QC	57,500	10	32.3*‡	6
Broadback	JB	QC	17,100	25	10.0‡	23
Rupert	JB	QC	40,900	17	25.3‡	8
Pontax	JB	QC	6,090	34	3.1‡	33
Eastmain	JB	QC	44,300	14	12.1‡	19
Opinaca	JB	QC	3,700	36	2.3†	37
La Grande Rivière	JB	QC	96,600	8	84.2‡	2
Roggan	JB	QC	9,560	33	4.0*†	30
Grande Rivière de la Baleine	HB	QC	43,200	15	19.6‡	12
Boutin	HB	QC	1,390	42	0.6†	41
Petite Rivière de la Baleine	HB	QC	11,700	28	3.7†	31
Goulet	HB	QC	5,970	35	4.5†	29
Nastapoca	HB	QC	12,500	26	7.9‡	24
Innuksuac	HB	QC	11,200	30	3.3†*	32
Kogaluc	HB	NU	11,300	29	4.9†*	28
De Povungnituk/de Puvirnituc	HB	QC	28,000	22	11.6†	20
Arnaud	UB	QC	45,200	13	17.8†*	14
Aux Feuilles	UB	QC	41,700	16	17.6†	15
Koksoak	UB	QC	110,136	5	55.6‡	3
False	UB	QC	2,140	39	1.0†*	39
À la Baleine	UB	QC	29,800	20	16.0†	17
Tunulic	UB	QC	3,680	37	2.2†*	38
George	UB	QC	35,200	19	23.7*‡	9
<b>Total, Average</b>	--	--	<b>3,013,945</b>	--	<b>16.8</b>	

\* Estimate based on <30 years of record (not necessarily inclusive of 1964-2013 period); some gauges/estimates seasonal; average of annual flows from Water Survey of Canada HYDAT database.

† Déry et al. (2005)

‡ Déry et al. (2016)



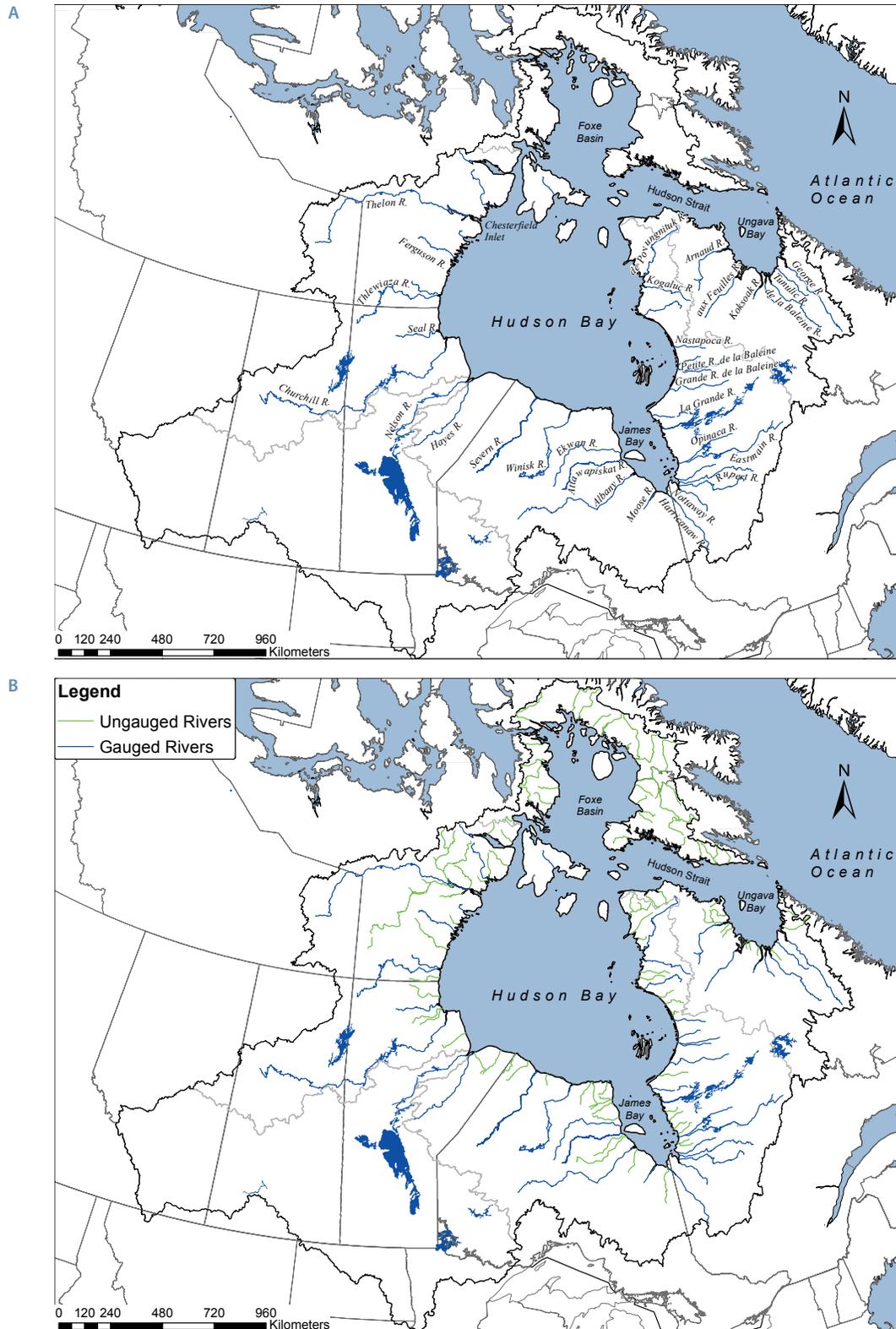
**FIGURE 2.** Thirty-year mean (1984–2013) monthly discharge into the Hudson Bay system, calculated from the same datasets and in the same fashion as for Table 2 excepting monthly values for the James Bay complex rivers. Monthly discharges for La Grande Rivière, Opinaca-Eastmain and Rupert rivers were estimated by multiplying decadal mean discharges reported by Déry et al. (2016) by monthly percent-of-annual discharges for the period 1984–2003 reported by Hernández-Henríquez (2010) (for La Grande Rivière) or by monthly percent-of-annual discharges estimated from prediversion hydrographs (for Opinaca-Eastmain and Rupert rivers).

**TABLE 2.** Freshwater loading to the HBS by discharge from the watershed. Discharges are 30-y means for the period 1984–2013. Values in parentheses in columns 2 and 3 are percent gauged drainage area and discharge, respectively. Totals include 1) discharge derived from Water Survey of Canada (WSC) records<sup>1</sup>, including discharge recorded at hydrometric stations in the lower watersheds, plus downstream discharge (the latter estimated as the product of recorded discharge multiplied by the ratio of watershed areas downstream and upstream of respective stations); 2) discharge for La Grande Rivière, Opinaca-Eastmain and Rupert rivers as reported by Déry et al. (2016) and 3) discharge for ungauged watersheds estimated from the calibrated HYPE model (refer to Section 4.2).

	Drainage area (km <sup>2</sup> )	Annual discharge (km <sup>3</sup> )
Foxe Basin	260,000 (54%)	40 (0%)
Hudson Strait	433,000 (49%)	155 (69%)
Hudson Bay <sup>1</sup>		
Northwest	613,000 (0%)	116 (63%)
Southwest	1,775,000 (29%)	210 (92%)
East	187,000 (79%)	61 (39%)
James Bay <sup>2</sup>		
East	353,000 (74%)	218 (94%)
West	365,000 (0%)	114 (85%)
	3,986,000 (69%)	914 (76%)

<sup>†</sup> Watershed runoff: 30 y means, 1984–2013; percent gauged discharge in parentheses; ungauged area modelled in HYPE.

<sup>1</sup> Gauged rivers included in this calculation: Albany, Attawapiskat, Broadback, Chesterfield Inlet\*, Churchill\*, Eastmain, Ekwan, George, Grande R. de la Baleine, Harricana\*, Hayes, Koksoak\*, À La Baleine, La Grande, Moose\*, Nastapoca, Nelson\*, Nottaway\*, Petite R. de la Baleine, Pontax, Seal, Severn, Thlewiaza, Winisk\*. Gaps in WSC records were filled by S. Déry using procedures reported in Déry et al. (2011). For this report, additional gap-free records were created for three Ungava Bay tributaries, the Koksoak, À La Baleine and George rivers. Asterisks indicate records at WSC stations on more than one tributary were combined to calculate the total watershed discharge (as identified in Table 1, Déry et al. 2011; plus WSC discharge data for the Caniapiscou and Aux Mèlèzes rivers combined to calculate Koksoak River discharge).\*



**FIGURE 3.** Location of the (a) largest of the 42 gauged freshwater outlets and major tributaries, and (b) ungauged tributaries (in green) of the Hudson Bay drainage basin; only major waterways shown.

**Chesterfield Inlet**

Located in the northwestern arm of Hudson Bay (Figure 3), the inlet is the terminus of the Thelon River. The Thelon drains 900 km across the Northwest Territories (Whitefish Lake) into Baker Lake, NU before discharging into Hudson Bay. The inlet comprises several islands and bays, and the community of Chesterfield Inlet, NU; residing just south of the Arctic Circle.

**Churchill River**

The Churchill River drains the second largest region (by area) in the HBDB, discharging freshwater into western Hudson Bay (Table 1) from northern Alberta, Saskatchewan and Manitoba. The 1,600 km long river is largely located within Canadian Shield terrain and includes many lakes. It is impacted by flow regulation, most notably at Southern Indian Lake where water is partially diverted south into the Burntwood River and then east into Hudson Bay through the Nelson River (Appendix A). Therefore, it is only the 13<sup>th</sup> largest contributor (by mean annual discharge) of freshwater to Hudson Bay. Regardless, owing to its large drainage area and strong seasonal cycling, the Churchill River estuary is a significant source of freshwater-marine coupling.

**Nelson River**

The largest river by drainage area and freshwater discharge to Hudson Bay (Table 1), the Nelson drains more than 1.1 million km<sup>2</sup> of central and western Canada, spanning four provinces (AB, SK, MB, ON), and four United States (ND, SD, MN, MT). Included in its drainage basin are the Saskatchewan, Assiniboine, Red and Winnipeg Rivers, all tributaries to Lake Winnipeg. Lake Winnipeg, the 11<sup>th</sup> largest freshwater lake in the world, drains into the lower Nelson River, where discharge is impacted by a series of regulation points controlled for hydroelectric production by Manitoba Hydro (Appendix A). The Nelson River estuary along the western shore of Hudson Bay is arguably one of the most significant freshwater-marine couplings in Hudson Bay owing to the large volumes of freshwater discharge and strong temporal cyclicity affecting sea ice formation and breakup.

**Hayes River**

Located just south of the Nelson River, the Hayes River drains parts of northeastern Manitoba before entering Hudson Bay's western shore immediately south of the Nelson River estuary at York Factory, MB. Originating just 90 km northeast of the northern tip of Lake Winnipeg (at Molson Lake), the river's drainage basin is the 6<sup>th</sup> largest (by area) of the HBDB, and the 11<sup>th</sup> largest contributor of freshwater discharge to Hudson Bay (Table 1).

**Moose River**

Fourth largest contributor of freshwater discharge to Hudson (James) Bay, the Moose River flows north out of the Precambrian Shield through the Hudson Bay lowlands before entering James Bay at Moose Factory, ON. It is the 7<sup>th</sup> largest drainage basin of Hudson Bay (Table 1), containing several significant tributaries such as the Abitibi, Mattagami, and Missinaibi Rivers. Affecting the Moose River are four hydroelectric developments from Ontario Power Generation, beginning in the mid-1960s, on the upstream Mattagami and Abitibi Rivers. Relative to the Nelson and La Grande Rivers, Moose River regulation has considerably less impact (i.e., more localized) on freshwater-marine coupling and cycling.

**La Grande Rivière**

Draining a significant portion of north central Québec 900 km westward into James Bay, this river is the 2<sup>nd</sup> largest in Québec by discharge. It is also the 2<sup>nd</sup> largest freshwater contributor to Hudson Bay, and the 8<sup>th</sup> largest by drainage area (Table 1). Similar to the Nelson, La Grande Rivière is regulated by Hydro-Québec in a series of dikes, dams and reservoirs for hydroelectric production (Appendix A). Water is diverted northward from the Eastmain, Opinaca, and Rupert Rivers (tributaries of James Bay) into the La Grande system for hydro-power production; and southwestward from the Caniapiscou River (tributary of the Koksoak River of Ungava Bay). Resulting from its significant freshwater contributions to Hudson (James) Bay and strong seasonal cycles impacted by regulation, this river is critical to the Bay's freshwater-marine coupling and annual cycling.

**Grande Rivière de la Baleine**

The "Great Whale River" lies to the north of La Grande Rivière, discharging directly into Hudson Bay as the 9<sup>th</sup> largest contributor of freshwater to the system (Table 1). A branch of this river now originates from the Caniapiscou Reservoir, and therefore is impacted, to a lesser extent, by a diversion from the Grande Rivière de la Baleine. The lower reaches of the river experience several drops in elevation and therefore have powerful currents and a series of waterfalls and rapids.

**Foxe Basin**

Located in a shallow, northern basin of Hudson Bay, Foxe Basin is situated between Baffin Island and Melville Peninsula and connected to Ungava Bay via Hudson Strait. None of the 42 monitored Hudson Bay freshwater tributaries discharge directly into Foxe Basin, and only a handful of smaller rivers drain from its rocky, steep shores. The basin remains significant to Hudson Bay freshwater-marine coupling, however, because of arctic freshwater transported in ocean currents through Hecla and

Fury Strait, and thick, rough sea ice which melts to produce freshwater that dominates most of the annual cycle.

**Ungava Bay**

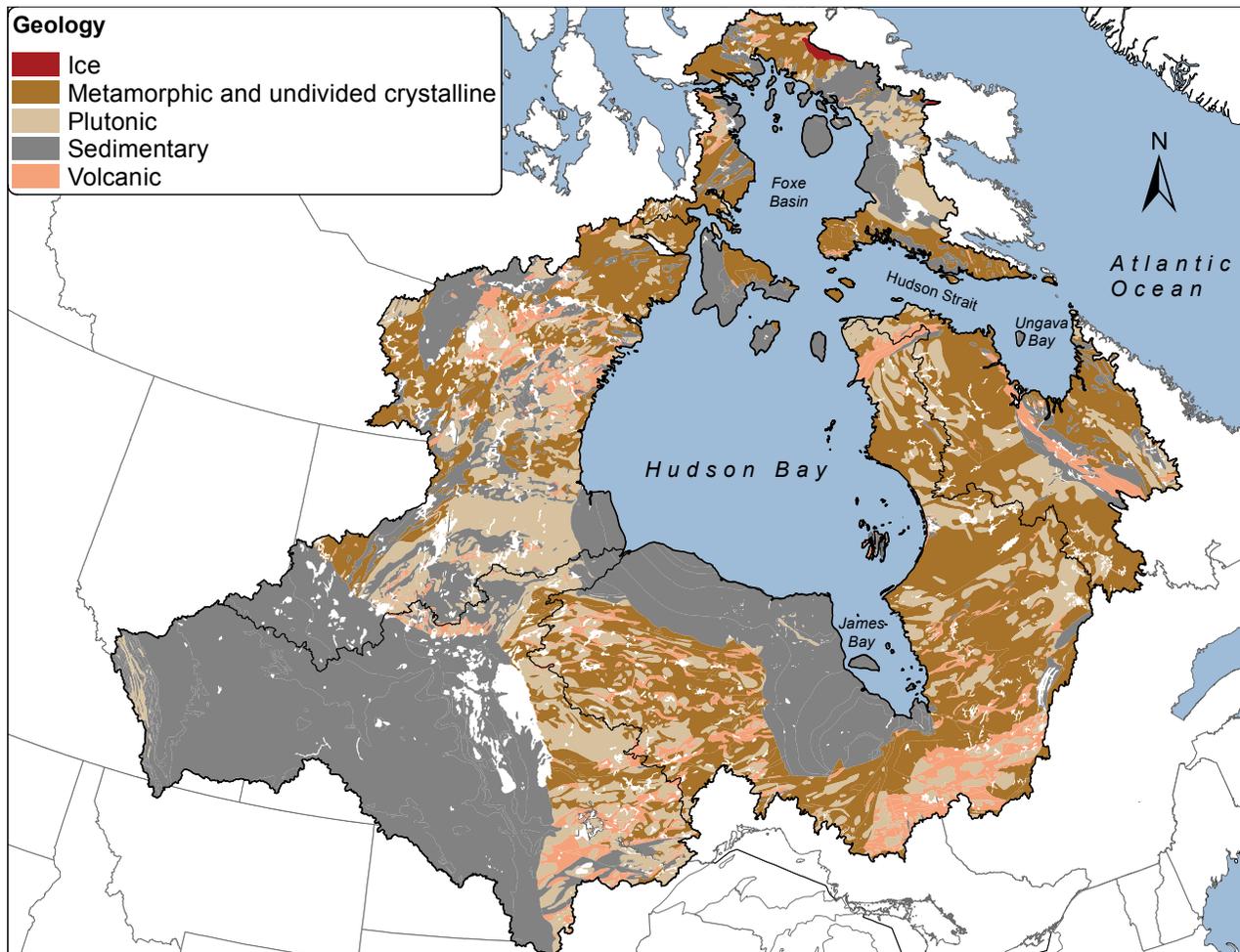
Connected to Hudson Bay via Hudson Strait, Ungava Bay is located at the northeast extent of Hudson Bay. Seven of the 42 monitored freshwater rivers enter through Ungava Bay and contribute freshwater to the Labrador Sea, including (in order of drainage area) the Koksoak, Arnaud, Aux Feuilles, George, À la Baleine, Tunulic, and False Rivers, all originating from northern Québec.

**2.2. Geology**

The HBDB sits within a large rock basin, depressed relative to surrounding Shield regions, consisting of Precambrian Shield and Hudson Platform formations (Stewart and Lockhart 2005). Shield regions are crystalline and typically rolling and deformed,

while the younger carbonate-dominated Hudson Platform is more low-lying and flat. Crystalline rock formations are the oldest and underlie the entire basin, constituting bedrock for the Québec coast (west of the Nottaway River) and eastern half of James Bay. Throughout the remainder of the HBDB, the underlying crystalline layer is overlain by younger sedimentary rocks of the Hudson Platform (Figure 4).

Glaciation has had a profound effect on the landscape of the Hudson Bay drainage basin. Continental ice sheets have covered it at least twice and possibly as many as seven times (Shilts 1982; 1984). Many of the modern characteristics of the HBDB were formed during the advance and retreat of ancient ice sheets, particularly the retreat of the most recent Laurentide Ice Sheet at the end of the Little Ice Age. Shaping the modern landscape were the abrupt drainages of lakes Agassiz and Barlow-Ojibway, which resulted in the penetration of the Hudson Strait marine system further down into Hudson



**FIGURE 4.** Hudson Bay drainage basin underlying geology.

and James Bays (Josenhans and Zevenhuizen 1990). Glacial retreat has altered the elevation of the drainage basin because of “unloading the land”, resulting in isostatic rebound, or lifting the landmass between 0.7 and 1.3 m per century (varying rates depending on where in the watershed you are) (Barr 1979). Significant to the hydrology of the HBDB is differential uplift of marine sediments, with lower rates of uplift in the southern portion of the HBDB enlarging some lakes as their (northern) outlets rise faster than their upper drainage basins. In the lowlands, surficial sediments around James Bay and along the southern and south-western shore of Hudson Bay are heavily influenced by tidal and wind activity and dominated by coastal marshes. At the watershed level, the glaciolacustrine regions of southwestern James Bay will influence the subsurface movement of water. Permafrost, low relief, and poorly drained sedimentary deposits yield numerous wetlands and highly organic, shallow soil complexes (Tarnocai 1982).

Continuous and discontinuous permafrost, common at latitudes above 51°N (Woo 1986), tends to limit the interaction of wetlands with groundwater (Woo and Winter 1993). In the HBDB, permafrost is continuous north of the Cape Henrietta Maria area (boundary between Hudson and James Bays), but transitions to sporadic and isolated permafrost moving further south toward the Hudson Bay lowlands (Figure 5). In addition to affecting the hydrology of the region, permafrost acts to stabilize otherwise weak soil and wetland complexes common to the region. Infrastructure in the north has long depended on this added rigidity for construction of roads, railways, buildings and hydroelectric transmission lines. But in response to accelerated warming in Arctic regions, permafrost soil temperatures have increased by approximately 2°C since the 1970s (Burn and Zhang 2009); resulting in slope instability, slumping, and damage to infrastructure that puts communities and infrastructure at risk (Figure 6). Thermokarst terrain, with ponds and

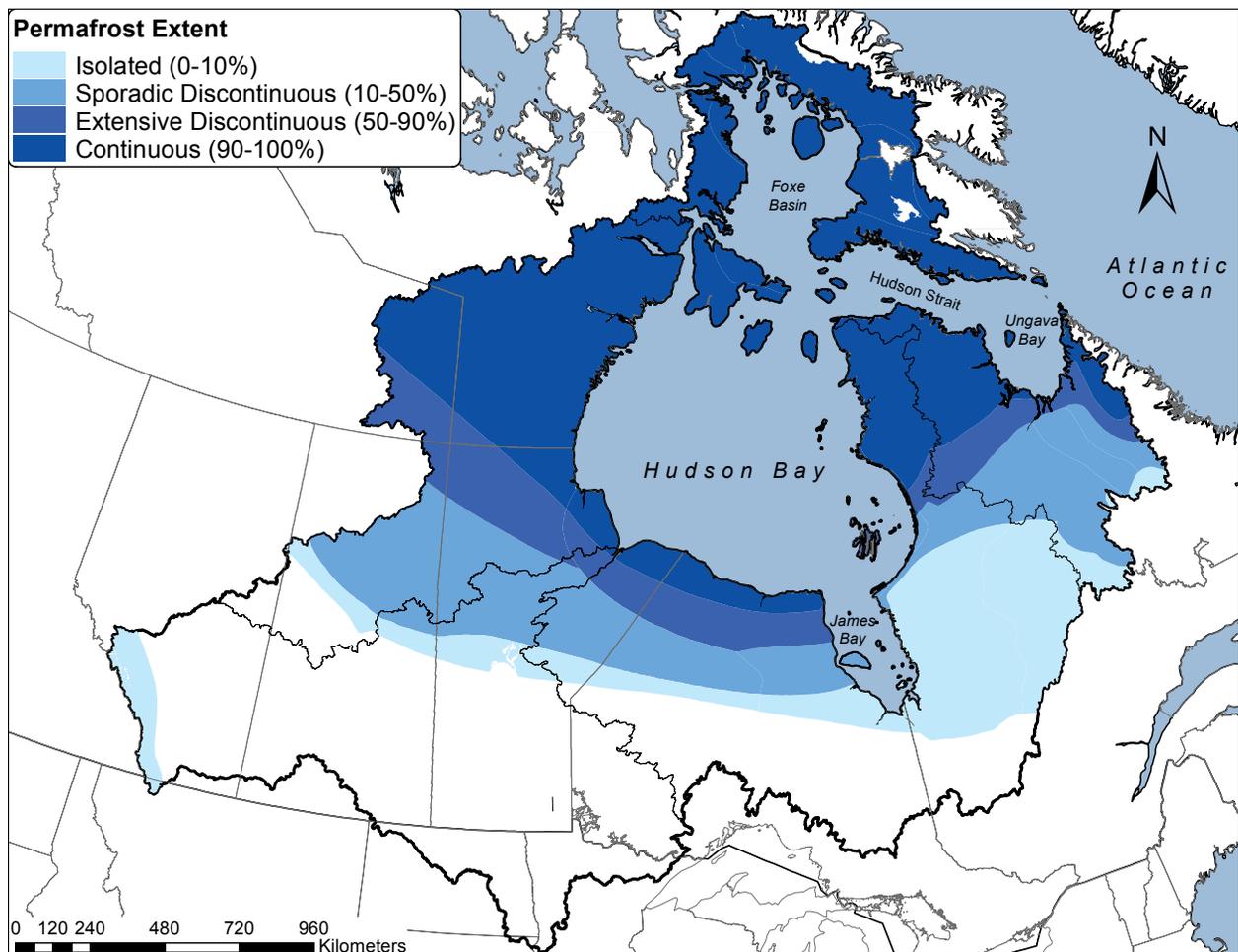


FIGURE 5. Permafrost regions within the Hudson Bay drainage basin.



**FIGURE 6.** Damage to rail lines connecting Thompson, MB to Churchill, MB as a result of thermokarst creating subsurface instability

wetlands in depressions created by thawing and subsidence of ice-rich soils, naturally shapes and erodes glaciolacustrine sediments and till plains in the HBDB, but is anticipated to do so at a faster pace and in more drastic ways under the influence of accelerated warming due to climate change (Kokelj et al. 2013).

### 2.3. Physiography

The landscape of the HBDB spans 11 ecozones (Figure 7), extending from the glaciated Rocky Mountains at the western edge, moving across the dry Prairie region and continental interior, to the mid-latitude cool-wet Boreal forest region, and northern Arctic tundra at higher latitudes (Déry et al. 2011). A small portion of the basin in the Canadian Rockies contains



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glaciers whose meltwater sustains summer flows beyond the spring freshet that dominates the hydrological regime in much of the south-western watershed. Glacial meltwater drains eastward via the Saskatchewan River, through Lake Winnipeg, and on downstream to Hudson Bay via the Nelson River. In the Precambrian Shield and Boreal Forest regions (Figure 8), extensive surface water in the form of lakes and wetlands similarly tends to weaken the spring freshet and sustains river discharge through the year.

Wetlands include bogs, fens, marshes, sloughs and swamps; all of which impact hydrologic systems by storing water. The exposed surface water retained in wetlands is susceptible to high evaporation rates during summer. West of Hudson Bay in the subarctic Shield region, wetlands are scattered across a landscape of bedrock with shallow organic soils and discontinuous permafrost. Field studies in this region have shown these wetlands moderate flow, except during winter and spring when shallow soils remain frozen (Roulet and Woo 1986). The James Bay lowlands, outside of the Canadian Shield, are home to peatland wetlands across the thermokarst land surface, formed by the collection of meltwater from discontinuous permafrost in shallow depressions (Pienitz et al. 2008). Projected increases in temperature within this region can increase evapotranspiration, affecting vegetation composition and causing loss of peat, which will impact freshwater discharge timing and magnitude (Moore 2002). Minerotrophic boreal fens, occurring as alternating patterned pools and vegetated strings, produce scattered runoff (Zeeb and Hemond 1998) and are abundant east of James Bay, covering 20% of La Grande Rivière basin (Tarnoca et al. 2000). In recent decades increased aqualysis, or increasing surface water coverage as hollows fill with water, of fens in the HBDB has been observed (Tardif et al. 2009).

The Prairies, which drain to Hudson Bay via the Nelson River, are home to another type of wetland: pothole depressions (Figure 9). They are glacial relicts that can be permanent features, or disappear from one year to the next (Euliss et al. 2004). The low relief of the prairie regions results in internal drainage, or regions that do not contribute water to streams but instead drain to pothole wetlands, local lakes or sloughs (Pomeroy et al. 2005). The net result is a reduced basin drainage area (i.e., effective drainage area), lower than that determined by elevation change alone (i.e., gross drainage area). Approximately 23% of the Nelson River Basin contains prairie terrain that does not contribute directly to streamflow (PFRA 1983).

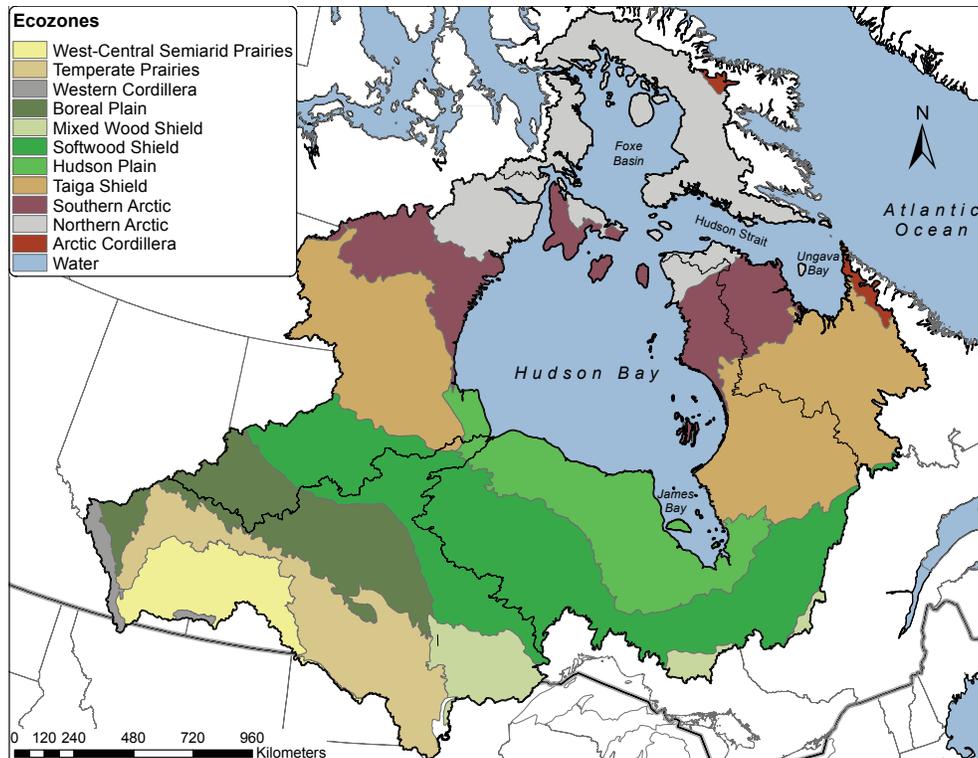


FIGURE 7. Ecozones of Hudson Bay drainage basin

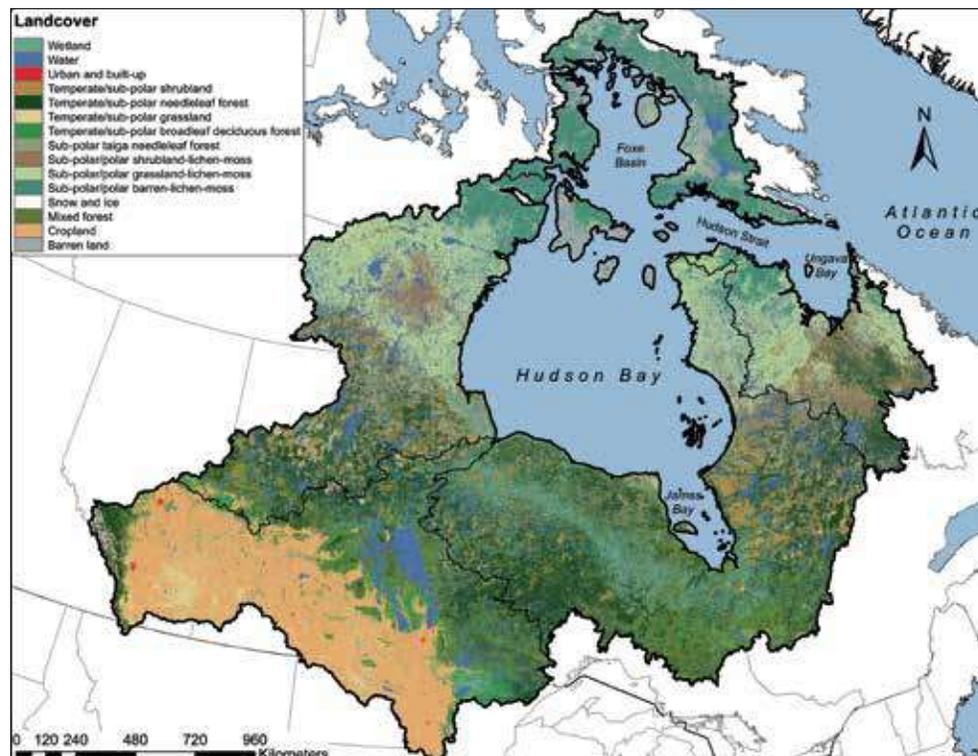


FIGURE 8. Landcover map of the Hudson Bay drainage basin.

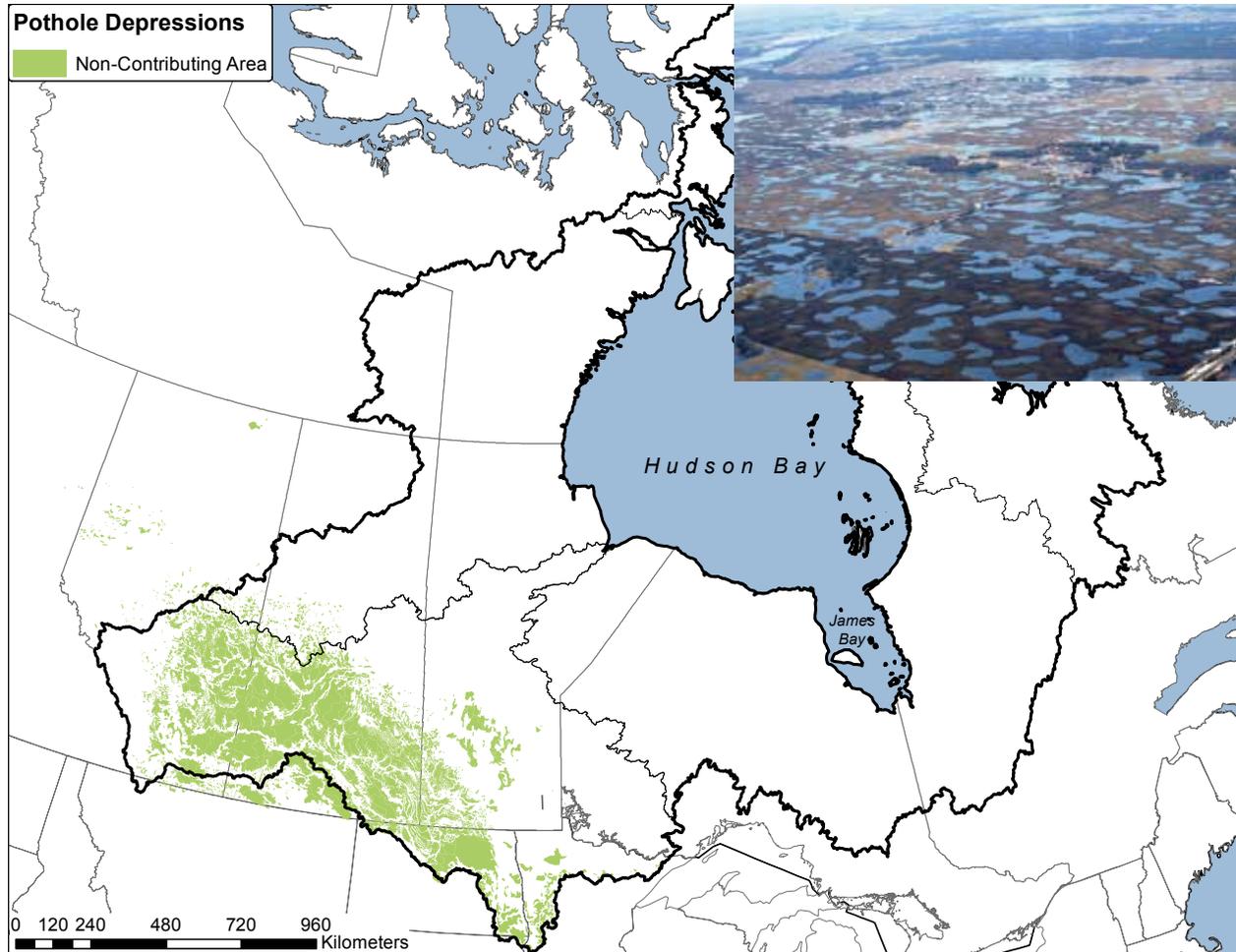


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**FIGURE 9.** Prairie potholes located within the Saskatchewan River region of the Hudson Bay drainage basin.

#### 2.4. Hydroclimate

The HBDB spans several climatic zones. Mean annual air temperature ranges from 4°C (Canadian Prairies and upper mid-west United States) to -12°C in Nunavut. The northern and southern regions of the basin tend to be drier (~300 mm annually) than the Boreal Forest region (~800 mm annually). Generally, the HBDB is characterized by long, cold winters with significant snowpack accumulation ranging from 100 mm mean annual snow water equivalent (SWE) in the Prairies, to 400 mm SWE in northern Québec (Déry et al. 2005). Snow cover typically begins by early October (mid-November in the south) and stays until mid-June (mid-April in the south) (McKay and Gray 1981). The primary driver of streamflow, or freshwater discharge, in the basin is snowmelt, with peak annual flow typically resulting from the spring melt: the basin therefore is classified as a nival (i.e., snowmelt-driven) regime.

Given most of the HBDB lies in mid- to high-latitude regions of Canada, observed climatological and hydrometric data are scarce and intermittent at times. Coulibaly et al. (2013) note that more than half of the HBDB is either ungauged or does not meet current World Meteorological Organization (WMO) standards for hydrometric gauging. Where hydrometric gauges do exist, significant gaps in records are common with data availability varying over time. Prior to 1964, there is an insufficient number of gauges with consistent data to accurately evaluate streamflow, limiting any historic trend analyses to 1964 and later (Déry et al. 2011). Care needs to be taken in the interpretation of streamflow data in this region due to the presence of possible error resulting from ice-affected discharge, frequent changes in the river regime (e.g., erosion and sedimentation), and infrequent gauge maintenance due to the remote location of the gauges. Gauged streamflow data are collected by a number of partners, including the WSC,

Ministère de l'Environnement du Québec, and hydroelectric regulators (Manitoba Hydro and Hydro-Québec).

## 2.5. Regulation

Over the past century, many rivers and lakes in the HBDB have been developed and regulated to utilize the wealth of water resources available. These resources come in the form of hydroelectric generation, domestic drinking water, and agricultural irrigation supply. In many cases the regulation of reservoirs has provided additional local benefits including flood mitigation, enhanced transportation routes, and recreational facilities. While these developments have benefited from the resources within the watershed, they have also altered the magnitude and timing of freshwater entering Hudson Bay; changes which should be considered when modelling freshwater discharge to the Bay.

There are well over 250 dams within the watershed listed in the Canadian Dam Association's (CDA's) register (Figure 10);

however, only a handful of these structures possess reservoirs with active storage large enough to significantly influence the timing and magnitude of freshwater reaching Hudson Bay on a monthly to annual basis. In the Nelson basin, these reservoirs include Reindeer Lake, Lake Diefenbaker, Lac Seul, Lake of the Woods, Cedar Lake, Lake Winnipeg, and Southern Indian Lake; and in La Grande basin, they include Caniapiscou, La Grande-3, Robert-Bourassa, and Eastmain reservoirs (Figure 11). Major regulation points within the HBDB and their inception dates are summarized in Table 2. It should be noted, however, that there was a stepped introduction of regulation in specifically the La Grande and Nelson systems, which impacts the historic discharge across several different decades.

Appendix A provides a more detailed description of the significant regulation points in the HBDB, and their influence on freshwater discharge into Hudson Bay, including Table A-1 that



FIGURE 10. Location of dams in the Hudson Bay drainage basin based on CDA criteria (2003) (Natural Resources Canada 2008).

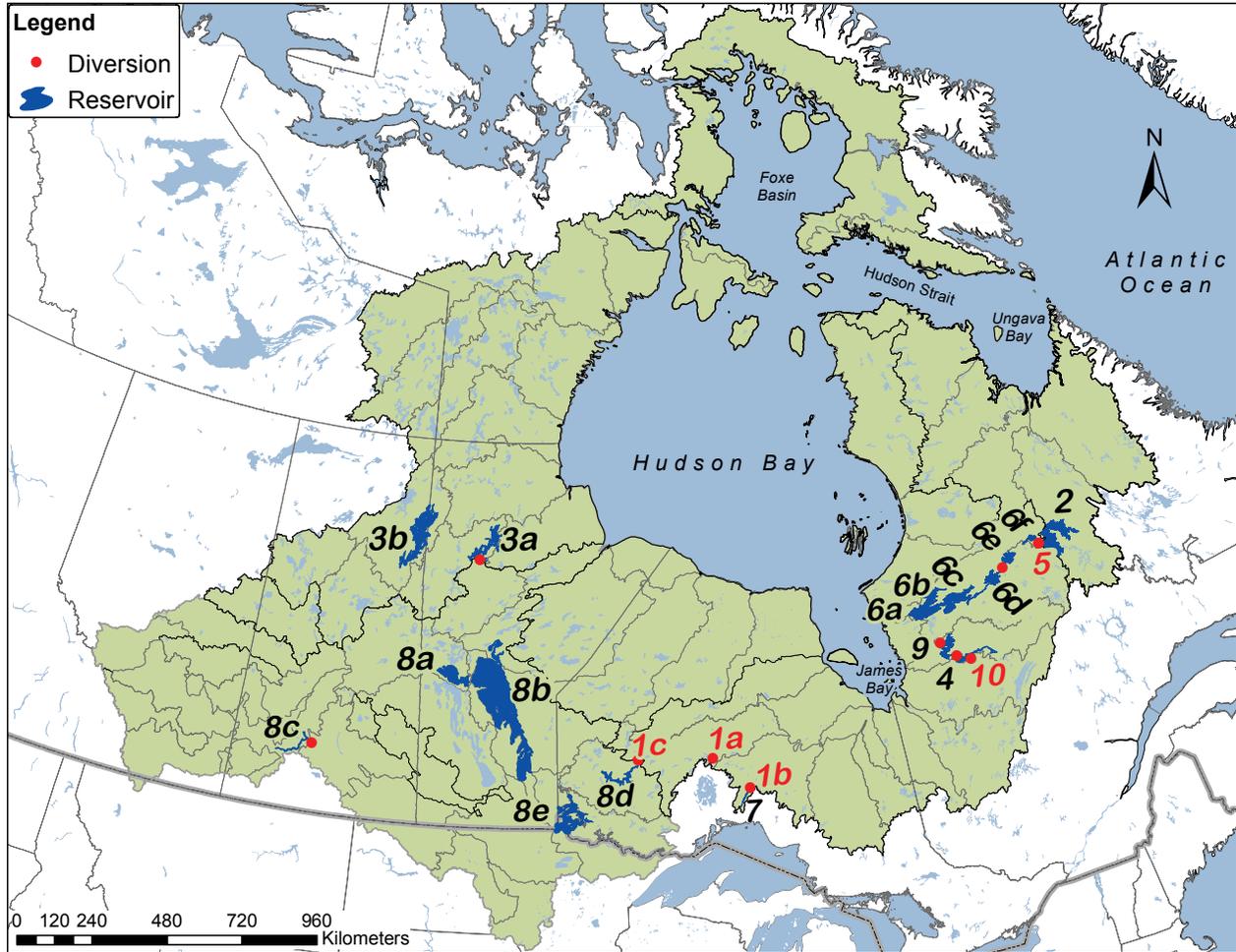


FIGURE 11. Location of major reservoirs within the Hudson Bay drainage basin. Location of diversions from Tables 3 and A-1.

TABLE 3. HBDB most major rivers affected by regulation and their commissioning dates (adapted from Déry et al. 2005). For a list of all reservoirs used for hydropower regulation, see Table A-1.

ID	River	Structure	First Year Commissioned*
1a	Albany – Ogoki	Diversion	1943
1b	Albany – Long	Diversion	1941
1c	Albany – Lake St. Joseph	Diversion	1958
2	Caniapiscau	Diversion	1993
3a	Churchill – Southern Indian Lake (SIL)	Dam, Reservoir, Diversion	1977
3b	Churchill – Reindeer Lake	Dam, Reservoir	1942
4	Eastmain (1- and 1-A)	Diversion	1976
5	Koksoak	Diversion	1982
6	La Grande Rivière	Dam, Reservoir	1980
7	Moose – Little Long	Dam	1963
8	Nelson	Dam, Reservoir, Diversion	1887
9	Opinaca	Diversion	1976
10	Rupert	Diversion	2009

\* note that in some cases rivers may have been affected pre-construction, during the period of construction. Date reflects the first structure, however in some cases additional structures were added altering the river over a period of time.

lists specific reservoirs controlled for hydroelectric production within the HBDB.

### 3. Historic freshwater regime

#### 3.1. State of hydrologic knowledge

The HBDB, like the pan-Arctic as a whole, is a primarily snow-melt-driven, nival streamflow regime with strong seasonality. The greatest discharge occurs during spring when snowmelt runoff can contribute up to three times as much volume as normal (i.e., mean) or low flow (i.e., base flow) volumes during the rest of the year. Despite this, the HBDB has the lowest variation in inter-seasonal freshwater discharge of all the major pan-Arctic watersheds: 46% of HBDB discharge occurs during spring, whereas the range is 46-66% across all pan-Arctic drainage basins (Lammers et al. 2001). Given parts of the HBDB reach fairly far south (relative to other pan-Arctic basins), higher amounts of rainfall-runoff in warm seasons may contribute to a lower spring-to-summer volume discharge ratio, with the extensive wetland complexes in the Hudson Bay lowlands also contributing. Mean annual freshwater discharge into Hudson Bay exceeds 525 km<sup>3</sup> yr<sup>-1</sup>, accounting for approximately 12% of all freshwater exports to the pan-Arctic ocean system (Déry et al. 2011).

Woo et al. (2008) provide an excellent description of the subarctic nival regime, which characterizes streamflow over the majority of the HBDB landscape. Long and cold winters allow snowpacks to accumulate and rivers remain ice-covered (Prowse and Ferrick 2002), with few (if any) significant mid-winter melt events. As air temperatures rise and snowmelt begins, seasonally frozen soils and permafrost reduce infiltration into the subsurface, causing meltwater to reach streams primarily as overland flow, or direct runoff (Hayashi 2013). As upper soil layers thaw, they can contribute large quantities of soil water runoff to nearby stream networks. Warming temperatures drive spring snowmelt and river ice break-up, resulting in the spring freshet (i.e., rise in flow) that typically begins during March in the southern regions and May or June further north. For example, Woo et al. (2008) show that the Rupert River in Québec has a later freshet than the Missinaibi River in Ontario, where peak discharge occurs in May. Warmer years with earlier spring snowmelt experience higher April flow volumes but tend to have a lower overall magnitude of freshet (i.e., peak streamflow) due to snowmelt occurring over a longer period of time (Burn and Hag Elnur 2002). Discharge declines during summer as evapotranspiration often exceeds rainfall. Autumn brings frontal rainstorms to the basin that produce peak streamflows, second in magnitude only to those that occur during spring. Come December and the return of colder

air temperatures, discharge drops as snowpacks begin to accumulate and runoff becomes negligible. The abundance of lakes and wetlands, and presence of glaciers in parts of the HBDB provide variations to typical nival regimes (Woo 2000).

Glaciers exist in the HBDB in the headwaters of the Saskatchewan River Basin in the Canadian Rocky Mountains, which ultimately drain to Hudson Bay via the Nelson River (Marshall et al. 2011). Existing at high altitudes and having cold surfaces, glaciers allow prolonged snowfall storage compared to lower altitude regions with warmer temperatures. Glaciers reduce streamflow seasonality by providing later (i.e., based on temperature alone) snowmelt runoff and by contributing glacial meltwater runoff during the summer (Meier and Tangborn 1961; Chen and Ohmura 1990). In the upper North and South Saskatchewan River basins, glacial melt is estimated to contribute (on average from 1975-1998) 44% of July-September streamflow (Comeau et al. 2009). The extent and volume of glaciers in the Canadian Rockies has been in general decline since the neo-glacial maximum around 1850. August to October streamflow in glacierized basins of the Rockies has declined since the 1990s despite increases in late summer precipitation since 1950 (Demuth and Pietroniro 2003). Further glacier decline in the Canadian Rockies is anticipated and will result in a transition towards a more typical nival regime for those headwater basins (Comeau et al. 2009).

Lakes are abundant throughout the Precambrian Canadian Shield. Regardless of size, lakes modify streamflow by storing and releasing large volumes of water, and through evaporative loss. Lakes can be considered hydrologic "gatekeepers" as, depending on their location within a stream network, they can lead to intermittent downstream flow (Spence 2006; Phillips et al. 2011). Perhaps most significantly, lakes can buffer extreme floods, such as those typically occurring in late spring.

The nival regime of the HBDB is also modified by the presence of wetlands (Section 2.3). Wetlands variably store, transmit and contribute water at different times over a year, and are not necessarily directly linked to stream networks, therefore often preventing or delaying runoff by storing water. In general, wetland-rich regions produce lower runoff yield (i.e., proportion of snow and rainfall) than non-wetland terrain, and less peaked streamflow with longer recession periods (Roulet and Woo 1988). Summer flows from a network of fens can be near-zero during dry summer years (Tardif et al. 2009), affecting total runoff and freshwater discharge in wetland-dominated regions. Over time during a warming climatic regime, water-filled fen hollows can merge to form shallow lakes that produce more frequent runoff events (relative to fen-dominated landscapes); however, peak runoff volumes become lower (Tardif et al. 2009). The semi-arid climate and low relief of the Prairies result in low runoff generation, where numerous potholes across



D. BABE

the landscape are often the terminus of this limited amount of runoff. Since streamflow from prairie landscapes largely depends on the interconnectivity of potholes, amounts can vary widely from year-to-year (Stichling and Blackwell 1957).

Blowing snow is an important winter process on the Prairies, Hudson Bay lowlands, Arctic tundra, and in the mountain alpine. Blowing snow sublimation losses are estimated between 15-41% of annual snowfall on the Canadian Prairies (Pomeroy and Gray 1995), 28% in Western-Canadian Arctic tundra (outside of the HBDB but representative of the Hudson Bay lowlands; Pomeroy et al. 1997), and 17-19% in the alpine region of the Canadian Rockies (MacDonald et al. 2010). Boreal forest stands intercept large quantities of snowfall, which then become prone to wind-driven sublimation, with losses estimated between 13-40% of total snowfall depending on canopy type and density (Pomeroy et al. 1998).

Historical trend analyses of streamflow discharge for the HBDB region have shown earlier peak discharge with decreased mean annual and monthly flow, except during the spring snowmelt period (Déry et al. 2005; McClelland et al. 2006). Increasing spring and winter discharge in subarctic regions has been attributed to warmer springs, and upper layer permafrost thaw, which can also increase summer flow (Yang et al. 2002, Smith et al. 2007). Trend analyses for western HBDB, particularly the Nelson-Churchill River basin, show strong decreasing trends in flow occurring in southeastern Manitoba and southern Alberta from the 1960s to 1990s (Westmacott and Burn 1997). From the 1910s to 2002, nine of 11 Albertan rivers show declining annual flow volume, partly due to irrigation (Rood et al. 2005). Rasouli et al. (2013) similarly show declining streamflow in the Athabasca River basin. Conversely, increasing

flow trends are occurring in mid- to northern Alberta, mid- to northwestern Manitoba, and the Winnipeg and Red River basins, with concern for potential future flooding in these areas (Westmacott and Burn 1997). Mean annual flows in the Winnipeg River basin are increasing (58% from 1924-2004) due to increases in winter discharge (60-110%) affected by regulation (St. George 2007). Years exhibiting extreme low annual flows in the Winnipeg River basin are the result of lower spring runoff following relatively dry summers and autumns.

Barriers to historic trend analyses include discontinuities in streamflow records distributed across high latitude regions and accounting for anthropogenic influence due to regulation in the records. In Section 3.2, we conduct our own comprehensive trend analysis using gap-filled historic discharge surrounding Hudson Bay, updating the previous works of Déry et al. (2005; 2011).

### 3.2. Trends in historic streamflow record

River discharge historically forms the largest input of freshwater into Hudson (including James) Bay and influences sea ice formation, sediment and pollutant fluxes, marine conditions, and ecological processes. Here 21 (of the 42 presented in Table 1) major rivers of the Hudson Bay drainage basin (Appendix B), covering 2.55 million km<sup>2</sup>, are used to assess historic variations and trends in freshwater discharge into Hudson Bay. This includes rivers affected by streamflow regulation (i.e., through dams, water retention in reservoirs, and diverted flows for enhanced hydropower production). Regulation typically enhances winter flows and reduces summer flows (Déry et al. 2011; 2016). Streamflow data are sourced from the Water Survey of Canada, Manitoba Hydro, Hydro-Québec and the Direction d'Expertise Hydrique du Québec and gaps are in-filled using the strategy of Déry et al. (2005) to provide continuous records for 1964-2013, a period of 50 years. They are then assessed for variations and trends over time (see Appendix B for methodology or Déry et al. (2016). It is worth noting that discerned trends are highly sensitive to the time period selected for analysis.

Based on the 21 rivers with sufficient gauged streamflow data, discharge into Hudson Bay averages 525.4 km<sup>3</sup> yr<sup>-1</sup> with annual variations of  $\pm 50.0$  km<sup>3</sup> yr<sup>-1</sup> (Table 3). An overall positive trend in Hudson Bay river discharge is observed from 1964-2013 (Figure 12). There is a noticeable decreasing trend in the first half of the study period, followed by a marked increasing trend in the second half (Figure 12). Déry et al. (2016) similarly report rising annual discharge to Hudson and James Bay since 1990.

Of note, significant increases are observed in the Nelson and La Grande Rivi re systems as flows are augmented by diverted waters from neighbouring rivers (Table 3; Table A-1). Portions of the Churchill River flows are retained by Southern

**TABLE 4.** Statistics of the mean, standard deviation (SD), coefficient of variation (CV) and change over time of seasonal/annual river discharge into Hudson Bay, 1964-2013.

Season	Mean (km <sup>3</sup> yr <sup>-1</sup> )	SD (km <sup>3</sup> yr <sup>-1</sup> )	CV	Change (%)
Winter	80.4	15.1	0.19	56.6*
Spring	162.7	18.6	0.11	-6.3
Summer	152.1	23.0	0.15	-6.9
Fall	130.2	17.6	0.14	37.5
Annual	525.4	50.0	0.10	6.9

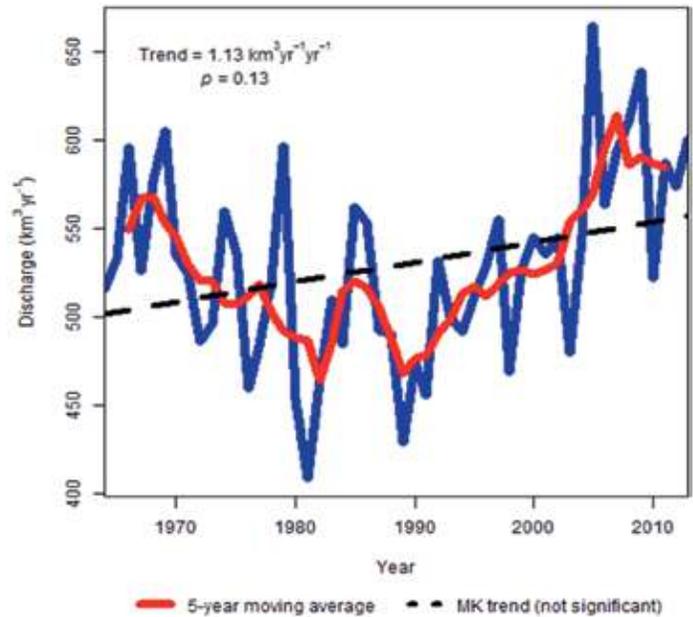
\* Statistically-significant changes ( $p < 0.05$ ).

Indian Lake and diverted into the Nelson River through the Burntwood River to enhance Manitoba Hydro's capacity to generate hydro-electricity on the lower Nelson River. Similarly, La Grande Rivière forms Hydro-Québec's largest hydroelectric facility, where flows from adjacent basins augment its power production by diverting portions of the Eastmain and Opinaca (since 1976), Caniapiscou (since 1983) and Rupert (since 2009) rivers, particularly during winter when hydroelectricity demand is highest (Hernández-Henríquez et al. 2010). These diversions increase freshwater releases into the estuaries of the Nelson and La Grande Rivière basins, greatly affecting local seawater salinity, sea ice production and melt, and ecological processes. Overall discharge to Hudson Bay, however, remains unaffected as all freshwater generated by the HBDB still makes its way into the Bay.

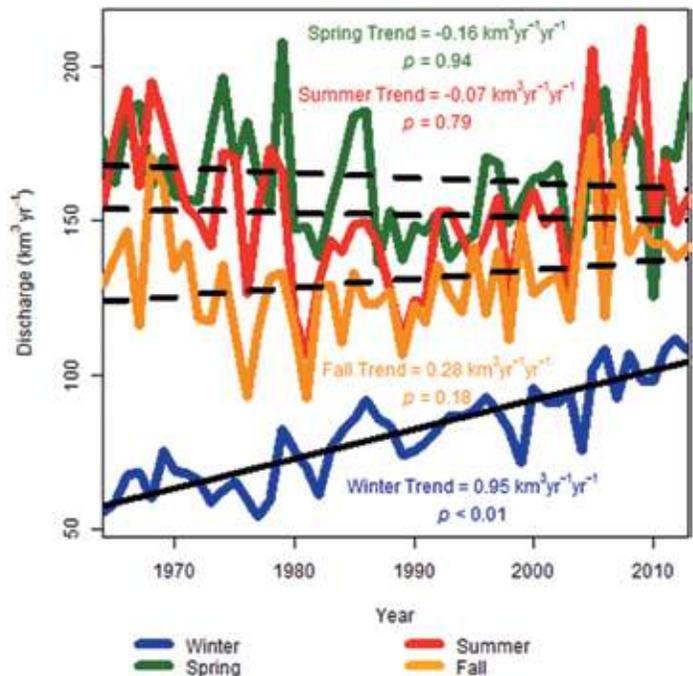
In turn, discharge for rivers with active diversion has declined markedly. Rivers affected by diverted flows are the Churchill, Eastmain, Caniapiscou, and Rupert. While these diversions do not generally affect total streamflow input into Hudson Bay, discharge from the Caniapiscou River diverts water from Ungava Bay, entering into James Bay instead. While other rivers show some timing advances of spring flows, they do not entirely offset the influences of flow regulation.

On a seasonal basis, streamflow from 1964 to 2013 discharging into Hudson Bay has increased during winter due to the regulation of flows and hydroelectric power demand during colder seasons (Figure 13). This is compensated by declining flows during summer when water is retained in large reservoirs, most notably in La Grande Rivière and Nelson River. There is minimal change in streamflow during spring or fall over the study period. In unregulated rivers of the study domain, advances in the timing of the spring freshet reflect earlier onsets of snowmelt, which is the main source of freshwater discharge for Hudson Bay. Research into the magnitude of this advancing freshet is on-going as part of the BaySys project.

While the seasonality of Hudson Bay inflows can be explained in large part by flow regulation, long-term changes are likely also attributable to climatic change. This is due to



**FIGURE 12.** Overall trends in Hudson Bay freshwater discharge (1964-2013).



**FIGURE 13.** Seasonal trend analysis (1964-2013) for 21 Hudson Bay freshwater rivers. Trends were determined using the Mann-Kendall trend (MKT) analysis. Solid lines represent significant trends at the 5% significance level; dashed are insignificant.

increasing precipitation (despite decreases in snowfall) in the Hudson Bay drainage basin and possible permafrost degradation (St. Jacques et al. 2009). As air temperatures warm in the Hudson Bay region, the atmosphere's ability to carry more moisture increases, leading to possible enhancements of precipitation, such as was observed in 2005. This results in an intensification of the water cycle marked by more precipitation, including rain-on-snow events and more frequent mid-winter melts and more frequent or intense rainfall resulting in increasing river discharge into Hudson Bay (Déry et al. 2009).

### 3.3. Impact of regulation on trends in streamflow

With a substantial portion of the Hudson Bay freshwater drainage being regulated or controlled by man-made structures, dams, diversions and reservoirs (Section 2.5), damping of the natural seasonal cycle occurs and tends to “flatten” annual streamflow variation, as noted by Anctil and Couture (1994). This can impact the Hudson Bay freshwater system by increasing the salinity in rivers discharging into Hudson Bay (Whittaker 2006; Messier et al. 1986), affecting sea ice formation and melt (LeBlond et al. 1994), and timing of freshwater discharge into the bay by increasing (decreasing) winter (summer) streamflow (Déry et al. 2011). When performing historic streamflow trend analyses, trends are developed from observed streamflow records – which include the effects of river regulation. Therefore, to fully assess trends in streamflow as a result of changing historical climatic conditions (separate from those driven by regulation), streamflow records would need to be “naturalized” and all effects from regulation removed. Given the amount and complexity of regulation within the HBDB (Appendix A), this would be difficult at best and in many cases, a guess of what the naturalized flow regime would have looked like. Déry et al. (2016) examine, in more detail, the impacts of regulation on freshwater discharge into Hudson Bay and subsequently compare regulated river discharge to nearby, unregulated tributaries.

Here instead, we have interpreted the records “as-is”, including the effects of regulation. Déry et al. (2011) studied the effects of regulation on freshwater discharge into Hudson Bay by looking at observed records pre- and post-regulation. They found, as a result of the James Bay Hydroelectric Complex, mean annual streamflow input to Hudson Bay decreased by 7.1 km<sup>3</sup> in a more recent period (1995-2008), and that notable increases in discharge in some regulated rivers may be partly explained by inter-basin diversion from the Caniapiscou River into the La Grande Rivière system. Interannual variability in streamflow discharge to Hudson Bay increased post-regulation for both the regulated and natural rivers, but had little seasonal variability with the exception of spring discharge caused by earlier snowmelt (Déry et al. 2011). Long-term storage

introduced by flow regulation impacts the intensity of the hydrograph by diminishing spring snowmelt peak flows and “flattening” the hydrograph (Woo et al. 2008).

It is therefore expected that regulation within the HBDB, particularly the Nelson and La Grande Rivers, will alter the timing and variability of streamflow both historically and into the future. Several studies have shown, however, that the presence and filling of reservoirs seems to have relatively little influence on the long-term trends in total annual streamflow entering Hudson Bay (Déry et al. 2011; McClelland et al. 2006). Since there is no method to predict future operations for the hydroelectric utilities regulating streamflow discharge (i.e., it depends on a number of factors related to economics, supply and demand for the systems), changes in regulation will not be considered in our analyses of future streamflow regimes.

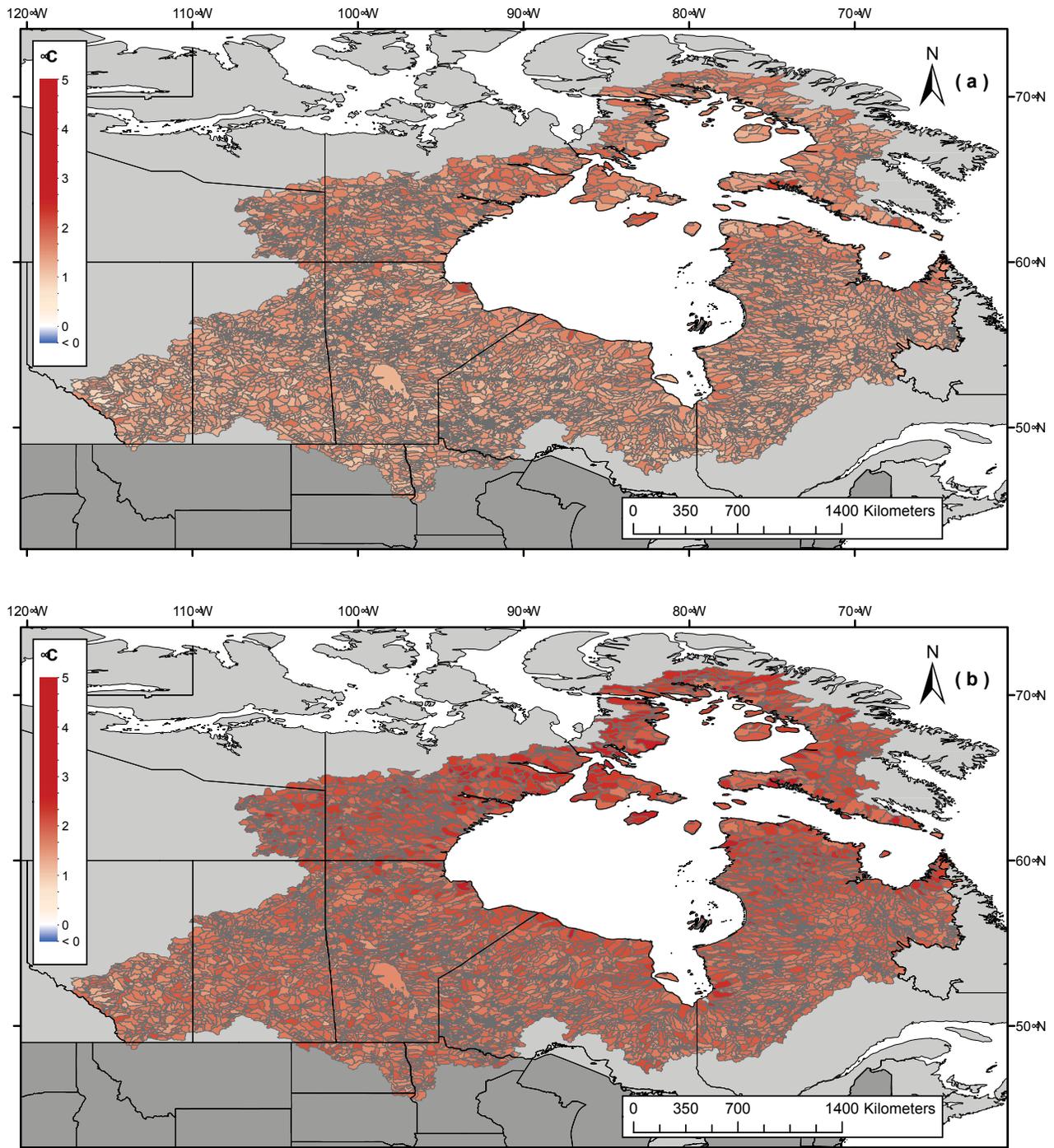
## 4. Projected freshwater regime

Projecting change to a system as expansive and complex as the HBDB is no small task. Given the lack of existing studies that specifically look to quantify possible changes in the freshwater regime over the entire HBDB, we developed our own models and projections to analyse the impacts of a changing climate on river discharge. For the reasons outlined above, future regulation development by hydropower producers and industry could not be projected, (though the model itself includes current regulation practice and infrastructure) therefore this section does not include changes in the freshwater regime associated with future hydroelectric development. In this section, we focus on the climate-induced change and the anticipated state of HBDB freshwater exports in the future (2021-2070) relative to a historical reference period (1981-2010). This involves establishing a system of models such that hydrologic models are driven by scenarios of future climate established by climate models. Our methods and results are discussed in the subsequent sections.

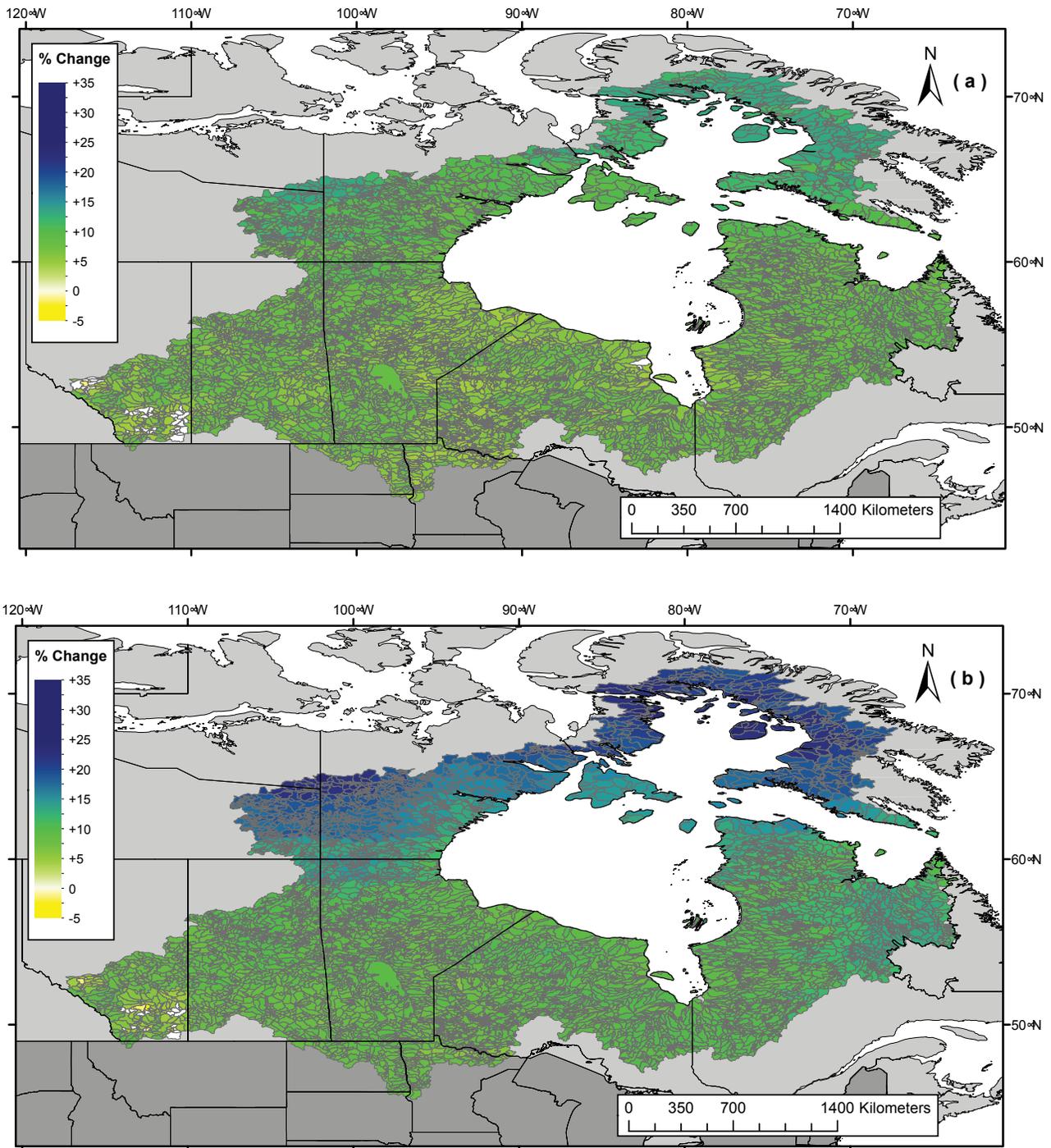
### 4.1. Projected future climate

Global Climate Models (GCMs) reproduce the physical processes and weather of the Earth as it revolves around the sun. The virtual Earth ‘climate model’ will generate movement of the atmosphere and ocean akin to what we know from radar and satellite images of the real world. In climate model experiments, scientists let these virtual Earths evolve over periods of 250 years and more.

The atmospheric processes of a climate model include the transfer of solar radiation (i.e., energy from the sun), which depends on the constituent gases of the atmosphere. By burning fossil fuels, humans are changing these constituent



**FIGURE 14.** Projected change in temperature (°C) based on ensemble average from 19 GCMs over the HBDB relative to the 1981-2010 reference period by (a) 2050 and (b) 2070. GCM inputs shown were processed to the HYPE subbasin scale were processed to the sub-basin scale.



**FIGURE 15.** Percent change in precipitation based on ensemble average of 19 GCMs over the HMB relative to the 1981-2010 reference period by (a) 2050 and (b) 2070. GCM inputs shown were processed to the HYPE subbasin scale were processed to the sub-basin scale.

gases. Using scenarios that estimate the future gas composition of the atmosphere, climate models serve as virtual laboratories to assess the impact of measured and projected future changes of greenhouse gases on the energy budget of Earth. While representing the same system, model simulations differ to some extent from the real world and amongst each other, providing a range of possible futures. When studying future climate change, this range needs to be considered.

Climate model simulations from the fifth generation of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) were used to drive a hydrological model over the HBDB domain to produce projected streamflow. Like in many other climate change impact studies, using the full set of around 150 CMIP5 simulations would have exceeded computational capacity, therefore 19 scenarios spanning the uncertainty range of the ensemble were used (refer to Appendix C).

The HBDB is anticipated to experience substantial warming during the 21<sup>st</sup> century. Retreating Arctic sea ice and reductions in pan-Arctic snow cover extent and duration amplify regional warming through cryosphere/albedo positive feedbacks (Serreze et al. 2007; Déry and Brown 2007). GCMs project greater temperature increases from 2021–2050 at high (northern) latitudes, with diminishing values moving southward (Figure 14). Climate data indicate average annual temperatures over the HBDB are expected to increase 2 to 3°C by 2050, up to nearly 5°C above 65°N latitude by 2070 (Figure 14). GCMs project precipitation increases associated with this regional warming (Figure 15), with increases along a strong latitudinal gradient (lower to the south, highest in the north) ranging from 0–15% by 2050, up to 30% in the northern HBDB by 2070. There is little longitudinal variation in the precipitation increases, illustrating the importance of Arctic amplification on hydrological changes in the Hudson Bay drainage basin.

## 4.2. Projected future flow

Computer-based modelling is needed to generate future streamflow projections. In some cases, statistical estimation can be used to extrapolate recent historical (based on observed data) trends, however due to the nature of climate change (a change from, or deviation from historical patterns) and long-term outlook in this study, hydrological models are the preferred method. Hydrological models take inputs of precipitation and temperature and calculate a suite of hydrologic processes: evapotranspiration, snowmelt, runoff and streamflow. Each simulated process is combined to compute overall streamflow for a given hour or day. Comparisons with the historical reference period (1981–2010) are then made by averaging the output into monthly, seasonal, or annual trends for analysis.

### 4.2.1. Review of existing projections

Regionally the effects of climate change on the HBDB are expected to alter the volume of runoff and river discharge, seasonal contributions and timing of discharge, and spatial and temporal discharge patterns. In this section, we discuss existing global projections of runoff for the HBDB from the latest global climate modelling efforts (CMIP5) driven by the latest atmospheric forcing scenarios (Representative Concentration Pathways; RCPs).

The Intergovernmental Panel on Climate Change (IPCC's) Fifth Assessment Report (AR5) presents a summary of global projections for several climate variables (e.g., temperature and precipitation) and annual mean runoff changes for 2081–2100 relative to 1986–2005 (Collins et al. 2013), where the multi-model ensemble mean indicates increasing runoff for all four RCPs. An overall increase in mean annual runoff is projected using HYPE across all scenarios for the HBDB, with greater increases in the northern and eastern regions. More uncertainty surrounding changes in runoff exists in the southern parts of the HBDB, including parts of the Nelson River drainage basin (Figure 3–4 in Jiménez Cisneros et al. 2014). Several studies have reported historic decreasing trends in river discharge across western Canada, including the headwater region of the HBDB despite generally increasing precipitation, likely the combined result of increasing temperatures and decreasing glacial melt (Naz et al. 2004; Prowse et al. 2009b; DeBeer et al. 2016). DeBeer et al. (2016) suggest there is considerable disagreement among climate-based projections over western Canada resulting from the complexity and interaction between hydrology and the land-surface in this region. The coastal region, northern (Nunavut), and eastern (northern Québec) regions indicate better agreement among projections (i.e., greater certainty) and typically coincide with increasing runoff.

Other studies have evaluated projected changes in Earth's freshwater regime at finer spatial and temporal scales relative to the IPCC's global projections. These studies show increasing trends in annual runoff in North America that is more pronounced than the global trend (Alkama et al. 2013), with increasing winter water supply but decreasing summer water supply (Kumar et al. 2014). Koirala et al. (2014) projected mean streamflow increases for the majority of the HBDB, most intensely in the northern and eastern regions. Higher magnitude flow events are largely projected to decrease, but low flow events are projected to increase globally. Cheng et al. (2017) found that in western Canada and surrounding regions, the finer the scale (or resolution) the more disagreement and uncertainty existed resulting from disagreement among CMIP5 GCM projections. That finding was recently reinforced by Gelfan et al. (2017) who used HYPE to simulate future discharge in the Mackenzie basin in western Canada.

The hydropower utilities have also undertaken their own projection studies for the Nelson-Churchill (Manitoba Hydro 2015c) and La Grande Rivière (Direction d'Expertise Hydrique du Québec 2015) basins. Hydro-Québec, using data from CMIP3, found both temperature and precipitation to be increasing over the eastern HBDB domain, with temperatures projected to rise between 2.5°C to 4.5°C, and precipitation from 10% to 15% along a south to north gradient (Guay et al. 2015). This is projected to translate into a 2% increase in average annual streamflow in the south, and up to a 14% increase in the northern sections of the eastern HBDB region. Manitoba Hydro reports statistically significant increasing historical annual temperature trends (up to 0.6°C/decade), projected up to 2°C to 3.4°C by 2050 (Manitoba Hydro 2015c). Historical records indicate mostly increasing annual precipitation trends from 10 to +45 mm/year/decade, with projected increases from 6% to 11% by 2050 (with the exception of summer, which may decrease by nearly 1% up to a 2.5% increase). For the Nelson and Churchill Rivers, this translates into projected increases in runoff (7% to 23%) for all major tributaries by 2050.

#### 4.2.2. HYPE model projections

Flow projections derived in this study for the HBDB from 2021-2070 are achieved using hydrological modelling forced by time series of projected daily precipitation and temperature (Section 4.1). The pan-Arctic implementation of the HYPE hydrological model (Arctic-HYPE; Andersson et al. 2015), developed by the Swedish Meteorological and Hydrological Institute, is used in this study. Appendix C describes this Arctic-HYPE model setup for the HBDB and the historical calibration performed that is necessary to have confidence in projected flow regimes.

It is important to openly acknowledge that projected discharge is highly dependent on the input data used to set up and calibrate the internal structure of the hydrological model, and the future climate scenarios used to drive the model. Observed hydrologic records are short relative to the projected time period analysed here, and data are not comprehensive of all Hudson and James Bay inflows (i.e., only 21 of 42 rivers were gauged). The model is calibrated to the rivers having observed data, and the model assumed to reasonably represent the hydrology of other regions, which may or may not be the case. Similarly, the climate scenarios used to drive the model simulations contain considerable variability in their interpretations of future climate. Though the range of all scenarios was reasonably represented, no one scenario is more correct than another – and similarly, for the projected discharge. Considerable disagreement among climate scenarios, particularly in the western Hudson Bay region, translates to differing statistical significance (Figure D-1) and uncertainty in projected streamflow (Figure D-2).

This study has selected the Hydrologic Predictions for the Environment, or HYPE hydrological model to translate future climate into streamflow. The HYPE model, like all hydrologic models, depends on calibration of model parameters, which adds an additional source of uncertainty to projected flows (Appendix C). Though the following section focuses on a review of recent literature, some preliminary results from the HYPE modelling are presented to lend context with on-going work, but need to be interpreted with caution. Scenarios of future flows do not encompass possible changes to the regulated regime, further discussed in Section 4.5. It should be noted that all projections presented herein are preliminary and subject to change based on on-going research from the BaySys project, including the uncertainty associated with these projections, which has been presented in Appendix D.

#### 4.3. Trends in projected streamflow record

Despite the different approaches to modelling, regional patterning in projected trends are generally in agreement with those reported in other studies (Section 4.2). All projected changes in streamflow are evaluated relative to modelled historical (1981-2010) flows to reduce the effect of residual model bias. Driving the Arctic-HYPE model with projected air temperature and precipitation over the HBDB reveals the latitudinal dependence of 21<sup>st</sup> century climate change. MacDonald et al. (2018) recently showed that streamflow projections from HYPE increase substantially in response to the stronger precipitation trends (i.e., above 65°N and the eastern portion of the HBDB), with more modest changes in other parts of the drainage basin. River discharge in the north-eastern HBDB (i.e., La Grande system) is generally increasing as a result of wetter future conditions, with steady-state to more modest increases across the western HBDB (i.e., Nelson River system). In contrast, Koirala et al. (2014) report generally increasing mean annual discharge across the Nelson River basin. The uncertain, modest changes in river discharge within the Nelson-Churchill portion of the HBDB are generally not statistically significant with  $p > 0.05$  (Figure D-1) and seem to result from climate model disagreement across the Prairie region (Figure D-2). Jiménez Cisneros et al. (2014) found between +10% and -10% change in projected runoff across parts of the western Hudson Bay region but point out that there is very little agreement among projected scenarios, which we similarly found.

Reflecting the increasing temperature (Figure 14), increases in evaporation (in mm) are projected across the Hudson Bay basin, with statistically significant increases occurring in Western Hudson Bay across the Canadian Prairies (MacDonald et al. 2018). This results in higher uncertainty in runoff and discharge projections for this region, and acts to offset more modest increases (not statistically significant) in

precipitation. As a result, runoff projections in the southwestern HBDB are not considered statistically significant (Figure D-3) resulting from climate model disagreement (Figure D-4).

The largest increases in discharge are projected to occur to the north and southwestern portions of the basin. This appears to occur as a result of the relatively lower increases in inflow (i.e., precipitation) to increasing temperature (Figure 14) in the southwestern portions of the basin, which drive statistically significant increases in evapotranspiration (MacDonald et al. 2018).

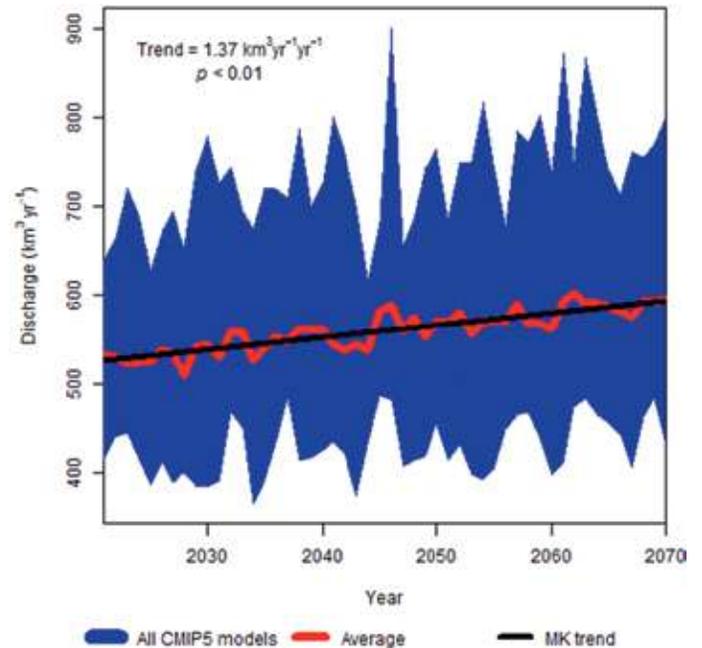
Using a HYPE configuration optimized to look at freshwater discharge into Hudson Bay relative to the historical period (Section 3.2), Figure 16 shows that the recent decadal increasing trends in river discharge continue, however at an intensified rate with projected annual average discharge to Hudson Bay (for the same 21 rivers) increasing by  $1.37 \text{ km}^3 \text{ yr}^{-1}$  from 2021-2070. This aligns with global trends in pan-Arctic discharge reported in the literature, such as those from Eurasia that report increased moisture transport to high northern latitudes (Zhang et al. 2013).

Seasonally, the largest projected increases in river discharge occur for winter and spring streamflow, with the smallest increases occurring during summer (Figure 17). Statistics of projected discharge trends by season from Arctic-HYPE are reported in Table 5. In future time horizons, all seasons experience statistically significant increases in discharge greater than those in the historic period; with the exception of the increase to projected winter streamflow increase which is less than historical (i.e., the introduction of hydroelectric regulation in the 1970s and 1980s augments the winter discharge rise). Not unexpectedly, the statistics indicate a large range (variability) in future streamflow, which is largely due to uncertainty

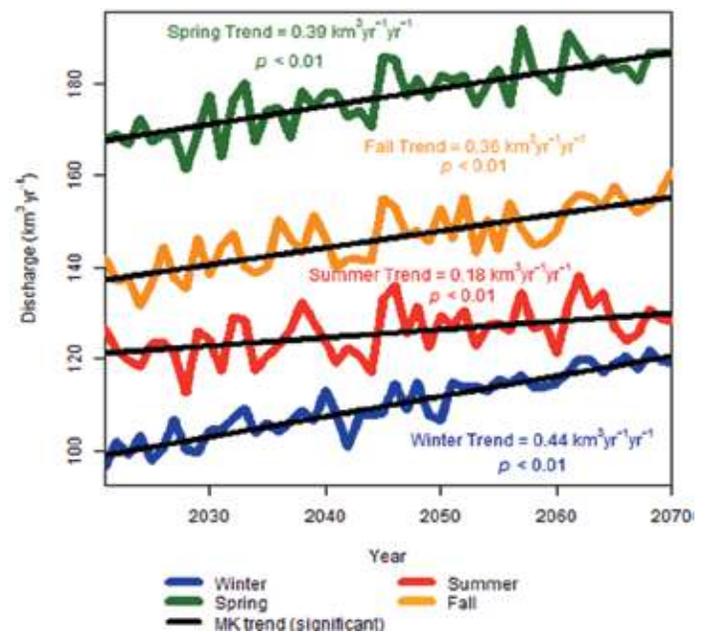
**TABLE 5.** Statistics of the mean, standard deviation (SD), coefficient of variation (CV) and change over time of modelled seasonal/annual river discharge into Hudson Bay, 2021-2070.

Season	Mean ( $\text{km}^3 \text{ yr}^{-1}$ ) [range of projections]	SD ( $\text{km}^3 \text{ yr}^{-1}$ )	CV	Change (%) [range of projections]
Winter	110.1 [96.0 – 123.8]	15.7	0.14	21.6* [-3.6 – 47.4%]
Spring	177.4 [157.1 – 203.0]	21.5	0.12	11.4* [-12.5 – 42.6%]
Summer	125.9 [96.1 – 158.0]	23.1	0.18	7.1* [-29.8 – 54.8%]
Fall	146.7 [127.2 – 176.5]	22.8	0.16	13.0* [-17.9 – 41.4%]
Annual	560.1 [488.8 – 655.3]	65.8	0.12	12.7* [-15.2 – 39.0%]

\* Statistically-significant changes ( $p < 0.05$ ).



**FIGURE 16.** Projected annual average trends in discharge for 21 Hudson Bay freshwater rivers (2021-2070).



**FIGURE 17.** Projected seasonal trends (2021-2070) for 21 Hudson Bay freshwater rivers. Seasons are defined as winter (DJF), spring (MAM), summer (JJA), and fall (SON).

(variability) in the future climate used to drive the hydrologic model (Section 4.1, Appendix D). Greater projected increases to fall and winter low streamflow coupled with more moderate increases to spring and summer flows will result in a gradual flattening of the hydrograph.

#### 4.5. Projected regulated regime

In all scenarios of future streamflow, regulation within major river systems (Section 2.5) was assumed to be held constant (i.e., no modification of reservoirs, storage volume or existing rule curves was made). Though this assumption is not entirely realistic, there is no mechanism to forecast future regulation within the HBDB. What we do know, however, is that air temperatures are expected to continue to rise across the HBDB over the 21<sup>st</sup> century (Section 4.1). Irrespective of the greenhouse gas emissions scenarios used in developing projections of Earth's future climate, the higher (northern) latitudes are expected to experience warming of approximately two to three times the global average (MacDonald et al. 2018).

In an effort to mitigate potential future increases in air temperature, there is a current thrust towards a low carbon economy fueled largely by international climate agreements to reduce the world's greenhouse gas emissions and reliance on non-renewable energy sources. The development of additional capacity to generate hydropower remains a priority for Canada's energy sector in partnership with Canada's First Nations peoples. Hydroelectricity forms a low-carbon and renewable source of energy such that development of infrastructure related to its generation will progress into the 21<sup>st</sup> century. Construction of new and/or expansion of existing hydroelectric facilities on HBDB rivers is either ongoing or in the planning stages by hydroelectric companies in Manitoba, Ontario and Québec; most notably for the Nelson, Moose and La Grande Rivière systems, respectively. Expansion of hydroelectric facilities across the Canadian Prairie Provinces is also anticipated, while the possible introduction of hydro-power generating stations in Nunavut is foreseen if economic activity (especially in the mining sector) expands rapidly in the coming decades. Thus the 21<sup>st</sup> century will observe continued development of hydroelectric facilities on rivers in the HBDB as demands for low-carbon energy sources rise.

Given these circumstances, it is likely that flow regulation in HBDB will change in the 21<sup>st</sup> century, particularly in systems with large water storage capacity. Peak demand for hydropower in Canada typically occurs in winter in relation to domestic, commercial and industrial heating. Hence the seasonal shifts in HBDB river discharge observed in the latter half of the 20<sup>th</sup> century and early 21<sup>st</sup> century may amplify in the coming decades. This may sustain trends towards greater river discharge during winter, while decreasing river

discharge in summer in regulated rivers. Warmer air temperatures in summer may increase energy demands for domestic, commercial and industrial climate control, especially during intense heat waves; however, this is likely to have a secondary impact (relative to winter impacts) at most on flow regulation annually. Increasing air temperatures and reductions in the duration of seasonal ice cover will also enhance evaporation from reservoirs, thereby reducing water availability in regulated systems. It is possible, therefore, that the HBDB will experience less seasonality during the 21<sup>st</sup> century, with increases in winter river discharge and decreases in summer river discharge. The 'shoulder' seasons (spring and autumn) are less likely to observe trends associated with flow regulation. River discharge to Hudson and James Bays in summer may also be affected by the competing effects of rising energy demands for climate control and of diminishing water availability through evaporation from reservoirs. Thus, the hydrological regime of the HBDB may progress towards greater control of flows during the 21<sup>st</sup> century, with the primary impact being a reduction on the seasonality of its river discharge.

## 5. Summary

In recent decades, the HBDB has been undergoing significant change to both climate (temperature and precipitation) and development of hydroelectric complexes, consequentially affecting the freshwater regime. In decades to come, temperatures are expected to continue to increase, possibly seeing a +5°C temperature change in the northern (>65°N latitude) HBDB by 2070. As air temperatures warm, the atmosphere can hold more moisture, resulting in increases in precipitation of up to 30% by 2070 – again impacting higher latitude regions most significantly. Previous studies and our own findings are in agreement that river discharge to the HBDB is expected to continue to increase but at a faster rate than during the recent historic period (1.13 km<sup>3</sup>yr<sup>-1</sup>yr<sup>-1</sup> from 1964-2013), with our projections indicating 1.37 km<sup>3</sup>yr<sup>-1</sup>yr<sup>-1</sup> more discharge on average (2021-2070) from 21 of the 42 rivers entering Hudson and James Bays. Increasing trends in river discharge exist across all seasons and are most prominent in fall and winter, but more moderate during summer when higher temperatures and evapotranspiration may offset increasing precipitation. Runoff across the HBDB is also generally increasing along a longitudinal (east to west) gradient with the largest increases along the northern and eastern portions of the bay, and the smallest increases across the western Hudson Bay region in some of the Canadian Prairie basins. Climate (and therefore streamflow) projections demonstrate very little agreement across portions of the western Hudson Bay region. Therefore, projected changes

in the flow regime in the Nelson River basin remain highly uncertain. Though we project (and have observed in recent decades) these changes to be occurring within the HBDB, the exact causes and relative contributions of each change factor (e.g., climate, hydroelectric regulation, land use change, etc.) are yet unknown. Based on the projected changes to temperature and precipitation, historical development of regulation in the HBDB, and increasing political will toward greener energy sources, development of hydroelectric facilities within the HBDB is anticipated to continue in the decades to come – and will continue to also influence the seasonality of river discharge in regulated rivers.

The interface between the freshwater and marine system will undoubtedly be impacted by such projected increases to river discharge and the degradation of spring runoff peaks relative to seasonal low flows. This undoubtedly will alter freshwater-marine system circulation, exchange, and the sea ice formation/breakup process. The impact of large shifts in both the timing and magnitude of freshwater export into Hudson and James Bays, and associated effects on the stability of the water column; sea ice formation, decay and breakup; and freshwater-marine ecosystem interfaces are not well understood. Results from our work are contributing toward a large interdisciplinary project focused on exploring these interface effects (i.e., BaySys), and the relative contributions of hydroelectric regulation in altering the delivery of freshwater exports to Hudson and James Bays.

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## APPENDIX A

A short description of the regulation affecting streamflow entering Hudson Bay is described in the following section, ordered by drainage basin from west to east.

### Regulation of the HBDB

#### Reindeer Lake

As the largest lake in the Churchill River Basin, Reindeer Lake serves as an off-channel storage reservoir for Island Falls GS, a hydroelectric generating station (GS) located on the Churchill River (Nelson River basin) ~45 km upstream of the Saskatchewan-Manitoba border.

Island Falls GS was originally built by the Churchill River Power Company (CRPC) to supply electricity for the town of Flin Flon and the smelter of the Hudson Bay Mining and Smelting Company. Construction of Island Falls began in 1928 and was completed in 1930 with a powerhouse of three units. Four additional turbines were installed during the period of 1936-1959 (Crippen Acres 1983). For the first 10 years of operation, Island Falls GS operated without the regulation of Reindeer Lake and it was quickly determined that dependable hydropower generation could be increased if it was used as a storage reservoir. CRPC began construction of a series of crib dams in 1937

to impound Reindeer Lake and by 1942 had completed the construction of Whitesand Dam, a concrete control structure equipped to regulate outflows of Reindeer Lake for increased dependable winter flows (Crippen Acres 1983). SaskPower took ownership of Island Falls GS in 1981 and assumed operations of the plant and Whitesand Dam in 1985.

In 1975, a study was undertaken jointly by the Canada, Saskatchewan, and Manitoba governments to determine the social, economic, and environmental impacts of hydroelectric development on the Churchill River. As a part of this study, work was undertaken to reconstruct and simulate the hydrologic regime of the Churchill River with the regulation of Reindeer Lake and Island Falls GS removed. The study found that regulation of Reindeer Lake had resulted in an overall increase in winter and early spring flows on the Churchill River, with a corresponding decrease in summer and autumn flows (Hofer 1975).

#### Southern Indian Lake

Located on the Churchill River, Southern Indian Lake (SIL) is a reservoir in Manitoba Hydro's system with the primary purpose of diverting flows from the Churchill River to increase flows and hydropower production of generating stations on the Burntwood and Nelson Rivers.

The Churchill River Diversion (CRD) is comprised of two control structures and an excavated channel that allows



diverted water from SIL to enter the Nelson River system via the Rat and Burntwood Rivers. CRD is operated in conjunction with Lake Winnipeg Regulation (LWR) to maximize overall power production on the lower Nelson River while adhering to the terms of the project's licenses. Construction of the CRD began in 1972 and was completed in 1976.

Prior to the CRD, river flows exited SIL at Missi Falls through two natural outlets at the east end of the lake and flowed down the Lower Churchill River into Hudson Bay. The CRD has added an average flow of 767 m<sup>3</sup>/s to the Nelson River via the Burntwood River, with a corresponding reduction in the Lower Churchill River downstream of Missi control structure (CS). The combined effect of both LWR and CRD has typically produced higher Nelson River flows in the winter than would have occurred without regulation. Average outflows during the summer months are similar to what would have occurred without regulation, as typically Lake Winnipeg outflows are reduced coincident to the increased diversion flows from Notigi CS. The CRD has also had a substantial impact on the Lower Churchill River flows, reducing overall volumes of discharge and significantly increasing streamflow variability (Manitoba Hydro 2015b).

### Lake Diefenbaker

Located on the South Saskatchewan River upstream of the City of Saskatoon, Lake Diefenbaker is the largest body of water in southern Saskatchewan. The reservoir operates to provide irrigation for Central Saskatchewan and the Qu'Appelle Valley, as well as providing other benefits to the area including hydroelectric generation, water supply, flood control, and recreation facilities.

Lake Diefenbaker is comprised of multiple structures at both Gardiner Dam/Coteau Creek GS, the primary outlet to the South Saskatchewan River; and the Qu'Appelle River Dam, a smaller earth fill dam constructed to contain the lake and allow for controlled diversion releases to the Qu'Appelle River through a gated diversion conduit. Construction of Lake Diefenbaker began in 1959, both dams and the Gardiner spillway were largely completed by 1967, and by 1970 the reservoir was fully impounded (Saskatchewan Watershed Authority 2012).

The relatively large storage capacity of Lake Diefenbaker has allowed for significant control of outflow from the lake, reducing the fluctuations of discharge from variable inflows to the lake while meeting water level and outflow targets and respecting dam safety requirements. In general, the reservoir is operated such that high inflows in late spring/early summer are captured in storage and released continuously throughout the rest of the year. The result of this regulation has been a significant dampening of extreme high and low flow events and an overall flattening of the annual hydrograph shape (Saskatchewan Watershed Authority, 2012).

### Cedar Lake

Cedar Lake is a reservoir located on the Saskatchewan River just downstream of The Pas. The reservoir is used primarily for regulating upstream inflows from Saskatchewan and local runoff for hydropower generation at Grand Rapids GS.

Grand Rapids GS was built during the period of 1960-1968 and was the first northern hydroelectric generating station constructed by Manitoba Hydro after hydropower sites on the Winnipeg River were fully developed. Cedar Lake is primarily used as a seasonal reservoir to ensure an adequate supply of hydropower generation through the winter months. Responding to the operation of the Grand Rapids GS, Cedar Lake rises from April to November when inflows are greatest and energy demand is lowest. From November until March, Cedar Lake is drawn down as water is taken out of storage for energy production purposes. Refilling of the reservoir then begins in the spring depending on the timing and magnitude of the freshet and summer precipitation.

The regulation of Cedar Lake has altered the timing and magnitude of the lake's outflows. Prior to the construction of the Grand Rapids GS, Cedar Lake water levels followed the natural hydrological cycle with the water levels rising in the spring, peaking in mid-summer and declining through the fall and winter. The downstream impacts of Cedar Lake are also compounded by the regulated inflows from upstream reservoirs in Saskatchewan, which began at approximately the same time as the construction of Grand Rapids GS. As noted previously, the operation of Gardiner Dam/Lake Diefenbaker has significantly altered flows on the lower Saskatchewan River. These upstream regulation activities have generally resulted in higher winter flows and relatively lower summer inflows to Cedar Lake, as compared to what would have occurred prior to development.

### Lake Winnipeg

As the sixth largest lake in Canada, Lake Winnipeg is the principal reservoir of Manitoba Hydro's hydroelectric generation network. Beginning in the late 1950s, Lake Winnipeg Regulation (LWR) was planned and developed by the governments of Canada and Manitoba to achieve two key objectives: to reduce shoreline flooding on Lake Winnipeg, and to advance the development of northern hydroelectric potential on the Nelson River.

In 1970, Manitoba Hydro was granted a license to regulate Lake Winnipeg outflow. LWR construction began in 1972 and was completed in 1976. LWR is an extensive engineered system of channels and structures that allows about 50% more water to flow out of the lake than would otherwise flow out naturally. Inflows into Lake Winnipeg vary tremendously from year to year, and with a relatively narrow operating range defined by the license, the reservoir is only capable of providing sub-annual

storage. Seasonal effects of LWR operations include increased average outflows in the winter months and corresponding decreases in average summer outflows. The improved outlet conveyance of Lake Winnipeg and restrictions on the operating range have also resulted in increased outflows during wet periods to provide flood relief around the shores of Lake Winnipeg, as well as reduced outflows during dry spells to provide low level support (Manitoba Hydro 2014).

### Lake of the Woods

Lake of the Woods is the largest lake in the Winnipeg River basin and is an international waterway located on the Canada-US border. The lake serves as a multipurpose reservoir, providing benefit to hydropower production on the Winnipeg River system, as well as recreational benefits to locals and cottagers in the area. With two main outlets located at the north end of the lake near the City of Kenora, Lake of the Woods discharges into the Winnipeg River, which flows onward through Manitoba and into Lake Winnipeg.

Lake of the Woods' eastern outlet was first partially controlled in 1892 and has been fully controlled since 1906 with the completion of the Kenora Generating Station. The western outlet is regulated by the Norman Dam and GS. Construction of Norman Dam began in 1893, but the powerhouse was not completed until 1925 (LWCB 2016). Outflows from Lake of the Woods are regulated by the LWCB under a treaty between Canada and the United States. This treaty prescribes maximum and minimum levels, within which the lake must ordinarily be maintained, to best serve multiple uses (LWCB 2016). A large portion of inflow to Lake of the Woods is also regulated via the Rainy River system, which also spans the Canada-US border. Water levels and flows in this system are regulated according to rule curves established by the International Rainy Lake of the Woods Watershed Board (IJC 2016)

### Lac Seul

Lac Seul is a reservoir located on the English River that is operated to provide storage for the benefit of hydroelectric generation on the English and Winnipeg Rivers. Outflows of Lac Seul are controlled through the operation of two generating stations situated at the lake's outlet, Ear Falls.

The original spillway and powerhouse at Ear Falls GS were built in 1928-29 by the Hydro-Electric Power Commission of Ontario; with reservoir filling completed in 1935. In early 2009, the construction of an additional powerhouse, Lac Seul GS, was completed (LWCB 2016). In addition to natural inflows from the Upper English River, Lac Seul receives inflows diverted from Lake St. Joseph via the Root River. This diversion has been in place since 1958 and operates to pass flow from Lake St. Joseph to Lac Seul for increased hydropower production on the

English and Winnipeg Rivers. Control structures on the Root River and Albany River, the natural outlet of Lake St. Joseph, regulate the amount of water diverted to Lac Seul; however, the Root River diversion dam is fully open for the majority of the time, with more than 80% of the water from the Lake St. Joseph basin being diverted to Lac Seul (LWCB 2016).

Lac Seul releases are regulated by the LWCB, subject to the terms of the LWCB Act as amended in 1958 and the operating range defined in the 1986 Orders-in-Council. Since its initial construction, Lac Seul has operated primarily to maximize hydropower production at downstream generating stations on the English and Winnipeg Rivers, though increasingly the needs of other users are being considered in regulation actions (LWCB 2016). Since regulation, average monthly releases from Lac Seul have been typically greatest over the winter period when energy demand is greatest and inflows are the lowest, with flows reduced over the summer to allow for refilling of the reservoir to summer target levels.

### Mistassini Lake

Although not a regulated system in itself, Mistassini Lake is important for Hydro-Québec's system due to it being the largest (by surface area) natural lake in Québec, with significant storage volume. Mistassini Lake's primary outflow point is the Rupert River, controlled by Rupert Dam, flowing downstream in a westerly direction before entering James Bay. Since 2009, downstream of Mistassini Lake, approximately 70% the natural flow of the Rupert River has been diverted northwards to the Eastmain River to feed the Eastmain-1-A development and La Grande hydroelectric project as part of the Eastmain-1-A/Sarcelle/Rupert Project (Hydro-Québec 2016b). The lake is an important natural headwater basin for the Eastmain-1-A.

### Eastmain River

The Eastmain River resides in northwestern Québec, naturally flowing approximately 800 km west into James Bay, and having a catchment area of approximately 46,400 km<sup>2</sup>. In the 1980s, Hydro-Québec constructed the Eastmain reservoir which diverts the river 41 km northwards to the Opinaca Reservoir, feeding the Robert-Bourassa Reservoir and La Grande Complex of generating stations (Hydro-Québec 2016). Eastmain-1 reservoir has a surface area of approximately 600 km<sup>2</sup> and is formed by the main dam and a total of 33 dikes. Eastmain-1 powerhouse, located approximately 800 km north of Montréal, is equipped with three turbines generating a total of approximately 480 MW of electricity, with the construction of Eastmain-1-A powerhouse (in 2012) increasing total power production to more than 8.7 TW. Construction of Eastmain-1-A saw a portion of flow from the Rupert River diverted into the Eastmain-1 reservoir to sustain power production (Tremblay et al. 2014).

**TABLE A-1.** Controlled hydroelectric reservoirs in the HBDB. Province abbreviations are ON-Ontario, QC-Québec, MB-Manitoba, SK-Saskatchewan.

ID	Reservoir	Province	Hydroelectric Complex	Commissioning Date <sup>1</sup>	Reservoir Surface Area (km <sup>2</sup> )
2	Caniapiscou - Brisay <sup>†</sup>	QC	La Grande	1993	4,378
3a	Churchill – Southern Indian Lake (SIL)	MB	Nelson	1977	2,356
3b	Churchill – Reindeer Lake	SK	Nelson	1942	5,665 <sup>*</sup>
4	Eastmain-1	QC	La Grande	1976	589
6a	La Grande-1	QC	La Grande	1995	709
6b	Robert-Bourassa <sup>†</sup> (LG-2-A)	QC	La Grande	1979	2905
6c	La Grande-3	QC	La Grande	1982	2,452 <sup>†</sup>
6d	La Grande-4	QC	La Grande	1984	836
6e	Laforge-1	QC	La Grande	1993	1240
6f	Laforge-2	QC	La Grande	1996	346
7	Moose – Little Long <sup>^</sup>	ON	Mattagami	1963	76
8a	Nelson - Cedar Lake	MB	Nelson	1967	3,176
8b	Nelson - Lake Winnipeg	MB	Nelson	1976	24,500
8c	Nelson – Diefenbaker	SK	Nelson	1968	430 <sup>‡</sup>
8d	Nelson – Lac Seul	ON	Nelson	1929	1,473 <sup>**</sup>
8e	Nelson – Lake of the Woods	ON	Nelson	1887	3,850
9	Opinaca	QC	La Grande	1976	998

<sup>1</sup> Based on first year of commissioning

<sup>†</sup> Source: Hydro-Québec (<http://www.hydroquebec.com/learning/hydroelectricite/gestion-eau.html>)

<sup>^</sup> Source: OPG report (Table 2.1-1) ([http://www.ceaa-acee.gc.ca/050/documents\\_staticpost/26302/38969E.pdf](http://www.ceaa-acee.gc.ca/050/documents_staticpost/26302/38969E.pdf))

<sup>\*</sup> Source: Environment Canada (1975). Hydrology (Saskatchewan) Final Report 2, *Churchill River Study (Missinipe Probe)*, Saskatoon, SK, 61pgs.

<sup>\*\*</sup> Source: Lake of the Woods Control Board (<https://www.lwcb.ca/reg-guide/index.html>)

<sup>‡</sup> Source: Saskatchewan Watershed Authority (2012). *Lake Diefenbaker Reservoir Operations: Context and Objectives*. 47pgs.

### Caniapiscou Reservoir

Located on the upper Caniapiscou River and within the Côte-Nord administrative region of Québec, this reservoir is the second largest in Canada. The reservoir, formed by two dams and 43 dikes, services the Brisay generating station and the downstream James Bay hydroelectric complex, providing up to 35% of Hydro-Québec's power production. It was the largest (in surface area) built as part of the James Bay Project. Filling a natural (glacial) depression in the highest part of the Laurentian Plateau on the Canadian Shield, the reservoir has a local catchment area of about 36,800 km<sup>2</sup> and a total capacity of 53.8 billion m<sup>3</sup> (Hydro-Québec 2016).

### La Grande 3 (LG-3) and Robert-Bourassa Reservoir

Robert-Bourassa Reservoir is situated downstream of the Caniapiscou Reservoir and similarly feeding the La Grande Complex (a total of eight generating stations); constructed as part of the James Bay Project, and one of the largest hydroelectric systems in the world. The La Grande Complex of generating stations drains westerly along the eastern shore of James Bay. Robert-Bourassa reservoir, constructed from 1974 to 1978 to

feed the Robert-Bourassa and La Grande-2 generating stations, has a maximum surface area of 2,835 km<sup>2</sup> and total estimated capacity of 61.7 billion m<sup>3</sup>. Forming the reservoir is the main dam and 31 smaller dikes. Together the generating stations, along with the La Grande 2-A (commissioned in 1991 to 1992), generate a combined 2,106 MW of power (Hydro-Québec 2016).

La Grande-3 generating station resides on the La Grande Rivière upstream of Robert-Bourassa reservoir. The LG-3 hydroelectric generating station was commissioned between 1982 and 1984 and can generate up to 2,419 MW of power, with the La Grande Complex system having a total installed generating capacity of 16,527 MW. The La Grande Rivière watershed naturally covers a region approximately 96,700 km<sup>2</sup> in size.

La Grande-1, also part of the James Bay Project, is the last generating station along the La Grande Rivière before James Bay. Commissioned between 1994 and 1995, the station installed capacity is 1,436 MW and is one of two generating stations that are "run-of-the-river" within the James Bay Project – relying on water flow in the river, controlled by upstream reservoirs, to generate power.

## APPENDIX B

### Methodology for historic streamflow trend analysis

A total of 21 rivers (Table B-1) are used to assess recent characteristics and trends in river discharge into Hudson Bay. The rivers are selected based on gauged data availability, gauged area, gauge proximity to Hudson Bay (including James Bay), record length, and data quality. Of note, there are very limited streamflow data for rivers draining into Hudson Bay prior to 1964 while recent (2014 onward) gauged data remain unavailable at this time, limiting the study period to 50 years. Time series of annual and seasonal discharge are created based on observed daily streamflow data for 1964 to 2013, then

gap-filled (Déry et al. 2005). Here winter refers to the months of January, February and March, spring comprises April, May and June, summer includes July, August and September, and winter comprises October, November and December. Statistics of mean, standard deviation (SD) and coefficient of variation (CV) of annual/seasonal discharge are assessed for all rivers draining into the Bay. The Mann-Kendall Test (MKT) is then used to assess trends in annual/seasonal discharge, with  $p < 0.05$  considered statistically-significant (Mann 1945; Kendall 1975; Déry et al. 2005). The effects of autocorrelation on trend analyses are minimized using a method developed by Yue et al. (2002). Trends are reported as percent changes in annual/seasonal river discharge between 1964 and 2013.

**TABLE B-1.** The 21 HBDB rivers used in the streamflow trend analysis. Mean annual discharges from Déry et al. (2005, 2016), unless otherwise indicated. Outlets indicate HB-Hudson Bay, and JB-James Bay; and Province/Territory indicates the location of the outlet (ON-Ontario, QC-Québec, MB-Manitoba, NU-Nunavut).

River	Outlet	Province/ Territory	Drainage Area, DA (km <sup>2</sup> )	Rank (DA)	Mean annual discharge, Q (km <sup>3</sup> )	Rank (Q)
Albany	JB	ON	118,000	4	31.8	7
Attawapiskat	JB	ON	36,000	18	11.4	22
Broadback	JB	QC	17,100	25	10.0	23
Chesterfield Inlet	HB	NU	259,979	3	41.3	4
Churchill	HB	MB	288,880	2	18.9	13
Eastmain	JB	QC	44,300	14	12.1	19
Ekwan	JB	ON	10,400	32	2.8	34
Grande Rivière de la Baleine	HB	QC	43,200	15	19.6	12
Harricana	JB	QC	21,200	24	7.8	25
Hayes	HB	MB	103,000	6	19.7	11
La Grande Rivière	JB	QC	96,600	8	84.2	2
Moose	JB	ON	98,530	7	39.0	5
Nastapoca	HB	QC	12,500	26	7.9	24
Nelson	HB	MB	1,125,520	1	102.7	1
Nottaway	JB	QC	57,500	10	32.3*	6
Pontax	JB	QC	6,090	34	3.1	33
Rupert	JB	QC	40,900	17	25.3	8
Seal	HB	MB	48,100	12	11.5	21
Severn	HB	ON	94,300	9	21.9	10
Thlewiaza	HB	NU	27,000	23	6.9	26
Winisk	HB	ON	54,710	11	15.2	18

\* Estimate based on <30 years of record (not necessarily inclusive of 1964-2013 period); some gauges/estimates seasonal; average of annual flows from Water Survey of Canada HYDAT database.

nd: insufficient points ( $\leq 3$ ) to compute mean annual discharge, or data not available.

## APPENDIX C

### CMIP5 clusters

Output from the fifth generation of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) were used to drive streamflow projections for the HBD. A suite of around 150 climate model simulations make up the CMIP5 ensemble. Using the full CMIP5 ensemble of simulations would have exceeded computational capacity within a reasonable time frame. A k-means clustering approach was used to reduce the number of climate scenarios to 19, whilst representing the uncertainty range of the ensemble (Casajus et al. 2016). Based on a set of selection criteria this algorithm identifies clusters of similar simulations and chooses the simulation closest to the cluster’s centre as representative of the cluster’s characteristics (Figure C-1).

While a good representation of the CMIP5 ensemble was the key objective, some constraints were applied to the selection process for BaySys. The k-means selection process was not operated freely, but guided to meet specific constraints around variable availability and use of the Canadian Earth System Model (CanESM). Clustering was performed using only a subset of the CMIP5 ensemble: giving priority to model differences over those in simulations of the same model, only the first member simulation of each model was employed. Climate simulations were limited to the RCP4.5 and the RCP8.5 scenarios for this study given the lower scenario (RCP2.6) was

TABLE C-1. Clustering criteria

Clustering criteria	
changes in	annual mean temperature
	annual mean precipitation
	spring mean temperature
	summer mean temperature
	fall mean temperature
	winter mean temperature
	spring mean precipitation
	summer mean precipitation
	fall mean precipitation
	winter mean precipitation

deemed unlikely given current levels of emissions and mitigation success, and the medium scenario (RCP6.0) was considered redundant as it overlaps with the RCP4.5 and 8.5 scenarios.

With these initial choices and the constraints outlined above, the k-means clustering was performed based on 10 change criteria spatially averaged over the HBDB domain (Table C-1). The changes are represented by the differences between the climate reference period (1981-2010) and the future period (2041-2070), which includes the 2050s and 2070s decades.

The final selection of simulations that met these requirements are shown in Figure C-2 in relation to simulations from all CMIP5 models.

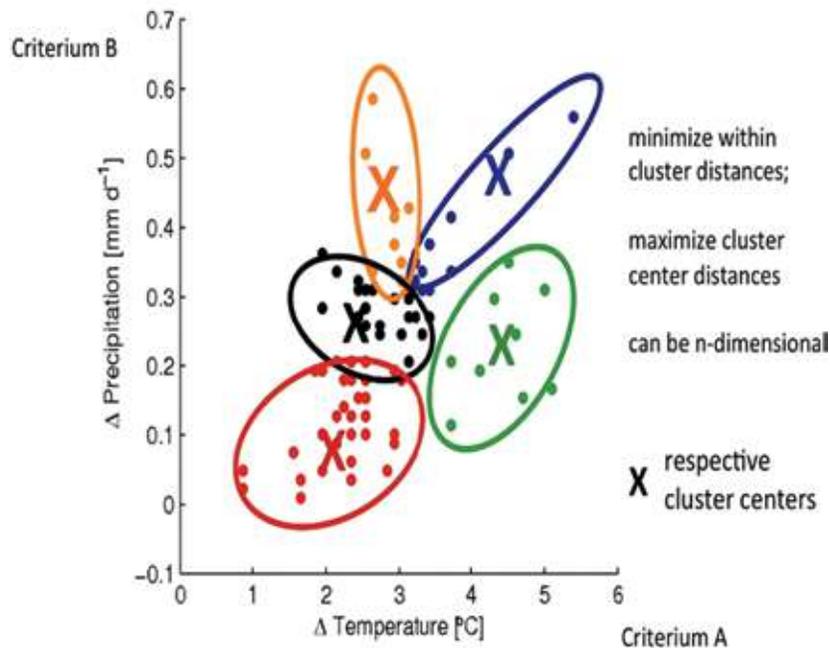
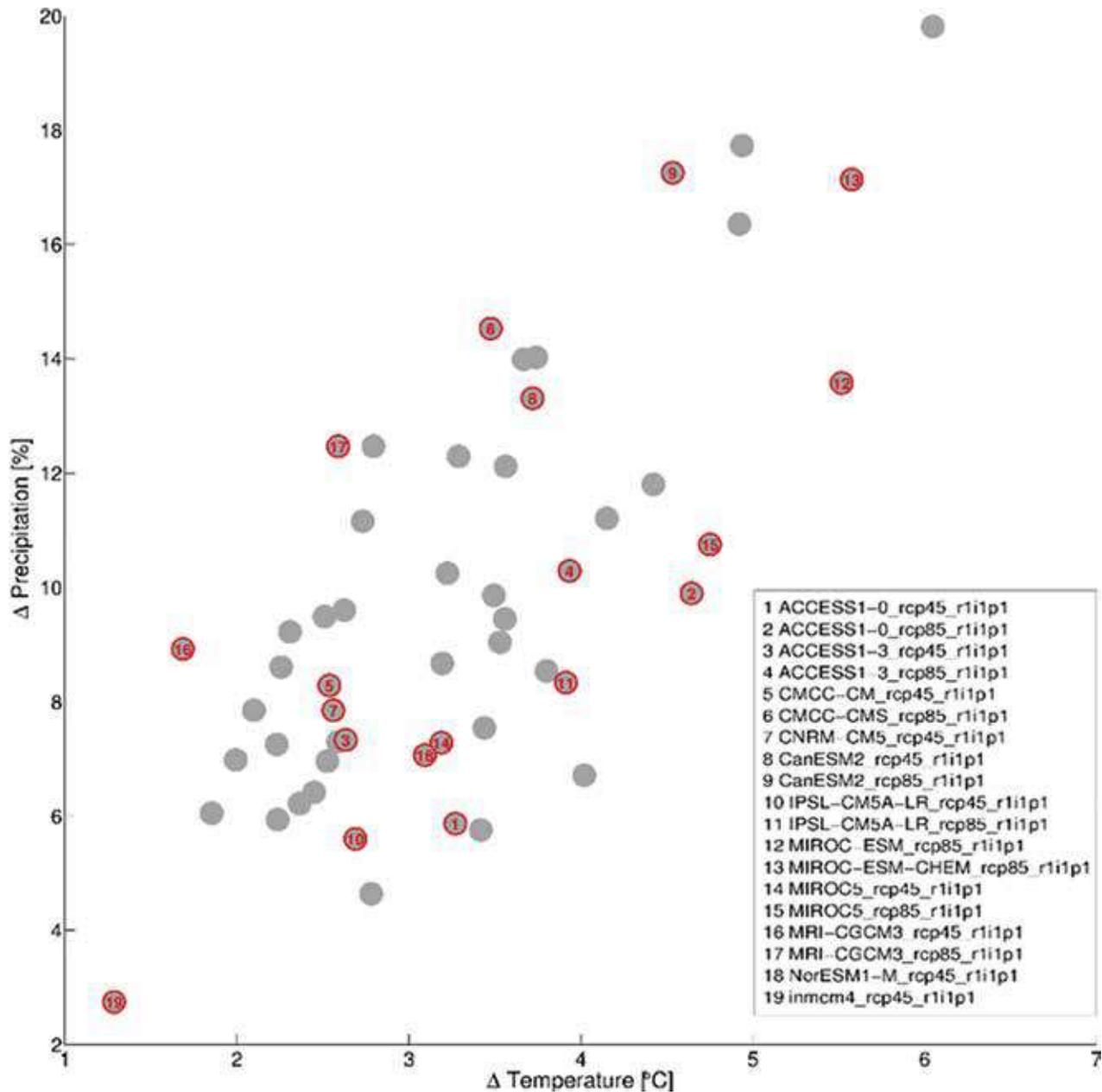


FIGURE C-1. Schematic of the k-means clustering algorithm. Figure is an illustration of the variability between two (temperature, precipitation) of 10 (Table C-1) criteria considered in the clustering process.



**FIGURE C-2.** Climate models selected for BaySys (red) as compared to all CMIP5 models (grey); the 2D space of changes in annual temperature and precipitation is based on k-means clustering using the 10 criteria outlined in C-1.

Daily values of maximum and minimum temperature along with precipitation were extracted for the selected simulations for the reference time period (1981-2010) and the future time period (2021-2070). The data were then bias corrected using a quantile mapping approach (Mpelasoka and Chiew

2009), using the gridded observation dataset from Natural Resources Canada (McKenney et al. 2011; Hopkinson et al. 2011; Hutchinson et al. 2009).

## HYPE model setup

Arctic-HYPE (Andersson et al., 2015) is a regional implementation of the HYPE hydrological model, which was developed by the Swedish Hydrological and Meteorological Institute (SMHI). It was developed for improved predictions of fresh-water discharge to the Arctic Ocean system in both present and future climates, and as a contribution to the WMO Arctic-HYCOS project. On top of the base version of HYPE, Arctic-HYPE has representations of cryospheric processes such of glacier accumulation and melt, lake and river ice, and an advanced snowmelt module (<http://www.smhi.net/hype/wiki/>). Calculations are performed at a daily time interval, forced by daily total precipitation, daily mean temperature, daily maximum temperature and daily minimum temperature. Three model enhancements are included in the Hudson Bay implementation of Arctic-HYPE: generalized lake outflow rating curve parameters based on similar physiographic characteristics, runoff-threshold based prairie pothole non-contributing area and reduced subsurface flow due to soil freezing.

The HBDB is setup in Arctic-HYPE as 6,668 subbasins with mean (median) area of 597.8 km<sup>2</sup> (351.0 km<sup>2</sup>). Streamflow routing occurs between subbasins. Within each subbasin, process calculations (e.g., evaporation, snowmelt, infiltration and runoff) are performed for different landcover and soil classes. Eight landcover types are used: crops, forest, open vegetation, bare, open water, glacier, wetland and urban. Seven soil types are used: coarse, medium, fine, organic, shallow/rock, glacial and urban. Table C-2 shows data sources used in Arctic-HYPE.

## Model calibration and validation

Historical simulations were performed from 1961-2013. A split calibration period is used to span both the early, relatively drier and colder period (1971-1975 and 1981-1985), and later wetter and warmer period (1991-1995 and 2001-2005). Model spin up was from 1961-1970, with remaining years used for validation. A Markov Chain Differential Evolution algorithm was used for calibration (Vrugt 2009). Calibration was performed using daily hydrometric data from the Water Survey of Canada. Of 246 hydrometric gauges in the HBDB, 101 gauges are used calibrating land surface parameters and 20 are used for calibrating dams and reservoirs. Table C-3 shows the approach used in calibration.

Table C-4 shows improvements in model performance from the initial parameter set through calibration. All measures of model performance improved from the initial parameter set.

**TABLE C-2.** Hudson Bay implementation of Arctic-HYPE v3.0 data sources and characteristics.

Characteristic/Data type	Information/Product	Source
Total area (km <sup>2</sup> )	4.0 million	-
Number of subbasins	6,668 (mean size 598 km <sup>2</sup> )	-
Historical period	1961-2013	-
Topography (routing and delineation)	HYDRO1k	USGS EROS
Soil characteristics	Harmonised World Soil Database (HWSD) 1.2	Nachtergaele et al. (2012)
Land use characteristics	ESA CCI LU 2010 v1.4	<a href="http://www.esa-landcover-cci.org/">http://www.esa-landcover-cci.org/</a>
Lake and wetland	Global Lake and Wetland Database (GLWD)	Lehner and Döll (2004)
Lake depths	Global Lake Database v 2	Kourzeneva (2010)
Reservoirs	Global reservoir and Dam database (GRand) v1.1	Lehner et al. (2011)
Discharge	1. Environment and Climate Change Canada, HYDAT (National Water Data Archive) 2. USGS (National Water Information System)	1. <a href="http://ec.gc.ca/rhc-wsc">ec.gc.ca/rhc-wsc</a> 2. <a href="http://waterdata.usgs.gov/nwis">waterdata.usgs.gov/nwis</a>
Precipitation and temperature	Global Forcing Data (GFD)	Swedish Meteorological and Hydrological Institute
Glacier fluctuations	World Glacier Monitoring Service (WGMS)	Zemp et al. (2012)
Evapotranspiration	FLUXNET	<a href="http://fluxnet.ornl.gov">fluxnet.ornl.gov</a>

TABLE C-3. Stages of Arctic-HYPE model calibration.

Stage	HYPE parameters and descriptions	Weighted objective function
0:	<b>Snow and evaporation (completed by D. Gustafsson, Swedish Hydrological and Meteorological Institute)</b> alb: albedo kc: crop coefficient fepotsnow: snowpack sublimation coefficient cmlt: snowmelt degree day rate cmrad: coefficient for radiative snowmelt	
1:	<b>Evaporation and Runoff</b> kc: crop coefficient for PET fc: fraction of soil available for evap wp: wilting point srrcs: recession coefficient for surface runoff rrcs: recession coefficient for subsurface flow ep: effective porosity cmlt: snowmelt degree day rate	0.40 × MDV 0.20 × RDV 0.40 × MNS
2a	<b>Lake discharge</b> ilrratk × 3: exponent for internal lake discharge curve ilrratp × 3: coefficient for internal lake discharge curve gicatch × 3: fraction of runoff directed to internal lake olrratk × 4: exponent for outlet lake discharge curve olrratp × 4: coefficient for outlet lake discharge curve	0.30 × MRS 0.40 × MNS 0.10 × MDV 0.10 × RDV 0.10 × MCC
2b	<b>Dams and reservoirs</b> qprod1 : production flow for first period of year qprod2 : production flow second period of year datum1: start day for production period 1 datum2 : start day for production period 2 qamp : amplitude of production flow qpha : phase of production flow qthresh: maximum release for flood control	Manual calibration for individual gauges
3	<b>Routing</b>  damp: fractional delay in river course rivvel: celerity	0.20 × MRS 0.60 × MNS 0.10 × MDV 0.10 × MCC

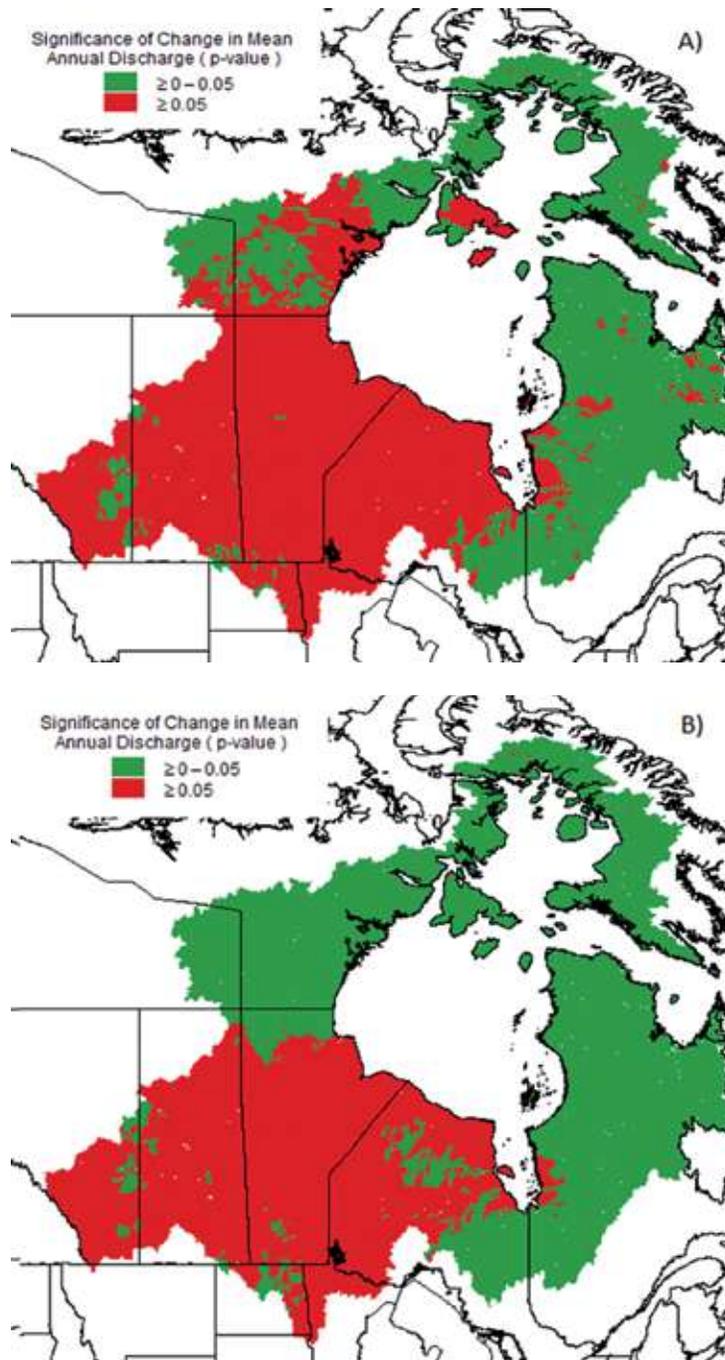
Objective functions: MDV – mean deviation of volumes (component of KGE); RDV – regional deviation of volumes (data from all stations combined into a single vector); MNS – mean Nash-Sutcliffe Efficiency; MRS – mean error in standard deviation (component of Kling-Gupta Efficiency); MCC – mean correlation coefficient (component of Kling-Gupta Efficiency)

TABLE C-4. Improvement of Arctic-HYPE performance from calibration.

Parameter set	Mean Deviation of Volume (%)	Regional Deviation of Volumes (%)	Mean Nash-Sutcliffe Efficiency	Mean Kling-Gupta Efficiency
Initial parameter set (all gauges)	29.0	31.6	0.01	0.31
Calibration	2.5	5.4	0.29	0.53
Validation	1.1	-0.5	0.32	0.54
Calibration (all gauges)	3.0	5.1	0.33	0.54

## APPENDIX D

### Additional discharge and runoff projection figures



**FIGURE D-1.** Statistical significance of projected change in mean annual discharge over HDBD relative to the modelled 1981-2010 reference period for (a) 2021-2050 and (b) 2041-2070. Statistical significance is assessed using Mann-Whitney two-sample Wilcoxon tests. p-values < 0.05 (green) indicate regions with statistically significant changes.

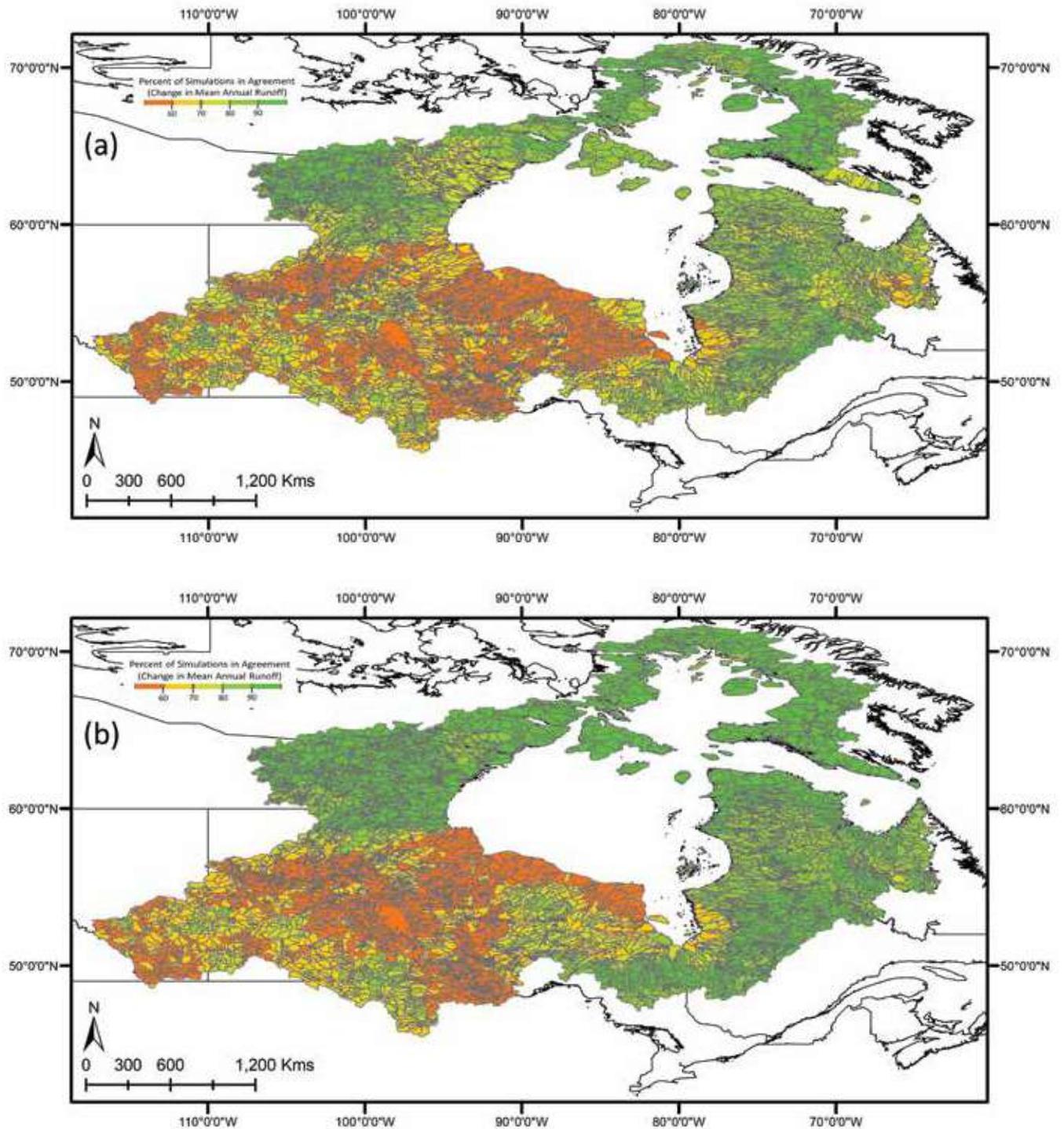
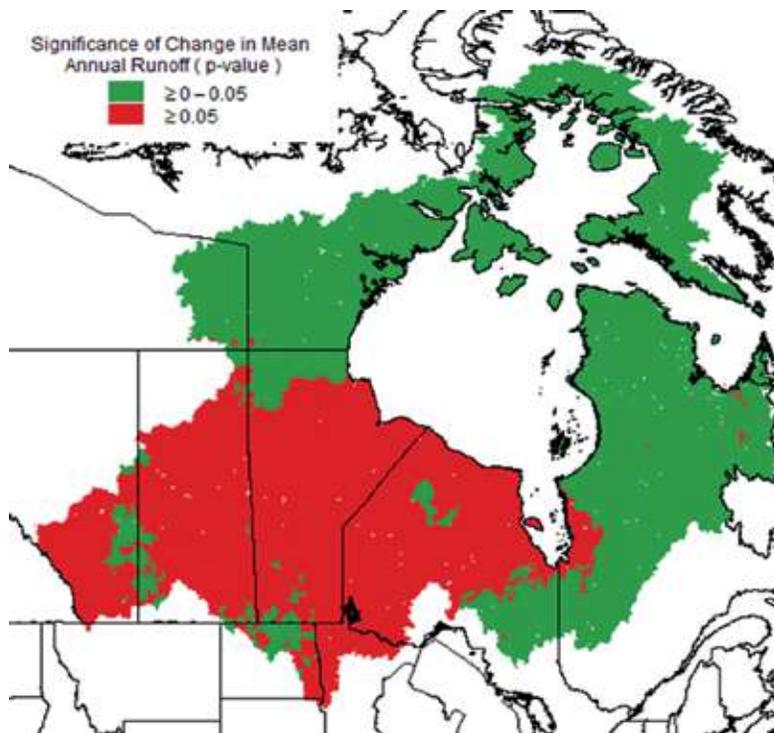
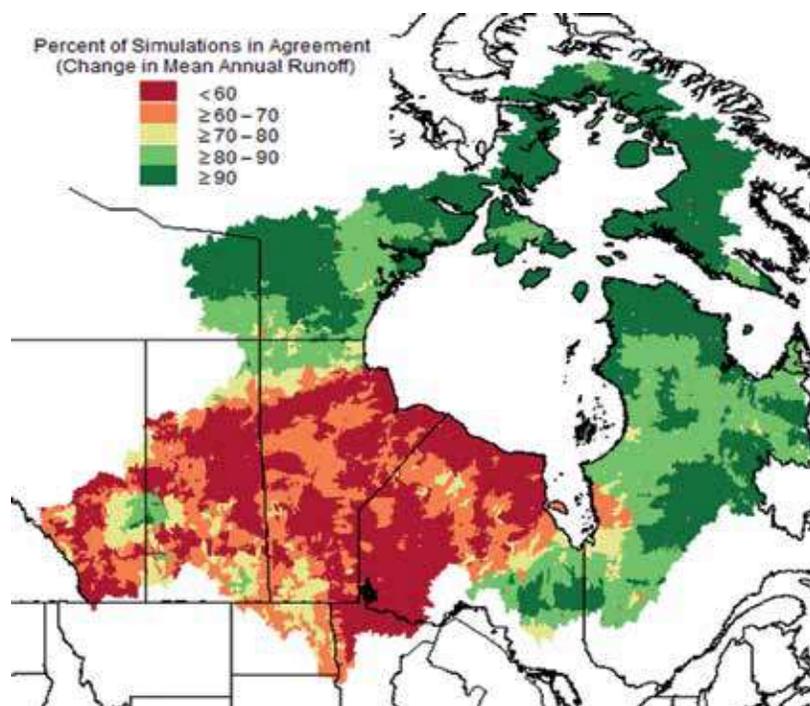


FIGURE D-2. Percent agreement of 19 CMIP5 simulations on the direction projected change in mean annual runoff over HDDB relative to the modelled 1981-2010 reference period for (a) 2021-2050 and (b) 2041-2070. Results shown by HYPE sub-basin.



**FIGURE D-3.** Statistical significance of projected change in mean annual 2021-2070 runoff over HDBD relative to the modelled 1981-2010 reference period. Statistical significance is assessed using Mann-Whitney two-sample Wilcoxon tests. p-values  $< 0.05$  (green) indicate regions with statistically significant changes.



**FIGURE D-4.** Percent agreement of 19 CMIP5 simulations on the direction projected change in mean annual 2021-2070 runoff over HDBD relative to the modelled 1981-2010 reference period.





I.v

# Freshwater-Marine Interactions in the Greater Hudson Bay Marine Region

## AUTHORS

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## Summary

The Hudson Bay Marine Region functions like a vast estuary; that is, inputs of freshwater dominate physical processes of vertical and horizontal mixing of its waters, and in doing so, strongly influence supply and recycling of nutrients that support all biological life in the system. Each year, rivers and precipitation together supply the Marine Region with the equivalent of about 1 m of water (if it were spread uniformly over its entire surface) and freezing withdraws almost as much from circulation in the water column each fall, only to release it at the surface when it melts the following spring. Winds and tides mix this freshwater with the saltier marine water below, but even so the layer of reduced salinity reaches only a few tens of meters deep by the end of each open water season. More saline, deeper water is supplied by flow of Arctic water into the region, with additional salt and constituents from entrained river water added by sinking of brine rejected during the process of sea-ice formation. The sources of fresh and marine water to the region are generally known, but most pathways are poorly defined and rates of key processes are not well quantified. Here, we review what is known of freshwater-marine interactions in the region, and identify the major uncertainties associated with the freshwater budget of the region.

## Key Messages

- **The physical oceanography and chemical characteristics of the Hudson Bay Marine Region waters are by and large the product of mixing inflowing Arctic marine waters with freshwater supplied from the atmosphere and the watershed around the region, and from the freezing and melting of sea ice each year. The abundance of freshwater supply makes the Marine Region's surface waters the freshest of the world's major oceanic regions.**
- **Annual freshwater inputs from the two largest sources to the Marine Region—rivers and the freezing process (in which fresh ice is formed by rejection of marine salts)—can be calculated from long term records (30 y+) but precipitation remains difficult to quantify and the annual inflow and outflow of freshwater through marine straits (i.e., coming from the Arctic**



A. DEVRIES

Ocean) has been estimated from only a single year or less of observational data. Thus, we know little of long-term averages, variability or trends in these major terms of the freshwater budget. Tracer data have revealed river water transfers between surface and deep waters, and inter-basin flow can be inferred from the overall freshwater budget, but no freshwater transfers between basins within the Hudson Bay Marine Region have been measured directly. For these, we must rely entirely on modeled oceanography.

- The freshwater lying over the surface of the Hudson Bay Marine Region inhibits the vertical mixing necessary to resupply surface waters with nutrients that are constantly settling to the deeps in any marine environment. Moreover, freshwater as ice cuts off the supply of light to the system for almost half the year. Together these effects have long been considered to inhibit primary production throughout much of the Marine Region. The first large-scale oceanographic observations of the sea-ice melt period in spring 2018 will improve understanding of the overall annual cycle of both freshwater and primary production.
- For the Hudson Bay Marine Region, interactions of hydroelectric development/regulation, which has shifted the timing and location of river discharge, and climate change, which affects river discharge and the sea-ice cycle, is an important area of study. Additional observations spanning the annual cycle and including coastal areas are needed in future work.

## 1. Why freshwater matters

To fully understand the greater Hudson Bay Marine Region one must consider the importance of freshwater to its ecosystem. Because it is an inland sea fed by rivers that drain a vast watershed—almost one-third of the Canadian landmass—the equivalent of almost a meter of freshwater, if spread over its entire surface, flows into it every year<sup>1</sup>. By this measure (i.e., the depth equivalent of pure freshwater) the Marine Region receives three times as much freshwater from its watershed as the Arctic Ocean, the freshest ocean in the world. A similar volume of freshwater is locked into seasonal sea ice each winter and redistributed around the Marine Region each spring and summer when the ice pack breaks up, drifts with prevailing currents and winds and eventually melts. The freezing process creates this freshwater in solid form by exclusion of marine water salts from the ice crystal structure. In the process, it forms pockets of relatively dense, near-freezing brine which, through the winter, seep down through the ice. It destabilizes the water column below and initiates vertical mixing, and in some places sinks and flows down into the deepest parts of the system, where it enhances the salinity and replenishes the oxygen content of the Marine Region's deep waters.

These processes involving freshwater, (i.e., river inflow and the sea ice formation and melt cycle) play a critical role in the functioning of physical and biological systems in the Marine Region. The seasonal ice forms a platform where polar bears and Inuit hunt seals. The sea ice protects the world's largest population of beluga whales from what would otherwise be their greatest predators, killer whales. Although ice provides a platform for concentrated primary production by ice algae (including *Melosira arctica*; Figure 1D) early in the spring when a well-mixed water column limits the productivity of free-floating phytoplankton, it also creates a long, dark season during which all forms of algal production are extremely low because there is very little light for photosynthesis. Less visibly, but perhaps more importantly, in spring, the introduction of freshwater from fluvial sources and sea-ice melt causes strong vertical stratification of the water column, with a freshened surface layer overlying a

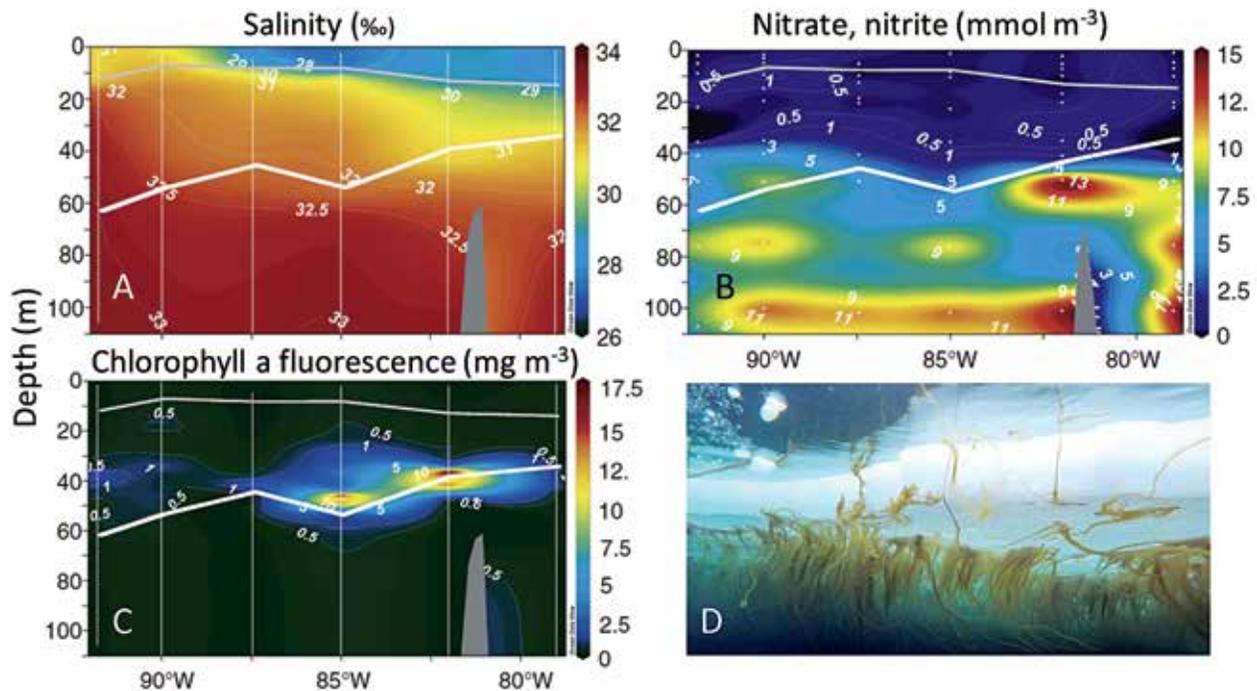
<sup>1</sup> We will frequently describe the amount of freshwater in each marine basin, or in the whole Hudson Bay Marine Region, in terms of depth, as if it were pure freshwater floating on the surface of the sea (that is, simply the volume of pure freshwater divided by the area of the basin). In fact, it always mixes with seawater to some extent. In mixing, it dilutes the salts in the seawater, reducing its salinity, and the amount of freshwater mixed into the seawater is readily calculated from the amount of this dilution. In the Marine Region, we assume the pure seawater endmember of this mixture has a salinity of 33‰. This is the reference salinity used by numerous (but not all) studies of freshwater in the Hudson Bay Marine Region; it is approximately the salinity of deep water flowing into Hudson Bay from Foxe Basin and Hudson Strait. At the other end of the mixing equation are river water and sea ice. Rivers flowing into the Marine Region typically contain as little as 0.1‰ salts. Sea ice expels salts as it ages, so that by the end of winter, it is likely to have a salinity of only about 4–6‰.

denser salty later beneath. In the offshore areas of the Marine Region, at least, the dominant effect of freshwater additions in spring and summer is to limit the nutrient supply to sunlit surface waters by upward mixing, and therefore to limit the development of a rich, productive marine ecosystem (Figure 1A-C).

This issue of 'too much freshwater' in Hudson Bay was recognized as early as in the 1930s, when a report of the Hudson Bay Fisheries Expedition of that time declared that "intense stratification... gives Hudson Bay the character of a large estuary. Below fifty metres the waters are for all purposes dynamically dead" (Hachey 1932). While the idea that the deep waters are "dynamically dead" is an overstatement, it is certainly true that Hudson Bay functions in some ways like one very large estuary. Except that many estuaries are very biologically productive. Why, in this case, should lots of freshwater inhibit productivity? After all, these rivers also carry loads of nutrients into the bay. Simply put, freshwater is much lighter than seawater, and it requires considerable energy to mix lighter and

heavier water. Whether it is produced in place by melting of sea ice or delivered by rivers flowing in from its watershed, the freshwater first spreads across the surface.

This is, of course, an over-simplification. While fresh and salt water do not mix easily, wind-driven waves and currents do eventually manage to mix the two together over the course of the open-water period. Still, these processes can only stir the freshwater down a few tens of metres and no further (Figure 1) creating a surface mixed layer that at the end of summer still remains much lighter than the more saline water below. The ubiquitous freshwater stratification during the open-water season makes it difficult for the fresher surface layer to mix deeper, or for the saltier water below to circulate back up to the surface. Provided the surface layer is not too fresh and sufficient sea-ice production occurs, brine inputs during sea ice formation can overcome the stratification and deeply mix the water column by the end of winter, thereby bringing some nutrients back up to the surface. These nutrients provide a



**FIGURE 1.** Cross-sections showing vertical distributions of A: salinity, B: nitrate and nitrite (the major algal nutrient in the system) and C: chlorophyll a fluorescence (an indicator of algal biomass). The thin grey line denotes the surface mixed layer, and the thick white line, the euphotic depth. The sections were recorded from 2–15 August 2004, and run west to east across Hudson Bay near 60°N latitude. Note that the highest concentrations of algae growing at the lower edge of the brackish surface mixed layer, an optimal depth near the lower limit of light adequate for growth and reproduction, but also near the upper reaches of more nutrient-rich deep waters. Source: Ferland et al. (2015). D: Algae (*Melosira arctica*) attached to the underside of a floe in the marginal ice zone in northern Hudson Bay in late June 2018. Photo taken by Laura Dalman in June 2018.



C. HORNBY

stock that may be used by all primary producers once sufficient sunlight penetrates to provide them with the energy to grow. In the surface, sunlit zone, they grow and accumulate biomass by metabolizing what nutrients they find around them, and in growing, provide food for ocean creatures, small and large. But every day, some part of this algal crop sinks, carrying its nutrients below the surface, productive zone. Throughout much of the world's coastal ocean areas, this slow but constant drain of nutrients from the sunlit layer is balanced by supply of new nutrients returned to the surface layer where waters well up from the deep. Such upwelling is retarded across much of Hudson Bay by the strong freshwater stratification, with the result that surface waters are not as rich in nutrients, nor do they host as large populations of consumers, as in many better-mixed coastal regions in the world's oceans<sup>2</sup>.

There are exceptions to this strong stratification paradigm within the Marine Region. Hudson Strait, in particular, has a much deeper surface mixed layer and is much more productive than Hudson Bay. Even within Hudson Bay itself, especially

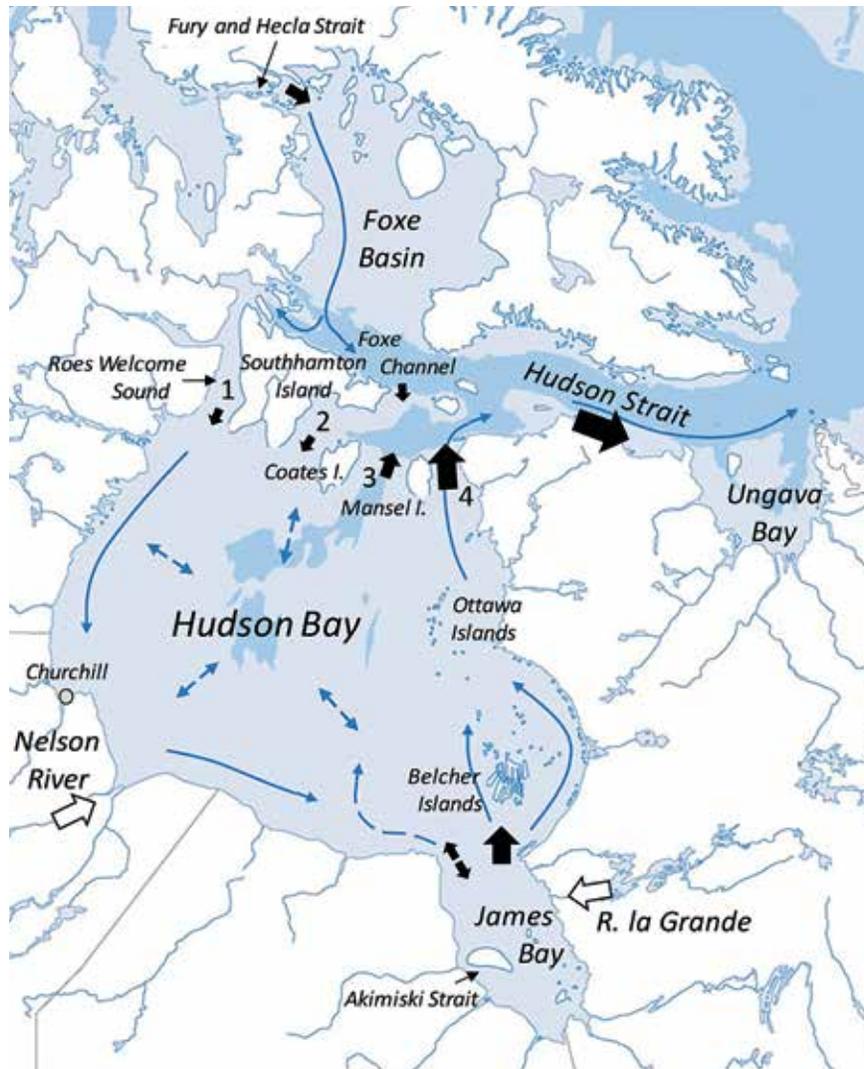
2 The relationship between strong summer stratification and low phytoplankton productivity in summer is very well described by Anderson and Roff (1980) using data collected over the entire Hudson Bay. Lapoussiere et al. (2012) measured organic matter settling out of the surface layer; their data support the conclusion that at least in central Hudson Bay, a large part of the summer phytoplankton crop sank below the euphotic zone in the summer months. Phytoplankton production—which supports other biological production in the sea, from microscopic creatures to whales and polar bears—is measured in grams of carbon produced by phytoplankton growth per square meter per day. Ferland et al. (2015), responsible for the information in Figure 1, determined that the average summer productivity in Hudson Bay and Foxe Basin are of the order of 0.32 and 0.37 g C m<sup>-2</sup> d<sup>-1</sup>, respectively, compared to 1.15 g C m<sup>-2</sup> d<sup>-1</sup> in Hudson Strait. These values are integrated over the depth of the euphotic zone and do not include production by ice algae or the spring bloom—both of which may contribute significantly to the annual total.

in the north near Southampton Island, in the southwest near the Nelson River estuary and along the southeast and east coasts, littoral waters are presumably better supplied by nutrients because they support rich ecosystems with abundant fish, seabirds and marine mammals. Near the coast, and in narrow straits and sounds, vertical mixing is enhanced by turbulence created when strong tidal currents interact with complex bathymetry, and off river mouths, by estuarine circulation, which entrains salt water (and accompanying nutrients) upwards into a flowing freshwater plume. Coastal areas of Hudson Bay are also well known for attached rather than free-floating primary producers, including ice algae, benthic algae, kelp, and eelgrass (*Zostera marina*—in estuaries along the east coast of James Bay). These species can sometimes thrive in coastal waters with high current velocities, which provide a continuous flux of nutrients even while concentrations are low.

Finally, the strong stratification/weak productivity paradigm exists in a near vacuum of quantitative information related to primary production by sea ice algae and benthic organisms, as well as phytoplankton productivity during the spring bloom that coincides with the return of the sun and the sea-ice melt period. There have been virtually no field observations of primary production in the Hudson Bay Marine Region from this period. In the spring of 2018, an expedition into the marginal ice zone was mounted to address this gap (BaySys 2015). Three authors participated in this expedition (Barber, Babb, McCullough). Our preliminary judgement is that the spring phytoplankton bloom, and in particular, under-ice algae (*Melosira arctica*; Figure 1D) will be found to contribute more to annual new productivity than was previously thought, at least in the northern and north-central regions of Hudson Bay, where freshwater inputs are lowest, summer stratification is weakest, and the water column mixes more deeply in winter compared to southern and eastern Hudson Bay. The results from this spring expedition will provide better information on the distribution of sea ice meltwater in the water column during the melt period and may improve our understanding of where the Hudson Bay Marine Region ranks in comparison with the productivity in other Arctic waters.

## 2. Introduction

The Greater Hudson Bay Marine Region is supplied by water from three major sources (e.g., Fig. 3, Straneo and Saucier 2008a; Figure 1 in Curry et al. 2014). Two of these are marine, and account for most of the volume circulation through the region. Water from the surface mixed layer of the Arctic Ocean enters the region, after flowing through the Canadian Arctic Archipelago, via Fury and Hecla Strait into northwestern Foxe



**FIGURE 2.** The Hudson Bay Marine Region, showing locations and major features of freshwater circulation mentioned in the text. Broad black arrows indicate relative freshwater discharge through major gateways. Broad white arrows identify the two largest rivers flowing into the Marine Region. Narrow blue arrows indicate general circulation of freshwater in Hudson Bay; the dashed arrow indicates spring/early summer circulation. Arrows into/out of the interior follow the conceptual scheme proposed by St. Laurent et al. (2011).

Basin (Figure 2). Water flowing from the Arctic through Baffin Bay and Davis Strait, passing mainly along the Baffin Island coast, enters the region along the north side of Hudson Strait (Figure 2). Some North Atlantic water may be added via the West Greenland current, which carries a mixture of Arctic and North Atlantic water northwestward along the Greenland coast until it turns and mixes with the southerly flow in the Baffin Current along the coast of Baffin Island; the contribution of this water to flow into Hudson Strait is not known. Of

these marine sources, only the flow through Fury and Hecla Strait carries water that can be considered “fresh” in the context of the Hudson Bay Marine Region. By far the largest source of freshwater on an annual basis is river discharge from the terrestrial watershed. Melting of sea ice contributes as much freshwater each spring, but formation of ice incorporates an approximately equal volume of freshwater back into the ice through the winter. This freeze-melt process is very important to seasonal physical processes in the marine system, and to the

biota inhabiting the system. Moreover, it redistributes freshwater, because ice may form in one place and melt in another. Still, over annual and longer periods, sea ice is not a significant net supplier of freshwater to the region. Precipitation may add a significant additional supply of freshwater to the region, even when evaporation is subtracted. However, based on the wide range of values in the literature, the total precipitation minus evaporation is not well known. Other than evaporation, there is only one outlet from the Hudson Bay Marine Region, that is, by flow along the southern side of Hudson Strait to join the Labrador current flowing south to spread ultimately into the North Atlantic Ocean (Myers et al. 1990). The conservation of volume requires that the flow eastward along the northern Quebec coast must equal the sum of all marine inflows via Fury and Hecla Strait and Hudson Strait, plus the net freshwater supply (that is, discharge from the watershed plus precipitation directly on the Marine Region, minus evaporation from the Marine Region).

In this chapter, we focus mainly on sources of freshwater to the Hudson Bay Marine Region, and spatial and temporal patterns of circulation of freshwater through the region. First, however, we will touch briefly on circulation of saline, marine water through the region, which determines the shallow paths of freshwater through the region.

### 3. Temperature–salinity structure

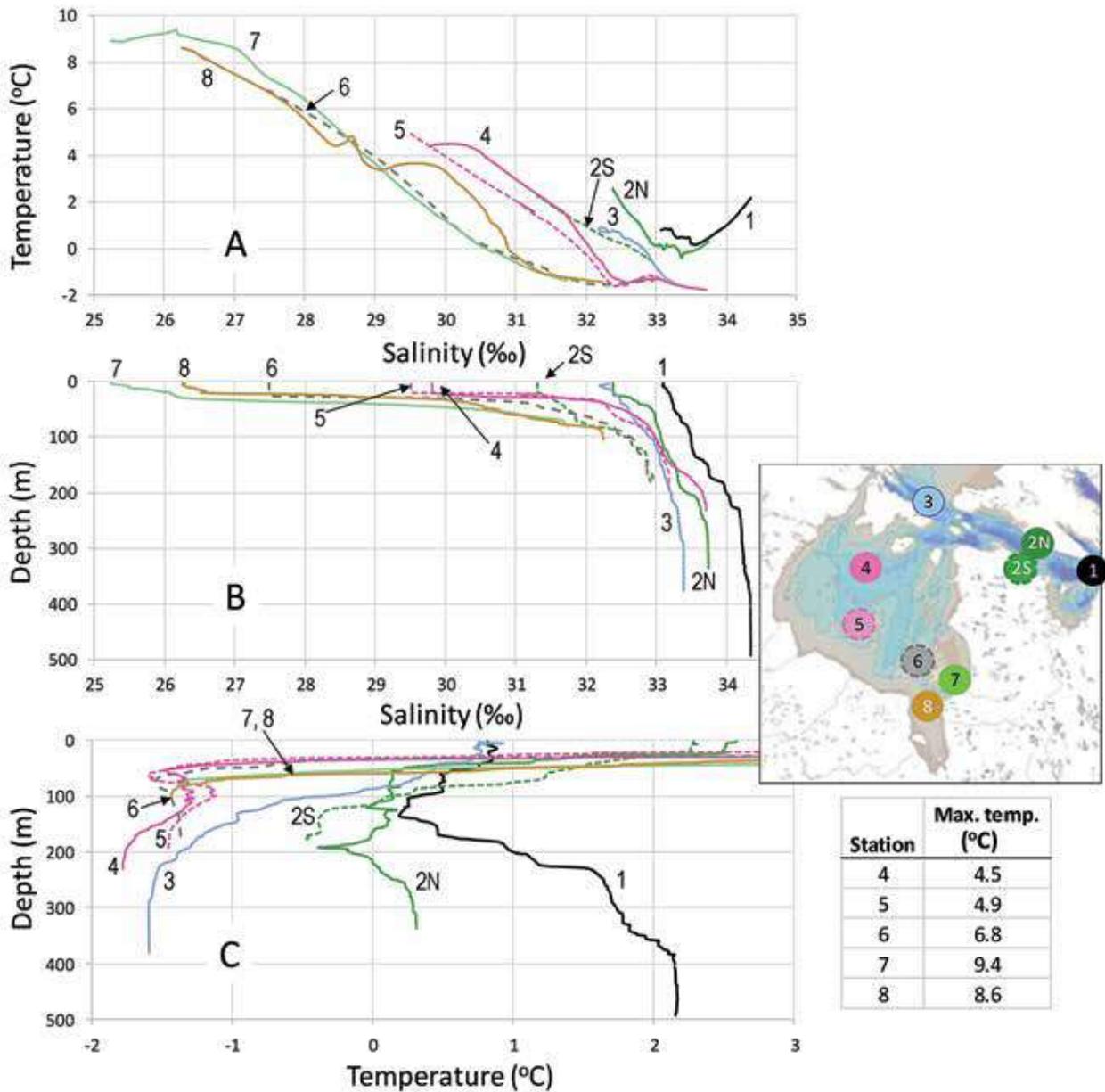
The vertical salinity structure of the Marine Region is created by a combination of local freshwater loading (river water, precipitation and sea ice meltwater) and brine production (rejected from sea ice during its formation), both of which modify inflowing Arctic Ocean waters. The residence times of waters within Hudson Bay, which determines how long they will be subjected to modification by local processes, is generally estimated at 5–15 years (Jones and Anderson, 1994; Granskog et al. 2011). The temperature–salinity structure in Figure 3 shows the gradual change in water mass properties around the Marine Region in late summer. The water properties in central Hudson Strait, at least along the northern side of the strait, reflect the influence of the westward flow of Arctic Water that has flowed southward along the Baffin Island shelf (e.g., Tang et al. 2004). The salinity of these waters in Hudson Strait is within the range of salinities reported for similar depths in the Beaufort Sea and in eastern Davis Strait (33–34‰ at 180–230 m in both cases; Carmack et al. 2016 for the Beaufort Sea; Curry et al. 2014 for Davis Strait) but is lower than the average salinity of 34.8–34.9‰ at 200 m in the northern Labrador Sea southeast of Hudson Strait (Treguier et al. 2003) (Figure 3). That is, deep water in Hudson Strait, just outside Hudson Bay, has

salinities comparable to the Arctic Ocean and Davis Strait. On the other hand, the surface mixed layer along the southern side of Hudson Strait carries excess water flowing out of Hudson Bay, that is, water freshened by river discharge from its large watershed and therefore a source of relatively fresh water to western shelf waters of the North Atlantic Ocean (e.g., Sutcliffe et al. 1983, Myers et al. 1990).

Jones and Anderson (1994) proposed that intermediate waters in Hudson Bay (100–130 m) were formed by advection of water masses from west Hudson Strait and southern Foxe Basin while deeper water masses were produced by overflow water from Foxe Basin. The saltiest deep water within Hudson Bay remains colder than the water in Hudson Strait at the same salinity, indicating influences of local processes within Hudson Bay or processes in Foxe Basin associated with sea ice formation (Figure 3). Based on salinity profiles recorded from onboard the *CCGS Amundsen* in 2005, the salinity of deep water in Hudson Bay, below 100 m depth, ranges from 33.1 to 33.7‰. In profiles recorded in southern Foxe Basin in 2006, the salinity of deep waters reached 33.4‰—although at Foxe Basin stations in deeper water it has been reported as high as 33.7–33.8‰ (e.g., at 340 m in Fig. 3 in Jones and Anderson 1994; 33.75‰ at 440 m reported by Defossez et al. 2008).

The two pathways of marine water through the Hudson Bay Marine Region are well described by Straneo and Saucier (2008a). About 2,200 km<sup>3</sup> of polar waters are drawn into the region each year through Fury and Hecla Strait which connects the Gulf of Boothia in the Canadian Arctic Archipelago with Foxe Basin near its northwest extremity. The strait draws from the surface mixed layer in the Gulf of Boothia (which itself draws from the Arctic Ocean surface mixed layer west of the Canadian Arctic Archipelago) so that the inflowing water is fresh compared to deep waters in the Marine Region, ranging from 32.0–32.1 in late winter down to 31.0–32.0 in summer (Ingram and Prinsenbergh 1998).

Flow into Hudson Strait contributes more than an order of magnitude more marine water to the Hudson Bay Marine Region than flow through Fury and Hecla Strait—26,700 km<sup>3</sup> annually (Straneo and Saucier 2008a)—and it is more saline. In the deep waters along the north side of Hudson Strait, salinity ranges from 33.6 to 33.7‰ (Figure 2) consistent with flow diverted from similar depths in the Baffin Island Current. It is not well-known how far this deep water penetrates into the Hudson Bay Marine Region. Defossez et al. (2008) argue convincingly that it does not contribute significantly to deep water in Foxe Basin. Rather, by examination of seasonal patterns in mooring records, they demonstrate that salt exclusion during sea ice formation in polynyas along the western coast of Foxe Basin accounts for annual renewal of the deep water in the south. This supports earlier work of Jones and Anderson (1998)



**FIGURE 3.** A. Representative temperature–salinity diagrams recorded in the Hudson Bay Marine Region from late September to late October in 2005 (ArcticNet) or 2006 (Merica). B and C: Salinity and temperature profiles at the same stations. Most profiles exhibit mixing within 10–20 m of the surface that is presumed due to ship operations. Maximum (surface) temperature is shown in the inset table for profiles extending to the right, beyond the chart scale. (Source: ArcticNet and MERICA data accessed at <https://www.polardata.ca/>).

who used alkalinity-salinity relationships as natural tracers of water masses in the Marine Region to reach the same conclusion—that Foxe Basin deep water was formed by processes within the basin, and that this dense water contributed to deep water in Hudson Bay.

Deep water flowing into Hudson Bay, whether from Hudson Strait or Foxe Basin, must pass over sills that are less than 200 m deep in straits east and southeast of Southampton Island, and about 50 m deep through Roes Welcome Sound, west of Southampton Island. During September-October 2005



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oceanographic surveys recorded on a mission of the *CCGS Amundsen*, the salinity at 200 m depth in southern Foxe Basin was 33.4–33.5‰ and in the northern half of Hudson Strait, 33.5–33.7‰. The salinity reported at the same depth in central Hudson Bay (Station HB NC in Figure 2) was 33.7‰ so that, based on salinity alone, the source could reasonably be polar water by way of Davis and then Hudson Strait. However, other evidence suggests that the source is the deep water formed in southern Foxe Basin. Jones and Anderson (1998) used alkalinity and dissolved inorganic carbon tracers as evidence that Foxe Basin deep water is the more likely source. Defossez et al. (2008) suggest a mechanism to explain how this transfer might occur; that is, that flow of dense water from the polynya regions into the deep southern region of Foxe Basin may be energetic enough to spill deep water over sills into northeastern Hudson Bay. More recently, Granskog et al. (2011) have argued that brine rejection during ice formation within Hudson Bay contributes to the salinity of the deep water there; if so, then the process must also transfer river water from the Hudson and James Bay watershed down to deep water in Hudson Bay. Currently, while the sources of Hudson Strait and Foxe Basin deep water seem well explained, complete understanding of the formation of Hudson Bay deep water awaits further study.

#### 4. Freshwater budget

The freshwater budget of a marine basin is simply an accounting of the total inputs and outputs, which must be in balance if the freshwater content of the basin is not to change over long time scales. Table 1 presents such an accounting. Although freezing creates a very large volume of freshwater as

ice each winter (as much or more than river discharge into the region) and releases it into the surface waters of the Hudson Bay Marine Region each spring, this volume represents an internal exchange with little effect on the input/output budget. Overall, just over 1300 km<sup>3</sup> of freshwater flows through the Hudson Bay Marine Region each year. The estimated total inflow of 1325 km<sup>3</sup> y<sup>-1</sup> is essentially equal to the independently estimated freshwater component of the outflow through Hudson Strait, 1310 km<sup>3</sup> y<sup>-1</sup> (Table 1). However, this apparent precision between inputs and outputs is surely fortuitous.

For instance, precipitation and evaporation depend on data from widely spaced weather stations (Prinsenber 1977) or are calculated using global forecasting models with limited validation data due to the same sparse *in situ* data (Straneo and Saucier 2008a, St. Laurent et al. 2011); the uncertainty is large enough that published estimates of net precipitation range from –190 to > 330 km<sup>3</sup> y<sup>-1</sup>. The estimate of freshwater carried into the region through Fury and Hecla Strait is based on data from two very brief oceanographic surveys conducted over half a century ago (Barber 1965, Sadler 1982). The freshwater outflow through Hudson Strait was calculated using data from several moorings, but with no more than a year of record from the south side of the channel (freshwater outflow), less than that from the north side (marine inflow) and the two data sets recorded in different years (Straneo and Saucier 2008a). Only the value for discharge from the terrestrial watershed is based on long term observational records of a quality that supports statistical analysis of variability and trends in the record (e.g., Déry et al. 2005, Déry et al. 2011, Déry et al. 2016) and these observational records account for only 65% of total freshwater discharge from the watershed of the Hudson Bay Marine Region.

Moreover, two large elements are missing from reported marine transport of freshwater into and out of the Marine Region. First, the moorings used in these calculations were positioned west (i.e., 'upstream') of flow out of Ungava Bay. Ungava Bay rivers alone account for 14% of the total fluvial discharge into the whole of the Hudson Bay Marine Region, and presumably a similar proportion of the freshwater discharge into the Labrador Sea. Second, advection of sea ice is not taken into account. Some ice drifts through Fury and Hecla Strait from at least mid-August until the strait freezes over (Prinsenber 1986), although we assume this to be negligible in comparison to freshwater transported in the liquid phase, so that we accept here the reported marine inflow of  $90 \text{ km}^3 \text{ y}^{-1}$  (Table 1). On the other hand, the amount of freshwater transported out of Hudson Strait as sea ice may not be negligible. Straneo and Saucier (2008a, p. 257) remark that if sea ice were included in the Saucier numerical model of the Hudson Bay Marine Region (Saucier 2004) it could contribute as much as  $190 \text{ km}^3 \text{ y}^{-1}$ —that is, an additional 19% of freshwater export through the strait. We have added fluvial discharge into Ungava Bay and ice advection to the freshwater flow reported by Straneo and Saucier (2008a) to conclude that the best current estimate of freshwater discharged from the Hudson Bay Marine Region is  $1310 \text{ km}^3 \text{ y}^{-1}$  (Table 1).

Terms of the freshwater budget are described and discussed individually in the sections below.

**TABLE 1. Annual mean inflow and outflow of freshwater into/ out of the Hudson Bay Marine Region. Freshwater discharge through marine straits is calculated relative to a reference salinity of 33‰.**

	$\text{km}^3 \text{ y}^{-1}$
<b>Inflow</b>	
Fluvial inflow* <sup>1</sup>	905
Net precipitation* <sup>2</sup>	330
Fury and Hecla Strait* <sup>3</sup>	90
<b>Outflow</b>	
Hudson Strait* <sup>4</sup>	1310

\*1 Discharge from the watershed averaged from 1984–2013; calculated for this report as described in the text.

\*2 Precipitation minus evaporation on HB-JB reported by St. Laurent et al. (2011) multiplied by the ratio of Hudson Bay Marine Region area to Hudson Bay-James Bay area.

\*3 Freshwater discharge calculated using discharge measured by Barber (1965) and Sadler (1982) and salinity suggested by Straneo and Saucier (2008a).

\*4  $990 \text{ km}^3 \text{ y}^{-1}$  freshwater discharge calculated by Straneo and Saucier (2008b) plus  $130 \text{ km}^3 \text{ y}^{-1}$  due to fluvial inputs downstream of their moorings, and  $190 \text{ km}^3 \text{ y}^{-1}$  ice advection (6  $\text{mSv}^3$ , p. 257 in Straneo and Saucier 2008a).

3  $1 \text{ Sv} = 1,000,000 \text{ m}^3 \text{ s}^{-1} = 31,536 \text{ km}^3 \text{ y}^{-1}$ . Hydrologists typically report river discharge in cubic meters per second ( $\text{m}^3 \text{ s}^{-1}$ ); oceanographers deal with much larger flows in marine systems, and typically report them in Sverdrups (Sv). For ease of comparison in this chapter, we report both river discharges and freshwater flow in the marine environment in  $\text{km}^3 \text{ y}^{-1}$ .

#### 4.1. Fluvial inflow

River discharge from the Greater Hudson Bay Marine Region Drainage Basin (HBMR Drainage Basin) (see Theme I, Chapter iv, Figure 1) was calculated for this report using a combination of observational and model-simulated data. Discharge has been continuously monitored for most of the 1984–2013 averaging period at hydrometric gauging stations representing 69% of the area of the HBMR Drainage Basin, and 65% of total freshwater discharge into the Marine Region (Table 2). Gap-filled monthly records based on the observational data were supplied for use in this report by S. Déry (University of Northern British Columbia). Simulated monthly discharge data for ungauged watersheds were supplied by T. Stadyk and M. Macdonald (University of Manitoba). The simulated data were created using the pan-Arctic implementation of the Arctic-HYPE model, forced with historical precipitation and temperature, and locally calibrated for HBMR Drainage Basin river discharge<sup>4</sup>. All watersheds comprising the simulated portion of the data set are unregulated. In a set of fourteen unregulated watersheds for which there were both observational and simulated data, the mean and standard deviation of the error (observed minus simulated runoff per unit area) were 4% and 13% of the mean. Nor are the observational data without potential error; in gauged records the uncertainty is at least 2–5% (Déry et al. 2011) and likely increase<sup>o</sup> when ice forms in gauged channels.

Prinsenber (1987) estimated that total river runoff from the watershed averaged  $852 \text{ km}^3 \text{ y}^{-1}$  over the period 1963–1983, where hydrometrically gauged discharge was prorated by the ratio of total to ungauged area. Shiklomanov and Shiklomanov (2003) used the same method to estimate a total of  $948 \text{ km}^3 \text{ y}^{-1}$  of fluvial discharge into the Marine Region. They did not clearly state the beginning of their averaging period, but from other information in their monograph, it seems likely that it extended from the 1960s up to 1999. The average discharge from the HBMR Drainage Basin estimated for this study, using combined observational records and data simulated in a calibrated, distributed model, is  $905 \text{ km}^3 \text{ y}^{-1}$  for the period 1984–2013 (Table 1). The differences may be in part due to the different methods used to estimate ungauged discharge, but may as reasonably be attributed to inter-decadal variability or longer trends in runoff since the 1970s, particularly in the eastern Hudson Bay-James Bay watershed (Figure A2 in Appendix A). Since the late 1980s, the eastern and western watersheds have

4 The creation of gap-filled discharge records, and HYPE modelling were completed as part of the Hudson Bay System Study led by the University of Manitoba in partnership with Manitoba Hydro (BaySys 2015). The method of gap-filling is reported in Déry et al. (2011). HYPE was developed by the Swedish Meteorological and Hydrological Institute for simulations of continental-scale runoff. The simulated river discharges used here were provided by authors Stadyk et al. from Theme I, Chapter iv, using meteorological forcing data from the WFDEI historical re-analysis data set. For details on the implementation and calibration of the model, see Macdonald et al. (2018).

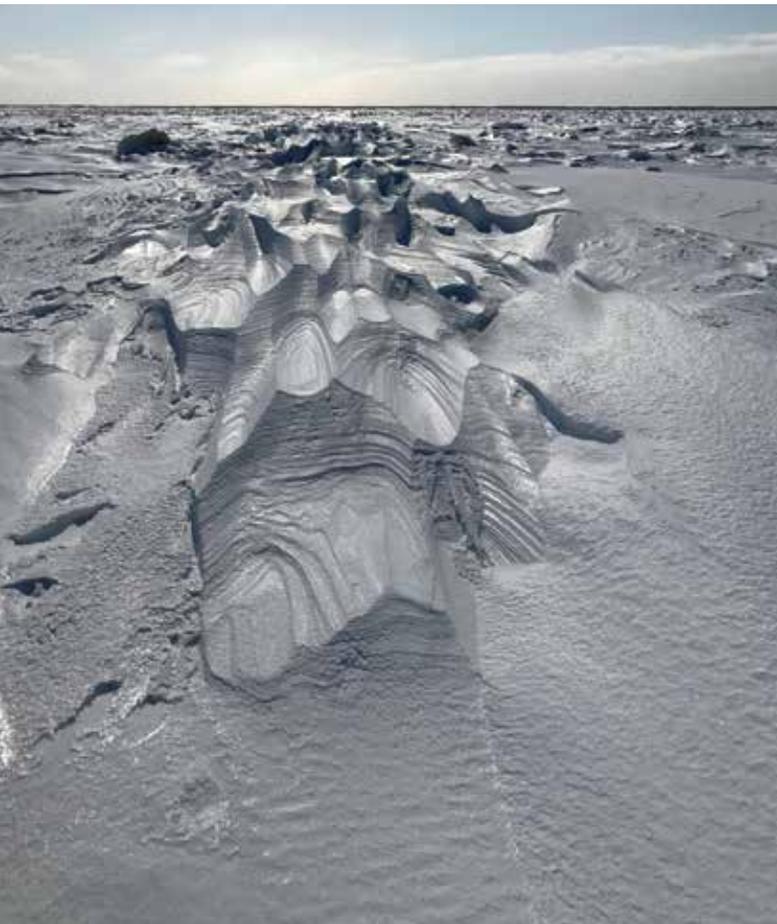
shared a general tendency to increasing discharge; overall, in the observational record, decadal mean discharge from 2004–2013 was 16% higher than from 1984–1993, at the beginning of the 30-year period represented by the data in Table 2 (calculated from data in Table 3 in Déry et al. 2016). For further information on variability and trends in the 50-year observational record from 1964–2013, see Theme I. Chapter iv.

There is also large spatial variation in runoff and discharge throughout the HBMR Drainage Basin. Across the watershed, runoff decreases from south to north, and from east to west (Table 2) from a low of about 100 mm in the Nelson basin to nearly 600 mm in river basins south-east of James Bay. Rivers flowing into James Bay or southwestern Hudson Bay supply almost two-thirds of the total freshwater discharge from the HBMR Drainage Basin. In the north, the Foxe Basin watershed—both small and relatively dry—contributes only 4% of all river discharge into the region. On the basis of load per unit surface area, James Bay receives the largest load. Annual discharge from its terrestrial watershed is equivalent to 4.8 m y<sup>-1</sup> spread over its surface area, that is, more than 5–10 times the depth added

elsewhere in the Hudson Bay Marine Region (Table 2). By this measure, Foxe Basin receives the least, 0.2 m y<sup>-1</sup>.

The two largest rivers account for 23% of the discharge into the Hudson Bay Marine Region—the Nelson River (109 km<sup>3</sup> y<sup>-1</sup>, the size of the drainage area compensating for low runoff and widespread non-contributing regions in the Plains portion of the watershed) drains a large, mostly prairie watershed into southwestern Hudson Bay, and La Grande Rivière (102 km<sup>3</sup> y<sup>-1</sup>) which drains shield terrain into eastern James Bay (1984–2013 mean discharges for both rivers, Déry et al. 2016). Both rivers are highly regulated by hydroelectric power development. The effects of regulation are described in detail in Appendix A. Of major concern here are 1) region-to-region diversion, removing 14% of annual discharge from the Hudson Strait watershed, and adding 5% to the discharge into James Bay; 2) within-region diversions which dramatically reduced flow into estuaries from several large rivers (the Opinaca, and Eastmain and Rupert Rivers in James Bay, and the Churchill River in western Hudson Bay) and which nearly doubled the discharge of the Grand Rivière (James Bay) and which increased the flow at the mouth of the Nelson River by about 20%; and 3) the creation of storage reservoirs which supported a large increase in winter discharge into eastern James Bay via the Grand Rivière, and to a lesser extent, into southwestern Hudson Bay via the Nelson River.

Figure 4 shows the seasonal variability in river inflow. The seasonal regime throughout the watershed and in various sub-watersheds (Table 2) is nival; that is, peak discharge is generated by runoff from spring snowmelt (Figure 4), although rainfall and relatively low evapotranspiration create a secondary peak in October. On average, the peak discharge arrives in James Bay in May, in northwestern Hudson Bay and Foxe Basin in July, and in the rest of Hudson Bay and Hudson Strait in June. In most of the Hudson Bay Marine Region, it roughly coincides with, and supplements freshwater loading by sea ice melt (Gagnon and Gough 2005). In Foxe Basin, sea ice melt lags discharge from the watershed by more than a month (Markham 1986). The spring peak is responsible for a greater fraction of the annual discharge in the northern HBMR Drainage Basin, and a lesser part in the southern watershed. Three peak flow months account for 52% of the annual flow into Hudson Strait and Foxe Basin, in May–July and June–August, respectively. In the large southern and eastern watersheds, natural storage in wetlands and large lakes, and artificial storage in hydroelectric reservoirs reduce the significance of the peak. Three peak flow months account for only 34% and 31% of annual discharge from the southwestern Hudson Bay and eastern James Bay watersheds, both in May–July. Stadnyk et al. (Theme I. Chapter iv.) note that the period of peak discharge has advanced significantly since the mid-twentieth century in hydrometrically gauged watersheds, due to warming springs and thawing of permafrost.



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**TABLE 2.** Freshwater loading from the HBMR Drainage Basin. Discharges are 30-y means for the period 1984–2013. Values in parentheses in columns 2 and 3 are per cent gauged drainage area and discharge, respectively<sup>5</sup>. Totals include 1) discharge derived from WSC records for gauged rivers<sup>1</sup>, 2) discharge for ungauged rivers estimated from a calibrated Arctic-HYPE model of discharge throughout the HBMR Drainage Basin<sup>2</sup>; and 3) discharge for La Grande, Opinaca-Eastmain and Rupert rivers as reported by Déry et al. (2016).

	Drainage area (km <sup>2</sup> )	Annual discharge (km <sup>3</sup> )	Annual Runoff (mm)	Surface area (km <sup>2</sup> ) <sup>*3</sup>	Discharge/surface area (m)
Foxe Basin	260,000 (0%)	40 (0%)	154	210,000	0.2
Hudson Strait	433,000 (54%)	155 (69%)	358	200,000	0.8
Hudson Bay <sup>*4</sup>				763,000	0.5
Northwest	613,000 (49%)	116 (63%)	189		
Southwest	1,775,000 (92%)	210 (92%)	118		
East	187,000 (29%)	61 (39%)	326		
James Bay <sup>*5</sup>				67,000	4.8
East	353,000 (79%)	209 (94%)	592		
West	365,000 (74%)	114 (85%)	312		
Marine Region	3,986,000 (69%)	905 (65%)	227	1,240,000	0.7

<sup>5</sup> In this paper, we confine our use of the term “discharge” to mean the volume river water flowing from the watershed into the sea. For clarity, the volume of flow in marine currents is described by terms such as “flow” or “advection”, but never “discharge”. We use “runoff” to mean discharge per unit watershed area, expressed as mm depth over the watershed surface.

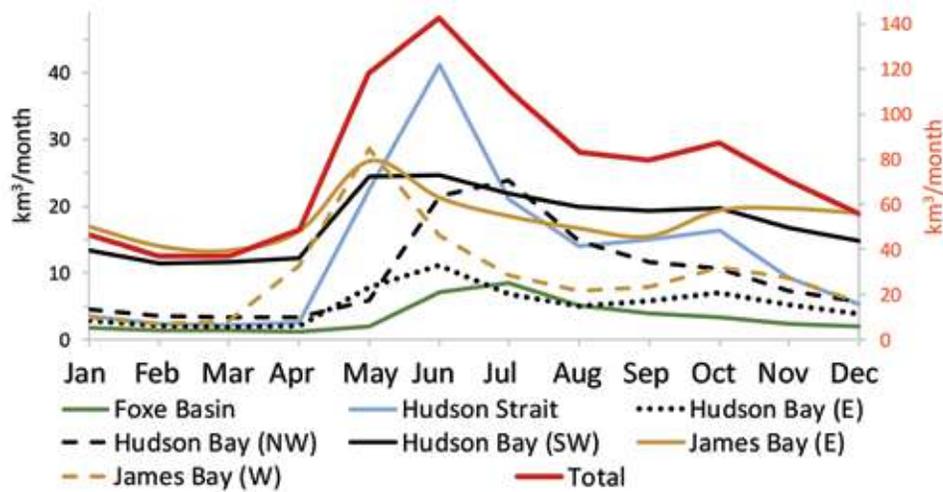
<sup>\*1</sup> Gauged rivers are the Albany, Attawapiskat, Broadback, Chesterfield Inlet\*, Churchill\*, Ekwan, George, Grande R. de la Baleine, Harricana\*, Hayes, Koksoak\*, La Baleine, La Grande, Moose\*, Nastapoka, Nelson\*, Nottaway\*, Petite R. de la Baleine, Pontax, Seal, Severn, Thlewiaza, and Winisk\*. Discharge records for these stations were supplied by S. Déry, with gaps filled using procedures reported in Déry et al. (2011). Asterisks indicate that records at hydrometric stations on more than one tributary were combined to calculate the total watershed discharge (see Table 1, Déry et al. 2011). For this data set, total discharge at the mouth of each gauged river was calculated as the product of recorded discharge at the most downstream hydrometric station(s) multiplied by the ratio of total to gauged watershed area. Discharge for the Koksoak\* River was calculated using hydrometric records at stations on its two major tributaries, the Caniapiscou and Melezes rivers. Annual discharge records for La Grande, Opinaca-Eastmain and Rupert Rivers were not made available for this study; for these three rivers, we incorporated decadal mean discharges reported by Déry et al. (Table 3, 2016).

<sup>\*2</sup> Data for ungauged river basins in the HBMR Drainage Basin were supplied by T. Stadnyk. The data comprised monthly mean discharges simulated in the pan-Arctic implementation of the HYPE hydrological model forced by the WFDEI temperature and precipitation data and calibrated using recorded discharge records as described above. See Theme I, Chapter iv, for details.

<sup>\*3</sup> Sources: Hudson Bay Marine Region—Saucier et al. 2004; FB—Ingram and Prinsenberg 1998; JB—Prinsenberg 1977; 2004; HB + JB = 830,000 km<sup>2</sup>—Prinsenberg 1984, Saucier et al. 2004, hence HB (excluding JB) = 830,000 - 67,000 = 763,000 km<sup>2</sup> (The area of HB exclusive of JB has also been reported as 747,300 km<sup>2</sup> by Prinsenberg 1977); HS (including Ungava Bay) = Hudson Bay Marine Region – (FB + HB + JB).

<sup>\*4</sup> Hudson Bay SW shore includes tributary rivers from (including) the Churchill River to James Bay. Hudson Bay NW includes tributary rivers north of the Churchill, and drainage into Hudson Bay from Southampton, Coates and Mansel islands.

<sup>\*5</sup> James Bay west includes tributary rivers from (including) the Harricana River to the western intersection of the James Bay and Hudson Bay coasts. James Bay E includes tributary rivers from east of the Harricana to the eastern intersection of the James Bay and Hudson Bay coasts (i.e., to Cape Jones).



**FIGURE 4.** Thirty-year means (1984–2013) of monthly discharge into the Hudson Bay Marine Region, calculated from the same datasets and in the same fashion as for Table 2 excepting for the rivers of the James Bay hydroelectric complex. The left axis refers to discharge from individual regions; the right axis refers to the total for the entire watershed. Absolute monthly discharges for the La Grande included in the total discharge into James Bay (E) were estimated as the product of relative monthly discharges for the period 1984–2003 reported by Hernández-Henríquez (2010) for the period 1984–2003 multiplied by absolute decadal mean discharges reported by Déry et al. (2016) for the same period. Monthly discharges at the mouth of the Opinaca-Eastmain River were estimated to be 10% of prediversion monthly discharges.

## 4.2. Precipitation

Straneo and Saucier (2008a) used re-analysis weather data issued by the Canadian Meteorological Centre for the period 1997 to 1999 to estimate  $30 \text{ km}^3 \text{ y}^{-1}$  net precipitation (i.e., precipitation minus evaporation) over the Hudson Bay Marine Region. Their estimates ranged from 10 to  $50 \text{ km}^3 \text{ y}^{-1}$  depending on the combination of data and atmospheric model used. In an earlier study, Prinsenberg (1977) came to the very different conclusion that net precipitation is negative, that is, that evaporation exceeded precipitation by  $192 \text{ km}^3 \text{ y}^{-1}$  (not including Foxe Basin and Hudson Strait). More recently, St. Laurent et al. (2011) used a numerical model to calculate net precipitation of  $222 \text{ km}^3 \text{ y}^{-1}$  over Hudson and James Bays.<sup>6</sup> In Table 2, we report a value of  $330 \text{ km}^3 \text{ y}^{-1}$ —that is,  $0.27 \text{ m y}^{-1}$  averaged over the entire Marine Region (extrapolated from the value reported by St. Laurent et al. 2011). The rate is within the range  $0.2\text{--}0.4 \text{ m y}^{-1}$  calculated for the Labrador Sea and the North Atlantic Ocean by Walsh and Portis (1999) but the large differences among the estimates for the Hudson Bay Marine Region indicate that there is considerable

uncertainty in the contribution of atmosphere–ocean fluxes to the freshwater budget.

Prinsenberg (1977) and St. Laurent et al. (2011) do agree that precipitation exceeds evaporation throughout most of the open water season. Prinsenberg (1977, his Figure 6) reported that net precipitation peaks in August, but becomes strongly negative by November, and remains so through the entire period of ice-cover. St. Laurent et al. (2011; Figure 5c) estimate net precipitation to hover near zero from January through May, and then to rise to a broad positive peak in August through October. About three quarters of the annual supply of freshwater by net precipitation is delivered in these latter three months. Over the entire Hudson Bay Marine Region, that would be of the order of  $250 \text{ km}^3$ , that is, roughly the same as the  $250 \text{ km}^3$  of river discharge delivered through the same period (Figure 4).

In brief, the annual freshwater loading from the terrestrial watershed exceeds direct transfers from the atmosphere by at least a factor of 3 to 4, and while the seasonal pattern is reasonably agreed upon, with inputs peaking from August through October, the absolute value is not well known. Some part of the differences among estimates may reflect different averaging periods. However, the uncertainty may be unavoidable, given the very low density of reporting weather stations in the region. It is unlikely that the uncertainty will be reduced until better observational data are available.

<sup>6</sup> St. Laurent et al. (2011) extracted precipitation from the high-resolution, data-assimilating operational global environmental model used for operational forecasting in Canada. They calculated evaporation within a high-resolution numerical ice–ocean model developed by Saucier et al. (2004) for the HB–JB domain, over the period August 2003–August 2004.

### 4.3. Marine inflow

The Hudson Bay Marine Region is part of a complex path by which freshwater from the Arctic Ocean surface mixed layer is carried through and around the Canadian Arctic Archipelago to the Labrador Sea in the North Atlantic Ocean. Eastward flow through Fury and Hecla Strait carries less than 5% of this freshwater transport<sup>7</sup>. The total and freshwater flows through the strait are  $2200 \text{ km}^3 \text{ y}^{-1}$  (0.07 Sv) and  $90 \text{ km}^3 \text{ y}^{-1}$  respectively (at a reference salinity of 33‰) based on *in situ* current meter measurements (Barber 1965, Sadler 1982) and assumed salinity values.<sup>8</sup>

Published estimates of freshwater transport through this trait have all relied on data from two brief oceanographic studies, Sadler's current velocity profiles made under ice over a period of 30–36 days in April–May 1976 and Barber's 36 hour record made in open water in September 1960. Recently, Ridenour et al. (in review(b)) used an Arctic-North Atlantic-Hudson Bay implementation of the NEMO oceanographic model<sup>9</sup> to estimate that over the period 2002–2016 freshwater flux averaged  $130\text{--}150 \text{ km}^3 \text{ y}^{-1}$  through Fury and Hecla Strait. That is, the recent model simulations agree with estimates from earlier, *in situ* data, at order of magnitude level. This rough estimate of freshwater inflow into the Hudson Bay Marine Region will not likely be improved without further study using moorings to determine seasonal and annual current velocity and salinity in the strait.

### 4.4. Outflow

Hudson Strait functions both as an inlet for Arctic and North Atlantic water flowing into the Hudson Bay Marine Region, and

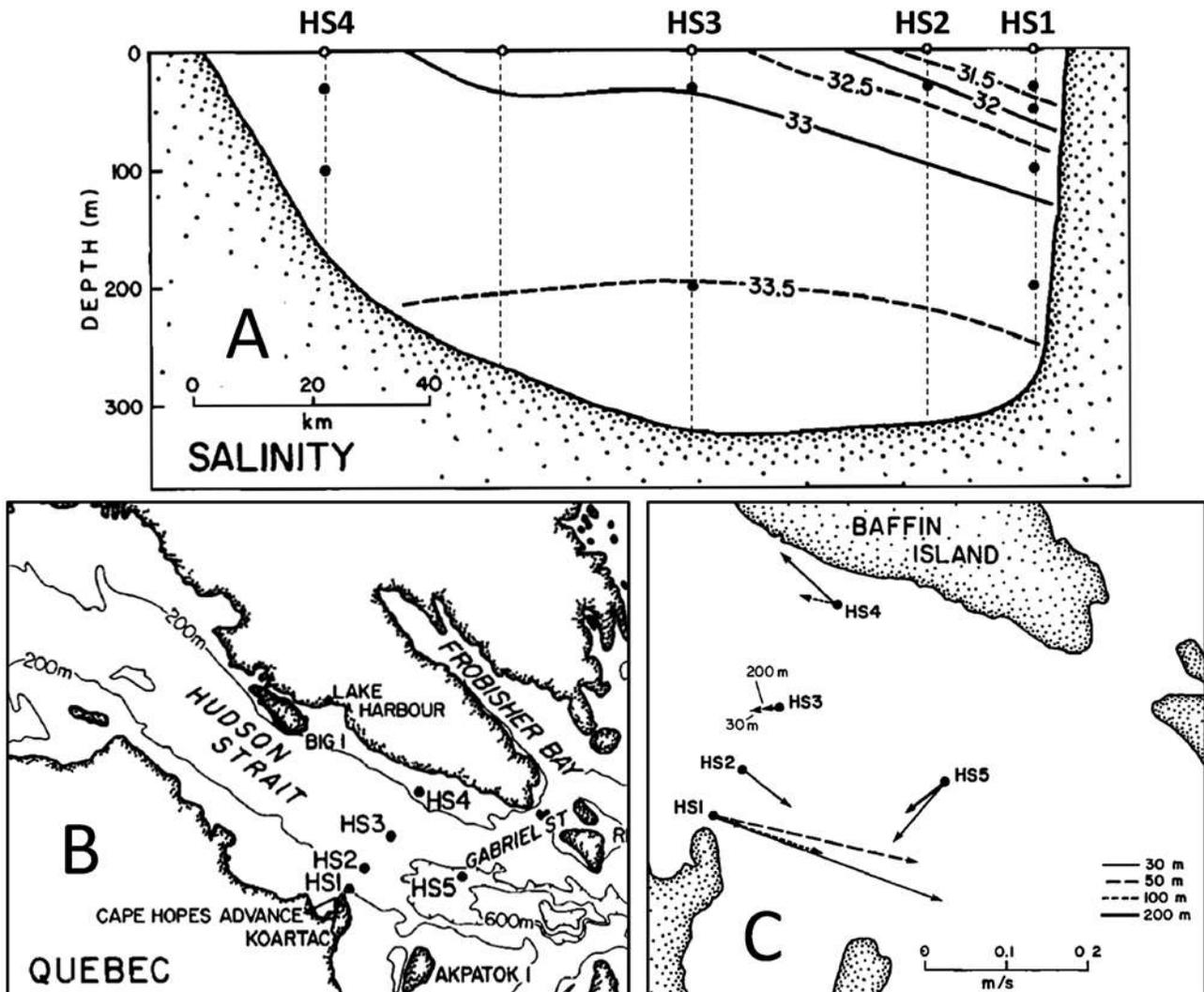
- 7 The combined flux of freshwater through Barrow, Jones and Nares Strait is of the order of  $93 \text{ mSv}$  ( $= 2900 \text{ km}^3 \text{ y}^{-1}$ , ref. salinity = 34.8‰, Table 3 in Münchow 2016); freshwater discharge through Fury and Hecla Strait is  $6.6 \text{ mSv}$  ( $= 200 \text{ km}^3 \text{ y}^{-1}$ , ref. salinity = 34.8‰, Straneo and Saucier 2008a).
- 8 To estimate freshwater content of marine currents, we use a reference salinity of 33‰, which is the salinity of both Hudson Bay and Foxe Basin waters at about 110 m depth (Figure 2) and the salinity of the inflowing along the north side of Hudson Strait (Straneo and Saucier, 2008b) the largest source of outside marine water to the region. It is also the reference salinity used in several earlier studies of freshwater in Hudson Bay (e.g., Barber 1967, Prinsenber 1984, St. Laurent et al. 2011). Freshwater is treated as having near zero salinity (0.05‰). Here, freshwater discharge is recalculated to be  $90 \text{ km}^3 \text{ y}^{-1}$  using summer and winter discharges as reported by Barber (1965) and Sadler (1982) ( $0.1$  and  $0.04 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ , respectively) and summer and winter salinities (31.5‰ and 32.05‰, respectively) as suggested by Straneo and Saucier (2008a).
- 9 Ridenour et al. (in review) used the NEMO (Nucleus for European Modelling of the Ocean) ocean model coupled with LIM2 (Louvain-la-neuve Ice Model) sea ice model in an Arctic Ocean-North Atlantic Ocean-Hudson Bay domain to simulate oceanographic conditions in the Hudson Bay Marine Region. Data quoted here are averages from 2004–2016. See Ridenour et al. (in review) for details regarding the forcing data. Here, we refer to results from their simulations using the HYPE dataset (measured discharge where available, integrated with modeled discharge over the ungauged domain) which most closely resembles the fluvial discharge data reported in Table 2.



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an outlet for excess water in the region. Some water is diverted from the Baffin Current (which flows southward along the north shore of Baffin Island) into the Marine Region along the northern side of Hudson Strait. Although some of this water may reach into southern Foxe Basin, much turns to the south side of the strait, where the residual flow is to the southeast. Flow along the south side transports water out of the Marine Region into the Labrador Sea, ultimately to spread through the north Atlantic Ocean. Figure 5 shows the salinity and velocity structure across the strait as reported by Drinkwater (1988) based on data recorded in August–October 1982. A very similar structure is reported by Straneo and Saucier (2008b) based on records from three moorings deployed in the south side of the strait from August 2004 to August 2005. Although currents are strongest in a wedge of relatively freshwater above the 32.5‰ halocline, there is also significant outflow of the more saline water below. They calculated the freshwater flux to be  $990 \text{ km}^3 \text{ y}^{-1}$  (reference salinity = 33‰, Straneo and Saucier 2008b) of the total flux of about  $30,000 \text{ km}^3 \text{ y}^{-1}$  (0.94 Sv, Straneo and Saucier 2008a) out of the Marine Region. They report a modest seasonality to this discharge, such that 70–80% of the freshwater transport occurs in the 60% of the year from August to mid-February.

Although the mooring array deployed by Straneo and Saucier (2008b) did not capture the full width of the outflow cross-section, their estimate of the southeastward discharge is corrected for this, and their results are supported by information and results reported by Drinkwater (1988) based on a mooring array across the entire strait, albeit with fewer instruments in the outflow path and with a much shorter period of



**FIGURE 5.** A: Hydrographic section across Hudson Strait. Dashed lines identify salinity profiles from casts in August 1982; dots identify locations of current meters deployed from mid-August to mid-October 1982. B: Current meter locations. C: Mean current velocities. (At HS1, vectors at 100 and 200 m depth are partially hidden by the surface vector. They indicate residual velocities of  $\sim 0.13$  and  $\sim 0.3$   $\text{m s}^{-1}$  ESE, respectively.) Source: Drinkwater (1988).

observation. In fact, Drinkwater (1988) determined essentially the same total outflow,  $29,000 \text{ km}^3 \text{ y}^{-1}$  ( $0.93 \text{ Sv}$ ). He estimated that southeastward flow in the upper 50 m on the south side of the strait accounted for half of this discharge, but he did not venture an estimate of the freshwater content of this flow.

The only other reported value that can be directly compared with the freshwater discharge of  $990 \text{ km}^3 \text{ y}^{-1}$  estimated from *in situ* data by Straneo and Saucier (2008b) has recently been determined by Ridenour et al. (in review(b)) using the NEMO model. They reported values for freshwater outflow ranging from  $810$ – $990 \text{ km}^3 \text{ y}^{-1}$ . Among model runs, most of the range is explained by the range of values for net

precipitation plus fluvial discharge input into the model, about  $950$ – $1150 \text{ km}^3 \text{ y}^{-1}$  (balanced by some change in storage over the period of the simulation).

We previously mentioned that both instrumented cross-sections (Straneo and Saucier, 2008b and Drinkwater (1988)) were west of Ungava Bay—that is, upstream of the outlet of the Hudson Bay Marine Region into the Labrador Sea, and that freshwater transport of ice was not included in these estimates. The largest rivers on the Québec shore of Hudson Strait empty into Ungava Bay; they account for  $130 \text{ km}^3 \text{ y}^{-1}$  of the  $155 \text{ km}^3 \text{ y}^{-1}$  of fluvial discharge into the Hudson Strait/Ungava Bay system, or roughly 14% of the discharge into the entire Hudson Bay

Marine Region. Corrected for the missing Ungava Bay drainage, the freshwater discharge out of the Hudson Bay Marine Region would be of the order of  $1120 \text{ km}^3 \text{ y}^{-1}$ . With an additional  $190 \text{ km}^3 \text{ y}^{-1}$  transported out of the region in the form of sea ice (Straneo and Saucier 2008a) the total freshwater exported into the Labrador Sea is more likely of the order of  $1310 \text{ km}^3$  each year.

## 5. Sea ice spatio-temporal regime

The sea ice and climate regimes of the Hudson Bay Marine Region are described at length in other chapters in this report (see Theme I. Chapters i. and ii.); here, we discuss aspects of sea ice and climate only as they relate to production of freshwater in both its solid and liquid forms and to interactions of fresh and marine water in the region.

Although the first reports on winter ice in Hudson Strait in the scientific literature date from as early as 1927, similar information on the mid-winter ice cover in central Hudson Bay became available only after air reconnaissance missions in the winters of 1948 and 1949 (Hare and Montgomery 1949)<sup>10</sup>. Indeed, prior to that, it was generally assumed that central Hudson Bay did not freeze solidly over, as the north Atlantic at the same latitude does not. However, it is now understood that Hudson Bay behaves as a closed ocean basin, meaning that its thermal budget and ice climate are not significantly influenced by advection of ice or sea water from adjacent regions, but rather is largely determined by local air temperature and winds (e.g., Gagnon and Gough 2005, Hochheim and Barber 2014). Advection may have a modest effect on the ice climate of Foxe Basin, which receives significant inflow of Arctic water through Fury and Hecla Strait. It is more significant to the ice regime in Hudson Strait, which receives advected water and ice (including some second year and multi-year ice) from both Davis Strait and Hudson Bay.

Figure 6 illustrates the spatio-temporal pattern of freeze-up and breakup<sup>11</sup> throughout the Hudson Bay Marine Region

<sup>10</sup> Much earlier information exists for the breakup, summer and freeze-up periods in Hudson Strait, Hudson Bay and James Bay, in the form of the ships' logs of the Hudson Bay Company. For instance, Catchpole and Faurer (1985) used ships' logs to prepare annual indices of ice severity encountered during the breakup period in Hudson Strait over the period 1751–1870. Catchpole and Hanuta (1989) used the same information to demonstrate that the most severe ice conditions occurred in years following major volcanic eruptions.

<sup>11</sup> In this chapter, we follow convention in using the term "breakup" to refer to the decay of the sea ice cover. In fact, whether open water forms by wind-forced deformation and advection of ice out of a region (breakup) or by melting in place is not readily distinguishable in satellite imagery, although the actual process can be inferred from environmental information. For instance, polynya expansion during a period of strong offshore winds, but during freezing conditions in mid-winter can readily be attributed to advection of ice out of the region. On the other hand, in the spring, loss of ice in the same region may be due to melt, or to wind forcing, or both. In terms of the supply of liquid freshwater to the surface mixed layer of Hudson Bay, we are more interested in when and where the sea ice melts than in where it breaks up.



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through the fall of 2013 to the summer of 2014. Although the order is typical, the timing of events should not be assumed to be typical. Rather, the description below, of sea ice regimes throughout the Marine Region, follows a recent ice climatology published by the Canadian Coast Guard (CCG 2013). For Hudson Bay and James Bay, we are able to refer also to recent studies by Klaus Hochheim, who reported average conditions over a 25-year period, 1980–2005 (Hochheim and Barber 2010; Hochheim et al. 2011); their climatology is summarized in Figure 7.

Ice typically forms first in Foxe Basin in mid-October, beginning near the outlet of Fury and Hecla Straits, developing first along the west coast, and reaching Foxe Channel by early November. Open water shows in satellite imagery as early as late April, both at the outlet of Fury and Hecla Strait in the northwest, and at the entrance to Roes Welcome Sound in the southwest. More widespread open water appears in June (CCG 2013) but considerable ice remains into late August. Historically, some ice did persist through the open water season and was incorporated into the ice pack the following year; however, in recent years the Hudson Bay Marine Region has routinely become completely ice free by late summer.

Along western shores in Hudson Strait, sea ice begins to form in November, almost a month later than in Foxe Basin. Sea ice coverage is widespread throughout the strait and Ungava Bay by mid-December. However, strong currents prevent consolidation of the ice pack, so that on the one hand, wide open leads repeatedly form and close throughout the winter (particularly along the northern coast and near the entrance to the Labrador Sea), and on the other hand, ridging and rafting affect some regions (particularly along the south shore and in Ungava Bay—Mussels et al. 2016). Leads typically begin to

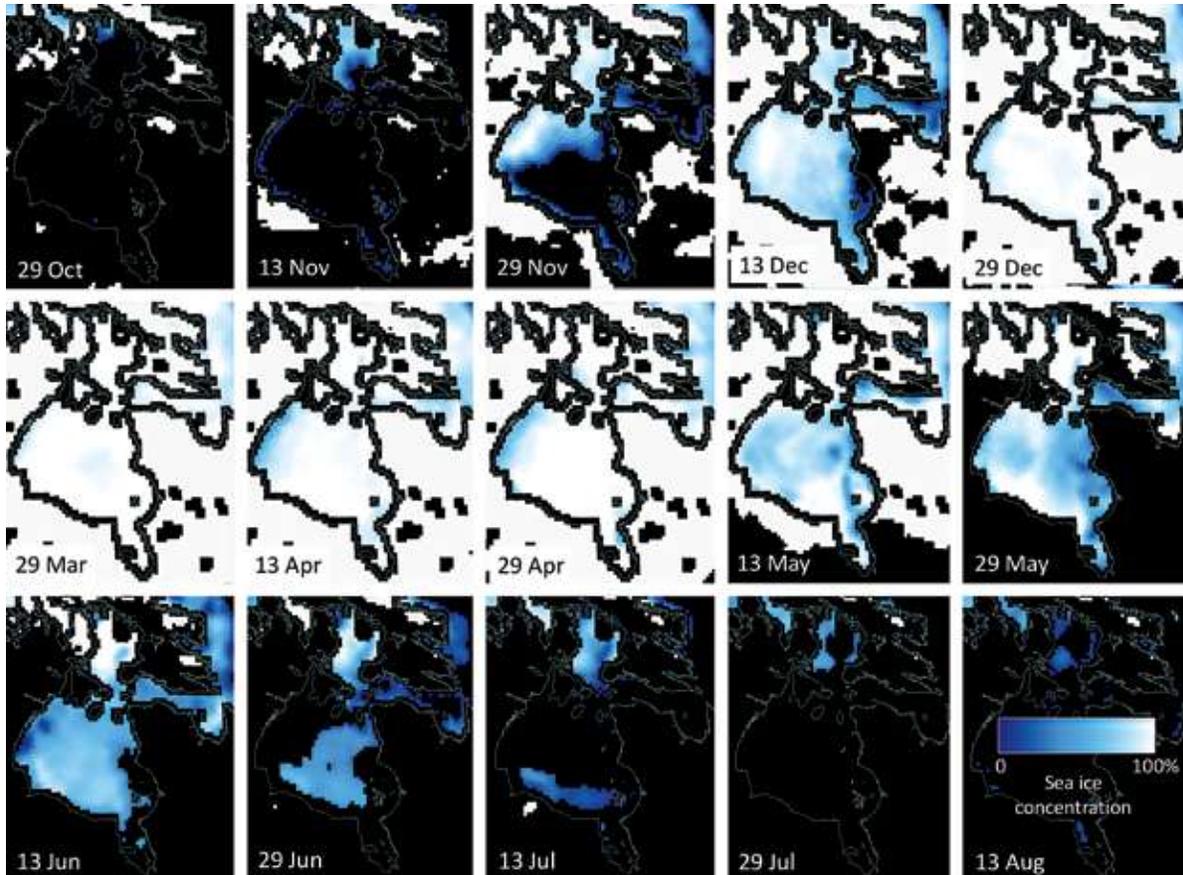


FIGURE 6. Spatio-temporal distribution of sea ice and snow cover from October 2013 to August 2014. Colour scale at lower right. The 2013–2014 ice year was selected based on inspection of the air temperature record at Coral Harbour on Southampton Island; seasonal temperatures were close to the average for the last decade. Source: NASA’s WorldView online resource ([worldview.earthdata.nasa.gov](http://worldview.earthdata.nasa.gov)) with SIC derived from passive microwave data.

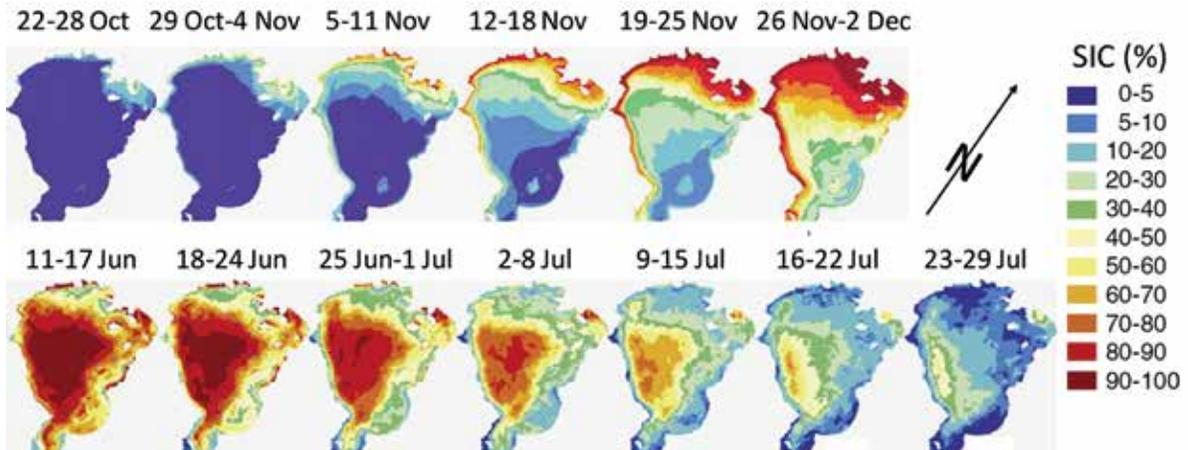


FIGURE 7. Sea ice concentration during the freeze-up and breakup periods in Hudson Bay and James Bay. SICs were determined from Canadian Ice Service data and represent averages for the period 1980–2005. Source: Hochheim and Barber 2010, Hochheim et al. 2011.

expand in May and become widespread by July (CCG 2013). In fact, satellite data indicate that in 2014 the strait was largely ice-free by July (Figure 6). In some years, Arctic multiyear sea ice, and occasionally icebergs, diverted from the Baffin Current drift into the eastern end of the strait, and floes of second year, and possibly multiyear ice sometimes drift into the western end from Foxe Basin. This ice may persist for months, so that while Hudson Strait is mostly open from August through October, it is rarely ice-free.

The processes of ice formation and decay are more protracted in Hudson Bay. Ice forms first in the northwest, beginning as early mid-October; by mid-November, it has spread to cover almost a third of the bay (Figure 7). Over the same period, a broad band of landfast ice forms along the western and southern coast as far as James Bay. Ice continues to spread outwards across the bay until the last open water freezes over, typically east of the Belcher Islands, in mid-December.

Throughout winter the coastal band of landfast remains immobilized, while a vast majority of the ice cover within the Bay is characterized as mobile pack ice and remains in near constant motion as a result of winds and tidal currents. Within the pack ice, floes drifting apart (diverging) lead to the formation of leads (narrow areas of open water within the pack ice), whereas floes drifting towards each other (converging) leads to dynamic ridging and rafting of ice floes into thicker pieces of ice. At the interface of the landfast and pack ice there is an extensive network of flaw leads that form when the pack ice moves offshore semidiurnally as a result of tides. Flaw leads can be several kilometres wide (e.g., Figure 1 in Stirling and Cleator 1981). Under freezing conditions, new ice forms continuously at the surface in open leads, although this ice is quickly compressed against, and adds to the *stamukhi* (ridges of deformed ice along the edge of the landfast ice) when the tidal cycle closes the flaw lead. Beyond the semidiurnal formation of flaw leads, larger more persistent areas of open water known as polynyas form in several regions around the periphery of Hudson Bay and Foxe Basin. Most appear to be latent heat polynyas; that is, they are formed when offshore winds drive ice away from the edge of the landfast ice and create an area of open water (Barber and Massom 2005). Larger polynyas occur south of Akimiski Strait in James Bay (Markham 1986), in Foxe Basin (Defossez et al. 2008; Hannah et al. 2009) and along the northwestern coast of Hudson Bay from the Nelson River to Roes Welcome Sound.<sup>12</sup> In his thesis describing polynya

formation in Hudson Bay, Gunn (2014) reported polynyas as wide as 60 km and up to 14,000 km<sup>2</sup> in size in mid-winter in this northwestern polynya. He also reported very large areas (up to 30,000 km<sup>2</sup>) of open water off the eastern and northern coasts of Hudson Bay in April (Gunn 2014) but these are better described as features of early breakup, rather than polynyas.

Areas of open water exposed within polynyas and coastal flaw leads during winter, lead to the near continuous formation of new ice and result in a thinner ice cover than would be expected for these areas. Persistent new ice formation and the subsequent sea ice growth lead to increased uptake of freshwater and brine rejection within these areas. Additionally, open water and new ice have lower albedos than snow covered sea ice and therefore increase the solar radiation absorbed by surface waters within these areas. In terms of sea ice breakup, the atmospheric forces that drive the polynya in northwestern Hudson Bay also cause breakup to begin in northwestern Hudson Bay in early May when air temperatures rise above 0°C and prevent the formation of new ice within the polynya. Open water spreads from northwest to southeast as the ice edge is forced southeastward by prevailing westerly winds, into the offshore pack ice that is weakened by the onset of ice melt. The breakup process continues through June and into July, with sea ice concentration now decreasing in both northern and eastern waters—although more slowly in central and southwestern Hudson Bay, where drift continually replaces melting sea ice. Typically, the last remnants of the Hudson Bay pack melt out in southern Hudson Bay, off the Ontario shore, into late July.

James Bay typically freezes over in late November although the process has begun as early as the first week of November or as late as early December. There, unlike in Hudson Bay, ice typically forms first along the east coast and spreads to the west. Breakup may begin as early as April around the coasts, especially in regions affected by flow from the large rivers along the Quebec side, with the bay becoming completely ice free as early as June or as late as August. Persistence of some ice into August may in part be explained by advection from the decaying pack in Hudson Bay.

The ice regimes described above are generalized from historical observations over several decades. In fact, freeze-up and breakup dates vary from year to year in response to interannual variability in regional climate, although between consecutive years, the difference is not often large. By inspection of time series charts in several publications (Table 2 in Gagnon and Gough 2005; Figures 10 and 11 in Markus et al. 2009; Figure 2 in Galbraith and Larouche 2011) the difference between one year and the next is typically a week or less, and rarely more than 3 to 4 weeks.

The ice regime in the Hudson Bay Marine Region has been shown to respond by teleconnections to major global climatic

<sup>12</sup> Wang et al. (1994, their Figure 10) reported a roughly 80,000 km<sup>2</sup> region in central Hudson Bay west of the Belcher-Ottawa Islands chain, within which 10–30% open water persisted throughout the winters of 1961–1964. By its location offshore, this may have been a sensible heat polynya related to upwelling; in any case, the authors associated this feature with anomalous climate conditions with respect to the period that they examined. To our knowledge, this feature has not been reported elsewhere in the literature.

processes. We have already noted that Catchpole and Hanuta (1989) reported that the most severe ice conditions in Hudson Strait occurred in years following major volcanic eruptions. Mysak et al. (1996) demonstrated anomalously early ice formation during strong simultaneous events in the North Atlantic Oscillation and the El Niño-Southern Oscillation. More recently, Hochheim and Barber (2010) showed that each of three major climate indices (the East Pacific/North Pacific Index, the North Atlantic Oscillation and the Arctic Oscillation) were highly predictive of fall surface air temperature over Hudson Bay, and that fall air temperature is a major predictor of the timing of freeze-up. Overall, then, climate phenomena occurring on a global scale leave their imprint not only on the long term trend, but also on the interannual variability of in the Hudson Bay Marine Region ice regimes.

Average freeze-up and breakup dates have also shifted in response to more persistent climatic trends. Hochheim and Barber (2014) calculated that through the period 1995–2010 the mean date of freeze-up was 1.6 to 2.4 weeks later than from 1980–1994, and mean breakup was 1.5 to 2.5 weeks earlier (in Hudson Bay and Hudson Strait, respectively). Expressed as rates, freeze-up retreated by 1.1 to 1.6 weeks per decade, and breakup advanced by 1.0 to 1.7 weeks per decade (Table 3). By regression analysis, Galbraith and Larouche (2011) showed that the trend in breakup could be broken into two periods, with small positive or negative trends before 1990, and consistently negative trends since (Table 3). While the two studies are in close agreement on recent breakup trends in Hudson Strait and

Foxe Basin (advancing by 1.7–1.9 and 1.0–1.3 weeks per decade, respectively) they calculate quite different rates (0.3–1.0 weeks per decade, Table 3).

Both Galbraith and Larouche (2011) and Hochheim and Barber (2014) used passive microwave data to determine sea ice concentration, and defined freeze-up and breakup by 50% ice cover (mid-freeze-up, mid-breakup). Markus et al. (2009) identified the onset of continuous freeze-up or melt, based on the actual phase change calculated from emissivity data in the same passive microwave record. Although the emissivity method identifies earlier points in the freeze-up and melt processes than the 50% ice cover method, the two parameters have similar trends through time. On average over the Hudson Bay Marine Region, represented by the onset of the processes, freeze-up retreated and melt advanced by 0.8 weeks per decade from 1979 to 2006. Both are less than the rates determined by Hochheim and Barber (2014) for mid-freeze-up and melt, 1.2 and 1.1 weeks per decade, respectively (through the slightly longer period 1980–2010); on the other hand, the advance in mid-breakup of 0.8 weeks per decade determined Galbraith and Larouche (2011) (through the shorter period 1990–2009). Considering the complexity of the process, these are not large differences. By the onset parameters the length of the ice-free season, averaged throughout the Marine Region, increased by about 6 weeks over the 30-year period; by the mid-period parameters, it increased by 6 or 7 weeks.

The change was a little less in Hudson Bay, and a little more in Foxe Basin and Hudson Strait (Table 3). In Hudson Bay,

**TABLE 3. Range and trends in freeze-up and breakup periods in Foxe Basin, Hudson Strait and Hudson Bay.\*1. The right-most column shows the change in freeze-up as a function of the rate of change in autumn surface air temperature (weeks/1°C).**

	Galbraith & Larouche 2011		Hochheim & Barber 2014		
	1971–1989 Weeks/decade	1990–2009 Weeks/decade	1980–2010 Range (weeks)	1980–2010 Weeks/decade	1980–2010 Weeks/1°C
<b>Freeze-up</b>					
Foxe Basin			12	1.3	0.9
Hudson Strait			8	1.6	0.7
Hudson Bay			5	1.1	0.7
<b>Breakup</b>					
Foxe Basin	–0.1	–1.3	7	–1.0	
Hudson Strait	0.3	–1.9	4	–1.7	
Hudson Bay	0.3	–0.3	5	–1.0	

\*1 Galbraith and Larouche defined freeze-up and breakup as the date when ice covers 50% of the surface area, based on Canadian Ice Service charts. They determined trends by linear regression over the periods 1971–1989 and 1990–2009, but did not attempt to establish the significance of these trends. Hochheim and Barber defined both as the date when 50% of the basin has a sea ice concentration  $\geq 60\%$ , based on analysis of passive microwave satellite data processed at the National Snow and Ice Data Center. Here, the difference between means of two 15-year periods, 1980–1994 and 1995–2010, divided by 15 years, is reported as a rate of change. In every case the difference was statistically significant ( $p \leq 0.001$ ).

mid-freeze-up retreated and mid-breakup advanced by 1.1 and 0.3–1.0 weeks/decade respectively, so that the length of the ice-free season increased by 4–6 weeks over 30 years. Further north the change was more marked; in Foxe Basin and Hudson Strait, the ice-free season increased by about 7 and 10 weeks, respectively.

These trends in both freeze-up and breakup were forced by climate change throughout the Marine Region. From 1950 into the 1980s, fall and spring surface air temperatures were essentially constant (or showed small negative trends). Over the next thirty years, they rose by 1.5–2.5°C (spring and fall, respectively) over Hudson Bay, and about 2°C in spring and 3–4°C in fall over Foxe Basin and Hudson Strait (Figure 3 in Hochheim and Barber 2014). Hochheim and Barber (2014) concluded that, overall in the Hudson Bay Marine Region, a 1°C rise in September–November surface air temperature delays freeze-up by 0.7–0.9 weeks on average. Climatic forcing of breakup is more complex; it is forced by both fall and spring temperatures, as well as spring winds. Nonetheless, they concluded that surface air temperature is responsible for 70–80% of the variability (in the timing of breakup) and, ultimately, also for the gradual lengthening of the ice-free season since the 1980s.

## 6. Sea ice thickness

Ultimately the duration of the ice season (freeze-up to breakup), new ice growth within polynyas and flaw leads, and the total sea ice volume within the Hudson Bay Marine Region dictates how much freshwater is stored within the seasonal ice cover and ultimately released and redistributed during melt. Numerous attempts have been made to quantify this volume of freshwater, but historically these efforts have depended on extrapolation from manual ice thickness measurements at a few locations on the coastal landfast ice. From this data, Markham (1981) estimated that the maximum thickness of undeformed ice ranged from upwards of 2 m in Foxe Basin to as little as 1 m in James Bay. However, sea ice is, of course, not undeformed. Rather, it is highly dynamic and becomes much thicker due to the formation of ridges and rafted pieces of ice during convergent ice drift, or rubble fields when the pack ice is forced onshore and converges with the landfast ice cover (Figures 8–10). Using data from airborne visual surveys of the pack ice reported earlier by Markham (1986), Prinsenberg (1988) made one of the first estimates of overall ice thickness throughout the Hudson Bay Marine Region to incorporate estimates for the effect of ridges—from averages of 2.4 m in Foxe Basin to 1.5 m in James Bay (Table 4). From budgets based on river discharge data and estimates of freshwater advection between basins, he concluded that even these values



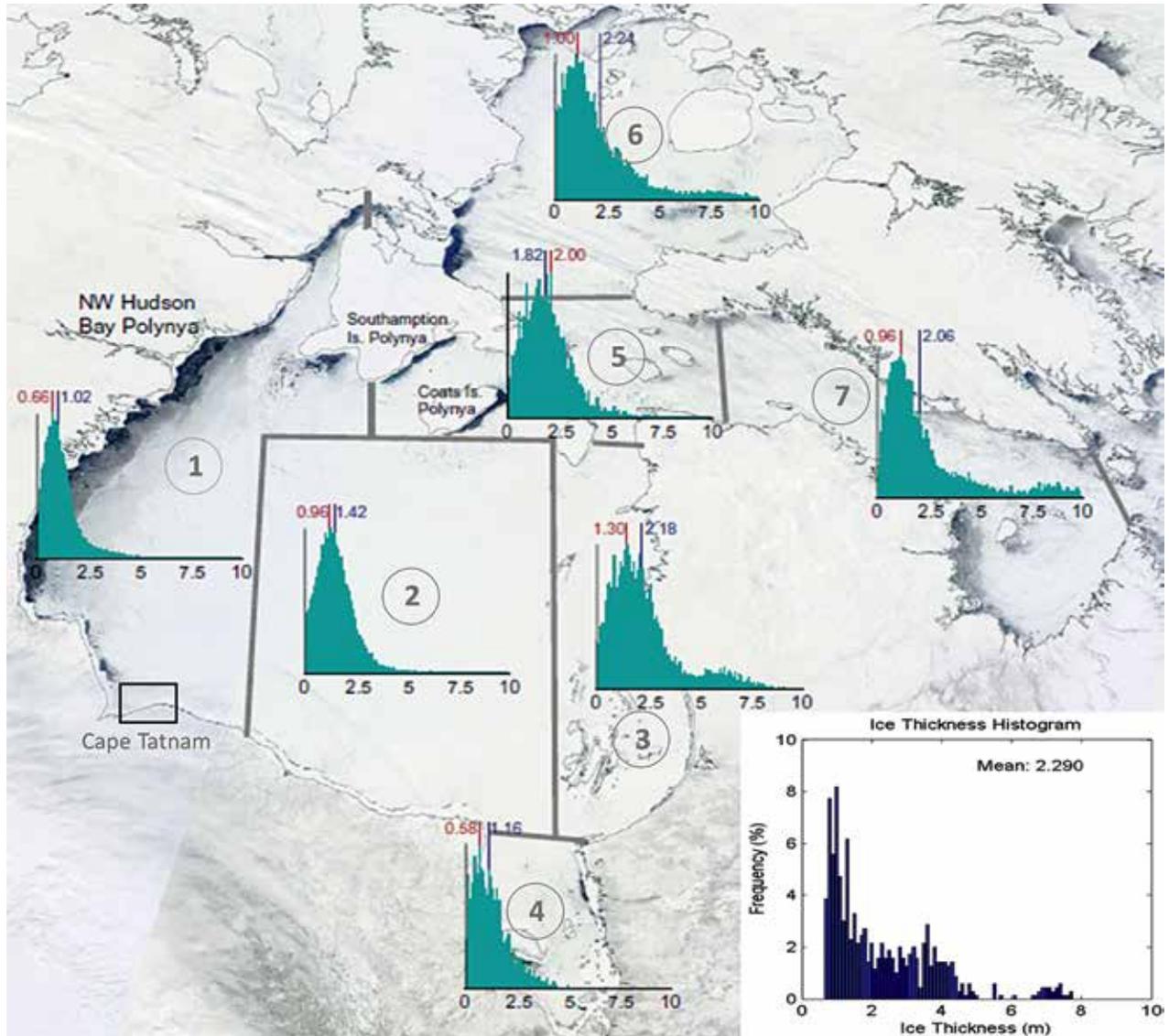
**FIGURE 8.** 0.7 m thick floe surrounded by pressure ridges in pack ice about 80 km northwest of Cape Tatnam on the southwest coast of Hudson Bay. Photo by G. McCullough, taken in mid-March 2009.



**FIGURE 9.** Rubble ice formed by deformation of the pack ice near Cape Tatnam on the southwest coast of Hudson Bay. Photo by G. McCullough, taken in mid-March 2009.



**FIGURE 10.** Rubble-fields formed when the pack ice is compacted against the shore. Photo taken from a helicopter, flying about 6 m above the surface, 10–15 km seaward of the landfast ice edge near Cape Tatnam on the southwest coast of Hudson Bay. Photo by G. McCullough, taken in mid-March 2009.



**FIGURE 11.** Normalized frequency distributions of sea ice thickness in the Hudson Bay Marine Region in April 2014. Circled numbers identify zones bounded by polygons. Mean and modal thicknesses (m) are printed in black and red font, respectively. Thicknesses range up to 7 m in eastern Hudson Bay, Hudson Strait and Foxye Basin—evidence of ice pile-up. Source: Landy et al. 2017. Inset at lower right: thickness distribution over deformed pack ice measured by helicopter-borne electromagnetic inductance, near Cape Tatnam in SW Hudson Bay, recorded in March, 2009. Figures 8–10 show representative views of this ice. Source: K. Hochheim, J. Iacozza and G. McCullough, University of Manitoba (unpublished data).

underestimated the true ice thickness by 10% in James Bay, and 40–60% in Hudson Bay and Foxye Basin, respectively.

More recently, it has been possible to use remote sensing tools to make spatially distributed estimates of sea ice thickness based on freeboard—the height of the ice surface above water. Landy et al. (2017) used satellite-borne microwave altimeter data (i.e., CryoSat data) to provide the first spatially and

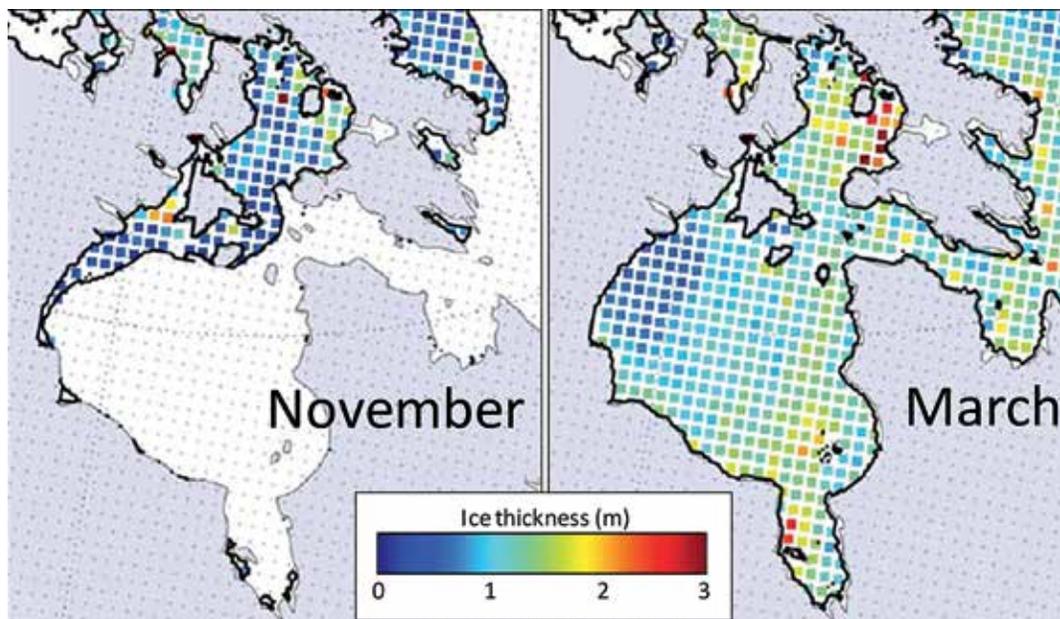
temporally complete observations of ice thickness throughout the Hudson Bay Marine Region and specifically provide observations of ice thickness within the mobile ice pack, a previous limitation to our understanding of the ice cover in the region. Landy et al. (2017) presented gridded field of mean ice thickness (50 km resolution) and also regional ice thickness distributions that show the modal ice thickness, which typically

represents undeformed ice floes, and the long right tail of the distributions, which represents deformed ice up to 10 m thick (Figure 11). The remotely sensed data shows general agreement with an *in situ* ice thickness survey conducted near the Nelson Estuary, that displays a modal thickness around 1 m, and a long right tail that represents ridges and rubble mostly 2–4 m thick, but with a few features 7–8 m thick (Figure 11 – inset at lower right). From the remotely sensed observations it is clear that sea ice throughout much of the Hudson Bay Marine Region reaches a peak thickness in April—except in James Bay, where the ice cover is thickest in March before it begins to melt during April. The mean field of ice thickness within the region during March (Figure 12) represents about 90% of the winter maximum in ice thickness, but for the quantification of freshwater contained within the ice cover (Figure 4), the ice volume for James Bay is taken from March, while Foxe Basin, Hudson Strait and Hudson Bay are derived from ice volume during April.

Figure 12 shows spatial variations in sea ice thickness in great detail compared to the regional averages available from earlier estimates based on sparse data. There is a strong gradient across James Bay, from < 1 m in the southeast to > 1.8 m in the northwest. The highest values north of Akimiski Island are locally anomalous; they may be due to extreme deformation by the strong tidal currents through Akimiski Strait, but we cannot be sure. On the other hand, the very high values in western Foxe Basin, up to 2–3 m, are not unexpected; the extreme deformation

of the Foxe Basin ice cover there was remarked by Prinsenberg (1988). The gradient across Hudson Bay from thinnest ice in the west to thickest in the southeast is not surprising in the light of known polynyas in the west and presumed prevailing ice drift to the southeast (Theme I. Chapter ii.) but this west/thinner to southeast/thicker gradient was not recognized in pre-satellite published studies. In Environment Canada's 1981 Ice Atlas of Canadian Arctic Waterways (Markham 1981) the ice thickness grading from < 1.5 m near the Belcher Islands to > 1.75 m off the northwest coast.<sup>13</sup> This is undoubtedly linear interpolation between observations at a few locations in the landfast ice, not questioned because it fits the temperature gradient. Figure 12 shows the opposite gradient, from < 1 m in the northwest to > 1.5 m in the southeast. Landy et al. (2017) divided the Hudson Bay Marine Region into zones, identified by polygons in Figure 11. Within zones 1, 2 and 3 (from west to east) the mean April ice thickness is 1.3, 1.4 and 1.7 m, respectively. The thinner ice in the northwest is presumably associated with the recurrent polynya in that region. In the southeast, the higher average is clearly influenced by a significant proportion of ice 4–8 m thick (the second mode on the frequency distribution in zone 3 in Figure 11) which represents rubble and ridged ice, deformed by compaction against the coast. Similar mechanical forcing is indicated in Foxe Basin and Hudson Strait, which creates instances of even thicker ice (ice distributions in zones 6 and 7, Figure 11).

<sup>13</sup> Markham's map is reproduced as Fig. 1 in Prinsenberg 1988.



**FIGURE 12.** Mean ice thickness in November and March. Values are averaged through the period 2003–2016. The ice edge is defined by > 20% sea ice concentration. The calculated uncertainty for all but a very few nearshore pixels is < 0.15 m. Source: Landy et al. 2017.

**TABLE 4.** Ice thickness and volume, and freshwater produced in the Hudson Bay Marine Region. Values reported by Prinsenberg (1988) are estimates derived from in situ information acquired in the early 1980s. Values reported by Landy et al. (2017) are derived from satellite altimeter observations and are averaged over the period 2003–2016.

Region	Prinsenberg (1988)	Landy et al. (2017)			
	Thickness <sup>1</sup> (m)	Thickness <sup>2</sup> (m)	Freshwater depth (m) <sup>3</sup>	Ice volume (km <sup>3</sup> )	Freshwater volume (km <sup>3</sup> )
Foxe Basin	2.4	2.1	1.4	341	257
Hudson Strait	1.9	1.6	0.9	221	166
Hudson Bay	1.8	1.4	0.9	1015	762
James Bay	1.5	1.7	1.1	103	68
<b>Total</b>				<b>1680</b>	<b>1253</b>

\*1 Ice thickness (Prinsenberg 1988) was interpolated between augur hole measurements made in late winter repeated over several years at several stations in landfast ice around the coast, corrected for pressure ridges based on aerial surveys.

\*2 Ice thickness (Landy et al. 2017) for the late winter months (when ice thickness was typically > 0.5 m) was derived from altimeter observations of freeboard using ICESat and Cryosat-2 data, corrected for snow depth. Here, we report monthly means for the month with thickest ice (March in JB, April in FB, HS and HB).

\*3 Freshwater content of the sea ice was estimated as a function of the rate of ice growth over the winter, assuming a pre-freeze-up surface salinity of 25 to 32‰. See Landy et al. (2017) for details.

Landy et al. (2017) determined that on average the maximum sea ice thickness developed each winter ranged from 1.7 m in James Bay to 2.1 m in Foxe Basin, over the period 2003–2016 (Table 4). For James Bay, their estimates are 14% higher than Prinsenberg (1988) estimated from early 1980s data (including ridges); for the remaining three regions they are from 12–23% lower. Arctic ice in general has thinned over the last half century (e.g., Lindsay and Zhang 2005, Rothrock et al. 1997). Given that from the 1980 to 2010, the freezing period was reduced by roughly 20–40% in the Hudson Bay Marine Region it may be that the difference between the Prinsenberg (1988) and Landy et al. (2017) can be explained by thinning due to climate warming (except in James Bay, where the positive difference would indicate thickening over the period). However, the information sources and methods underlying these two estimates differ too greatly to be confident of this inference.

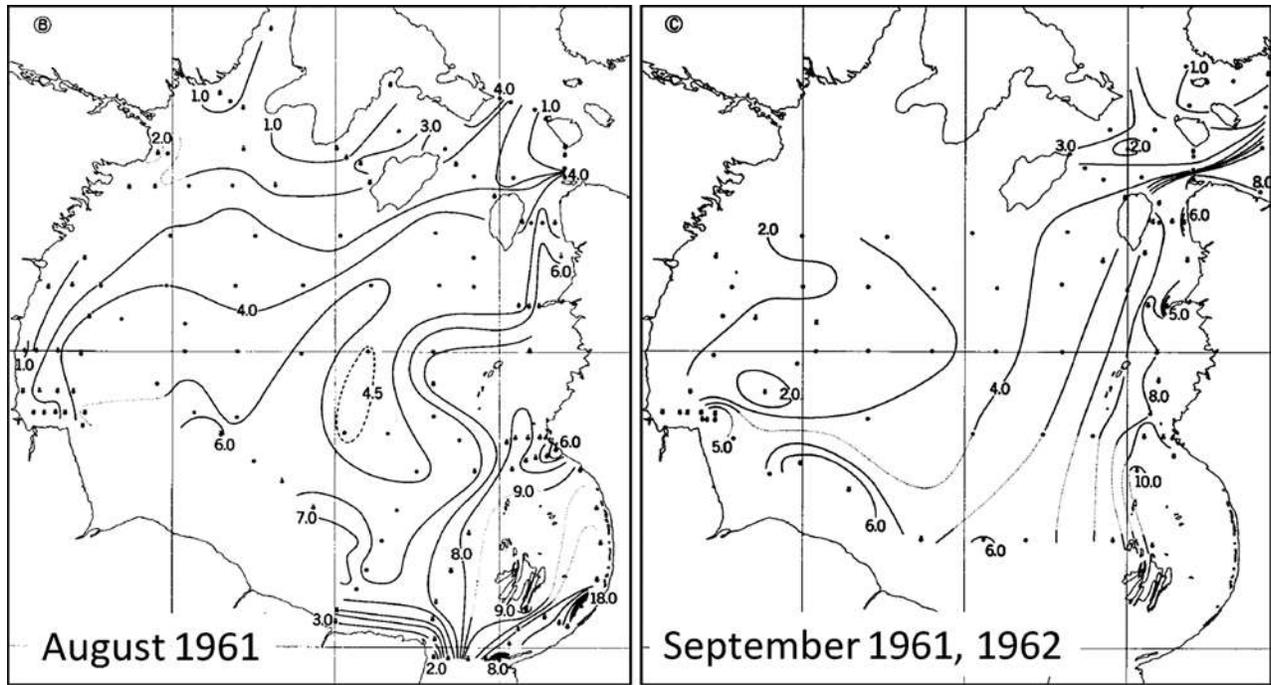
Landy et al. (2017) determined that ice formation removed, and melt added 1.0 m of freshwater to the surface of the Marine Region each summer (area-weighted mean of values in Table 4). They found that melting sea ice contributed an average 0.9 m of freshwater over the surface of Hudson Bay, about one-third more than the 0.7 m supplied by fluvial discharge (Table 2). In general, their remote sensing-based estimates of freshwater derived from sea ice melt are lower than earlier estimates<sup>14</sup>. Prinsenberg (1988) estimated 1.4 m for Hudson Bay and James Bay, compared to the 0.9 m estimated by Landy et al. (2017).

14 Widespread areas of very fresh ice were observed along the southern coast of Hudson Bay from the Nelson to at least the Severn River. It is not clear whether these formed over relatively fresh littoral plumes, or freshened by drainage through the winter. If the former, then this relatively fresh ice is not accounted these estimates. This fresh ice is the subject of a publication in review (Barber et al. 2019).

The older estimate is based on very limited information—that is, augur-hole measurements in the land fast ice at only a very few locations, and coarse estimates of ridge contributions based on aerial surveys—and does not, for instance, take into account the thin ice associated with polynyas in the northwest. It seems reasonable to accept the more recent work, and with it the lower contribution of sea ice melt, compared to fluvial discharge, than has previously been reported.

## 7. Freshwater inventory

An inventory of freshwater in Hudson Bay was first calculated by Barber (1967) using data from stations distributed over all but southwestern Hudson Bay, that were visited in August 1961. In that summer, the surface salinity ranged from < 10‰ along the Quebec coast from James Bay to Richmond Gulf east of the Belcher Islands, through 30‰ near latitude 61°N and 32‰ across the northern reaches of Hudson Bay, to 32.5‰ at the western entrances to Hudson Strait. The bay contained the equivalent of an average freshwater depth of 4.8 m, with as much as 8–18 m south and east of the Belcher Islands, 4–5 m in the central bay, and < 1 m along the northwest and northern coasts (expressed as equivalent depth of pure freshwater, assuming a reference salinity of 33‰, Figure 13). Prinsenberg (1977) determined an average freshwater depth of 4.6 m (at the same reference salinity) using data from an even more comprehensive survey of the bay in 1975. Both authors reported the entire freshwater inventory to the bottom or to the 33‰ halocline, if more saline water was reported in the lower profile. Prinsenberg (1977) attributed the difference in their results to variability in seasonal accumulation.



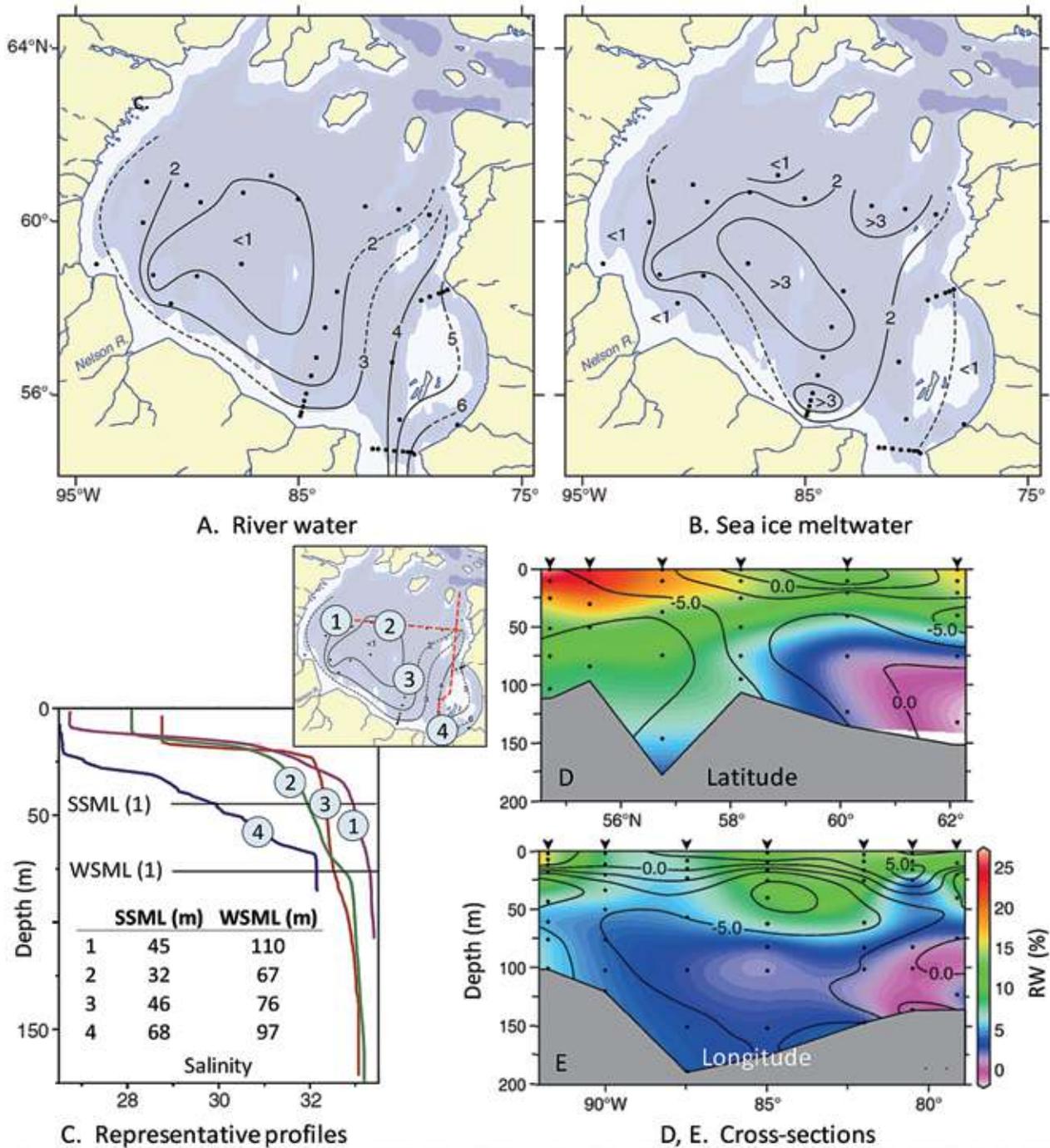
**FIGURE 13.** Distribution of freshwater in Hudson Bay in mid- and late summer, 1961–1962. Data were recorded on cruises of the *Calanus*, *Theta* and *John A. Macdonald*. Stations are shown as dots. Reference salinity = 33‰. The southwestern region not sampled in August 1961 was ice-covered at the time of the survey. Source: Barber 1967.

More recently Granskog et al. (2011) used oxygen isotopes and salinity as tracers to distinguish freshwater contributions from river discharge and sea ice melt. They make a strong case that the freshwater distribution in Hudson Bay cannot be understood independently of brine production when salt is rejected during sea ice formation, particularly in flaw leads or polynyas. They considered the vertical water column to form two layers through the winter months—a winter seasonal mixed layer (WSML) reaching from the ice to the deep waters—and then to reform into three distinct layers through the summer—a new upper summer seasonal mixed layer (SSML), separated from the deep waters by the remnant WSML (see inset C in Figure 14). The SSML reforms each year as newly supplied river water and sea ice meltwater is mixed down into the upper 30–60 m of the water column by wind-forced turbulence. Through the winter, brine formed by salt rejection during freezing either mixes into or sinks through the surface waters. In coastal waters turbulence created by interaction of tidal currents with bottom topography and the ice cover forces vertical mixing (e.g., Wang et al. 2012), and more generally throughout the Marine Region, convective mixing gradually weakens vertical density gradients, so that by late winter the new SSML has mixed with the previous year's remnant WSML, merging the two into a renewed,

vertically well-mixed WSML reaching from the ice to 70–100 m or deeper.

This cyclical development of summer and winter seasonal mixed layers was represented directly in a mooring record in western Hudson Bay, with instruments at 19, 54 and 94 m depth (Prinsenber and Ingram 1991; their Figure 6) where what had been a strong density gradient between 18 and 54 m before freeze-up was erased by early January; salinity decreased at 18 m and increased at 54 m, presumably by addition of salt rejected during freezing at the surface and by associated convective mixing with deeper water. Salinity continued to decrease at 19 and 54 m (and to increase at 94 m) until early April, by which time salinity and temperature at all three instruments was nearly equal (from 33.92–32.96‰ and  $-1.73$  to  $-1.76^{\circ}\text{C}$ , respectively) forming Granskog et al.'s (2011) WSML from the surface down to more than 94 m depth. Granskog et al. (2011) further argue that some dense water formed in flaw leads and polynyas in Hudson Bay sinks into the deep waters below 100 m. They estimate that this process removes as much as 6–18% of river water loading from the surface mixed layers in Hudson Bay.

Panels A and B in Figure 14 show the autumn, 2005 distribution of river and sea ice melt water in the SSML, which accounted for most of the freshwater load from sea ice melt



**FIGURE 14.** Seasonal accumulation of freshwater in the summer seasonal mixed layer (SSML, 30–60 m depth) expressed as m of pure freshwater referenced to a base salinity of 32.8‰. **A:** Map of river-derived freshwater. **B:** Map of sea ice melt-derived freshwater. Units are m of freshwater. Data were recorded during the MERICA-nord program in early September 2005, and an ArcticNet mission from 15 September to 20 October 2005. Stations are shown as dots. **C:** Representative salinity profiles; horizontal lines indicate the depth of the summer (SSML) and winter (WSML) seasonal mixed layers at station 1; boundaries at other stations are indicated in the table. Station locations are shown on the inset reference map. **D, E:** S–N and E–W cross-sections showing river water (colour scale) and sea ice meltwater (isolines). In Panels D and E, the total inventory in the entire water column is shown, as distinct from the seasonal accumulations shown in maps A and B. Negative sea-ice melt values on contour lines reflect net sea-ice formation. Cross-section locations are shown as red-dashed lines on the inset reference map. Source: Granskog et al. 2011.

and river discharge in the immediately preceding spring and summer. (Values mapped in Figure 13 are the total freshwater inventory throughout the water column and are expected to be higher than the seasonal values in Figure 14.) Each year, river water contributes < 1 m of freshwater to the SSML in central Hudson Bay—far from the sources, and relatively isolated from coastal circulation (discussed in a following section). On the other hand, it accounts for most of the annual freshwater loading to the SSML in southeastern Hudson Bay, from 3 to > 6 m north of James Bay, through which passes almost half of the river water entering Hudson Bay (Table 2) and < 2 m off the southwest coast, where southern rivers supply another third. From James Bay north to 59°N latitude along the eastern coast of Hudson Bay, river water mixes to the bottom, well below the SSML as defined for the rest of the bay (Panel D in Figure 14).

Sea ice supplies additional freshwater to the upper water column of the Marine Region from spring through early summer. Some aspects of the spatial distribution sea ice meltwater (SIM) are readily explained by the distribution of sea ice thickness in late winter (comparing Figures 12 and 13). In particular, the low SIM in the northwest coincides with the least late winter sea ice thickness anywhere in the bay. Moderately high SIM (about 2 m) in a broad zone along the western side of the Belcher-Ottawa Islands chain is associated with the highest ice thickness in the bay; it is likely that much of this sea ice melted in place. On the other hand, the large offshore pool of high SIM (within the 3 m contour) in south-central Hudson Bay is well to the west of this thick ice. Rather, it is within the south-central region where the ice pack persists longest into summer (Panel B in Figure 14) where weak and melting sea ice is continuously replaced by predominantly southeastward drift—so that much of it melts well to the southeast of where it formed, in effect transporting freshwater in solid form across the bay.

The last remnants of the pack typically melt off the southern coast of the bay (Figure 7) mostly west of the pool of high SIM near the mouth of James Bay. Meltwater found here autumn (Figure 14 shows freshwater distributions found in a September–October survey) may reflect a confluence of two currents in the SSML—high SIM surface water flowing southeastward along the south coast, following the general counterclockwise surface circulation in western Hudson Bay Hudson Bay (St. Laurent et al. 2011) meeting westward-flowing currents generated by the high fluvial discharge into James Bay (Saucier et al. 2004, Ridenour et al. in review(a)).

The very high freshwater inventories remarked by Barber (1967) are indeed mostly river water. It accounts for at least 10 m, or nearly all of the freshwater south and east of the Belcher Islands, and > 6 m throughout the eastern third of the bay, and along the southern coast at least as far west as the Nelson River.

## 8. Freshwater circulation

Within the Hudson Bay Marine Region, freshwater is transported from Foxe Basin and James Bay into Hudson Bay, where it tends to circulate in a counterclockwise direction around the coast, and then out to the Labrador Sea via Hudson Strait. The circulation of this freshwater between and within basins is described region-by-region below.

### 8.1. Foxe Basin

Arctic water flowing through Fury and Hecla follows the west coast of Foxe Basin south to where the current splits around Southampton Island (Figure 12.9 in Prinsenberg 1986). It carries with it 90 km<sup>3</sup> y<sup>-1</sup> of freshwater from the Arctic Ocean (Table 1) plus another 40 km<sup>3</sup> y<sup>-1</sup> supplied by fluvial discharge from the watershed (Table 2). About 20% of the freshwater in the current passes into Hudson Bay through Roes Welcome Sound, and the remainder flows around the east end of Southampton Island, thence also into Hudson Bay<sup>15</sup> (St. Laurent et al. 2011). The freshwater influx from external sources is dwarfed by the 341 km<sup>3</sup> released by ice melt each year (Table 4) so it is likely a large fraction of the total export to Hudson Bay occurs during the melt and the open water season, when this freshwater is not locked in the ice pack. When the pack opens enough, late in the melt season, some freshwater is also exported by ice drift, mainly into Hudson Strait (Markham 1986).

### 8.2. James Bay

Prinsenberg (1984) described the general circulation of James Bay as it was in 1976, before hydroelectric regulation caused significant changes to discharge regimes in the eastern watershed. (Effects of regulation on fluvial discharge into the Hudson Bay Marine Region are described in Appendix A, attached to this chapter.) In the winter, Hudson Bay surface water flowing into James Bay passed cyclonically (counterclockwise) around the coast. The salinity of the inflow in was about 31‰; mixing with river water reduced it to 28‰ by the time it flowed out along the Quebec side. In summer, surface water followed the same path, but at lower overall salinities; it was diluted from 25‰ to 23‰ during its passage through the bay.

#### 8.2.1. La Grande Rivière plume

Between 1976 and 1995, several studies were completed to describe the freshwater plume of La Grande Rivière and

15 St. Laurent et al. (2011) used a numerical model to simulate flow into and out of Hudson Bay and James Bay. They reported freshwater flow of 16 and 57 km<sup>3</sup> y<sup>-1</sup> respectively, into Hudson Bay via channels 1 and 2 shown in Figure 2. Note that the sum of their simulated flows does not equal the total freshwater flow into Foxe Basin. The difference may be due to flow directly from Foxe Basin into western Hudson Strait, or it may simply reflect the imprecision of both either (or both) input and output estimates.

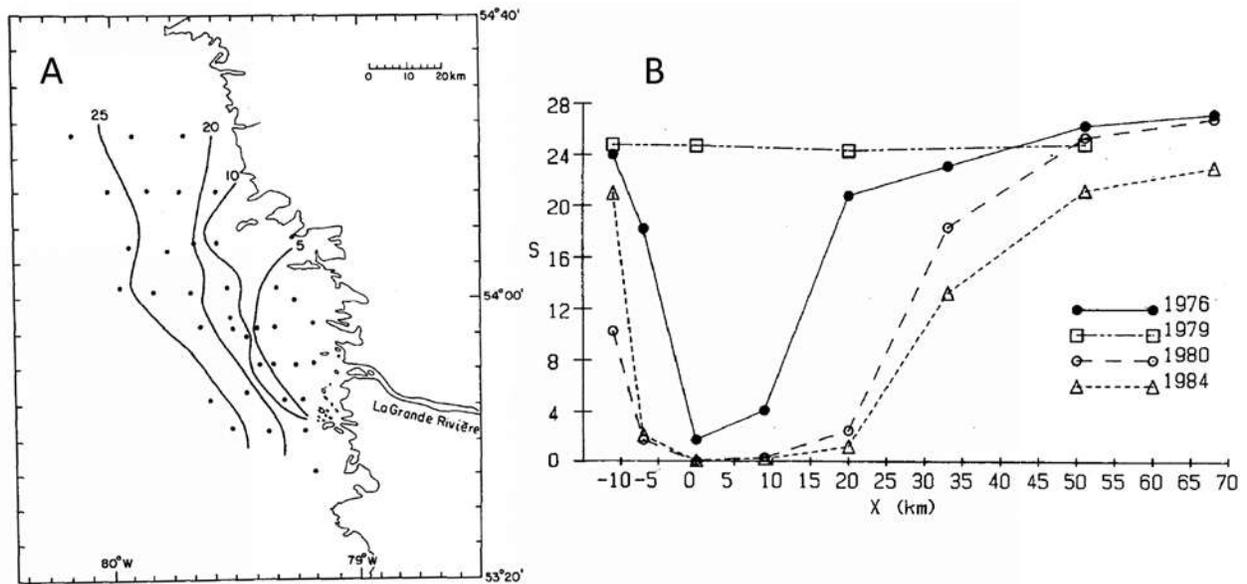
changes associated with hydroelectric development. The emphasis was the winter season because development shifted peak discharge into the winter months, increasing it about 10-fold (Table 5; see also Appendix A for information on river regulation). In contrast to the open-water season, when river plume characteristics vary as a function of river discharge, tidal amplitude, coastal circulation, and wind, under the ice, there is a reduction in vertical mixing driven by wind forcing, which generally leads to river plumes having a larger extent (Ingram 1981, Freeman 1982, Ingram and Larouche 1987). Ingram and Larouche (1987) characterized the freshwater plume of La Grande Rivière in February 1984 when the discharge rate was  $2600 \text{ m}^3 \text{ s}^{-1}$  or six times the natural February rate. Incorporating data from 1976, 1979 and 1980, Ingram and Larouche (1987)

found that the surface areas of the plumes increased directly as a function of discharge (Table 5). In 1984, the plume could be found 70 km north of La Grande Rivière mouth with an observed area of reduced salinity roughly 20 km wide along the coast (Figure 15). The salinity at 2 m water depth at a distance of 70 km from the river mouth was about four units lower in 1984 (~22) compared to 1976 (Figure 15b).

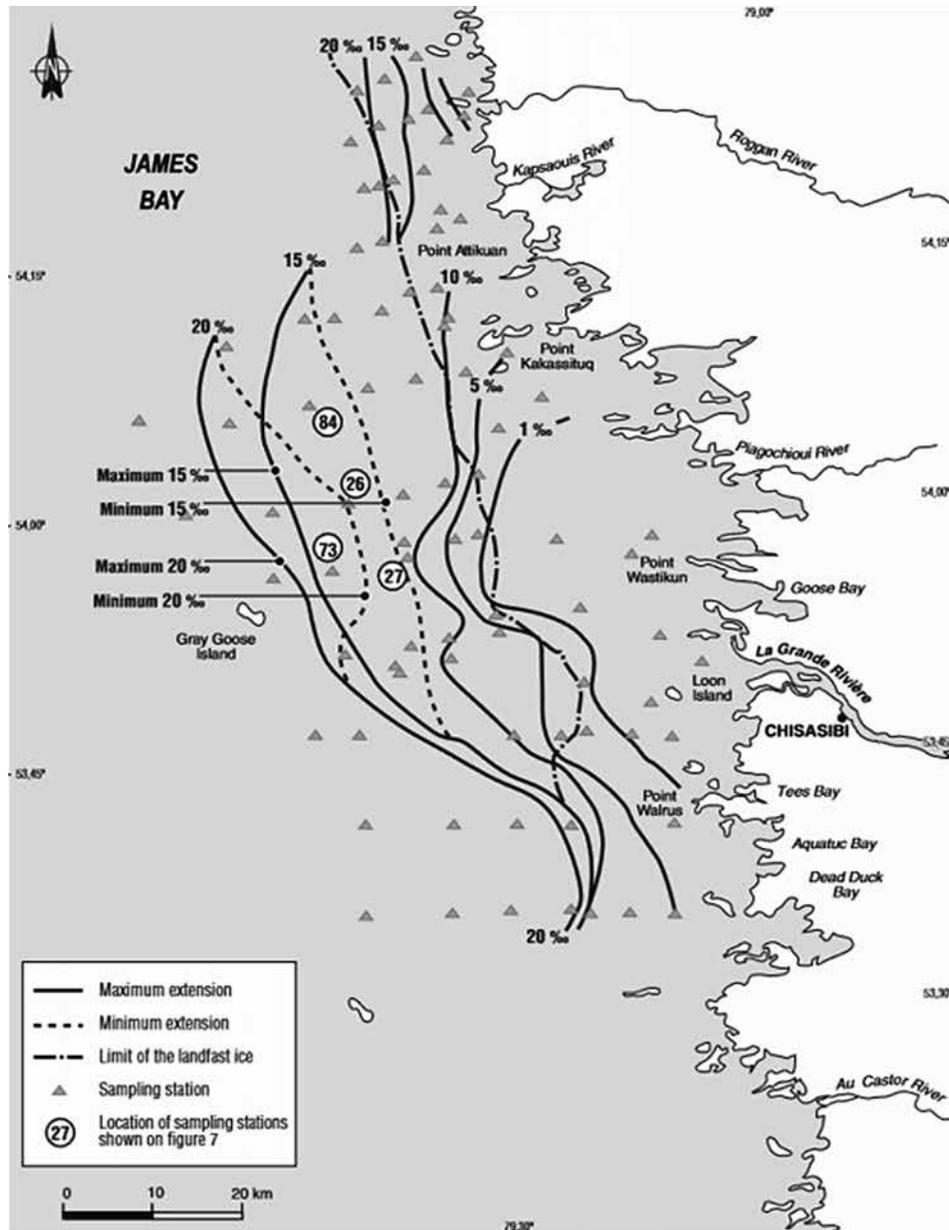
A later report commissioned by Hydro Quebec (Messier, 2002) characterized the extent of La Grande Rivière plume in 1987/1989, 1993 and 1995. During the 1987 and 1989 period, the discharge values varied between  $3700$  and  $4000 \text{ m}^3 \text{ s}^{-1}$ , and the area of the plume extended to  $2000 \text{ km}^2$ . The 5‰ isohaline extended from 35 km south of the river mouth to 30 km north of the mouth. The outer edge of the plume marked by the

**TABLE 5.** The extent of La Grande Rivière plume as a function of winter discharge between 1976 and 1984, for different isohaline values (Sources: 1976–1984—Ingram and Larouche 1987; 1987 onwards—Messier, 2002).

Year	Discharge ( $\text{m}^3 \text{ s}^{-1}$ )	Area (S=5) ( $\text{km}^2$ )	Area (S=10) ( $\text{km}^2$ )	Area (S=20) ( $\text{km}^2$ )	Area (S=25) ( $\text{km}^2$ )
1976	460	200	400	800	1800
1979	0	0	0	0	0
1980	1750	650	900	1300	2800
1984	3000	1200	1650	2300	> 4300
1987/89	3700–4000	1050		3000	
1993	4600			3200–3500	
1995	4400			2100–2800	



**FIGURE 15.** Salinity of northeast James Bay surface waters (2 m depth) under the ice cover in February 1984 (A) and as a function of distance from La Grande Rivière mouth for each of the four study years indicated in Table 5 (B) (Ingram and Larouche 1987).

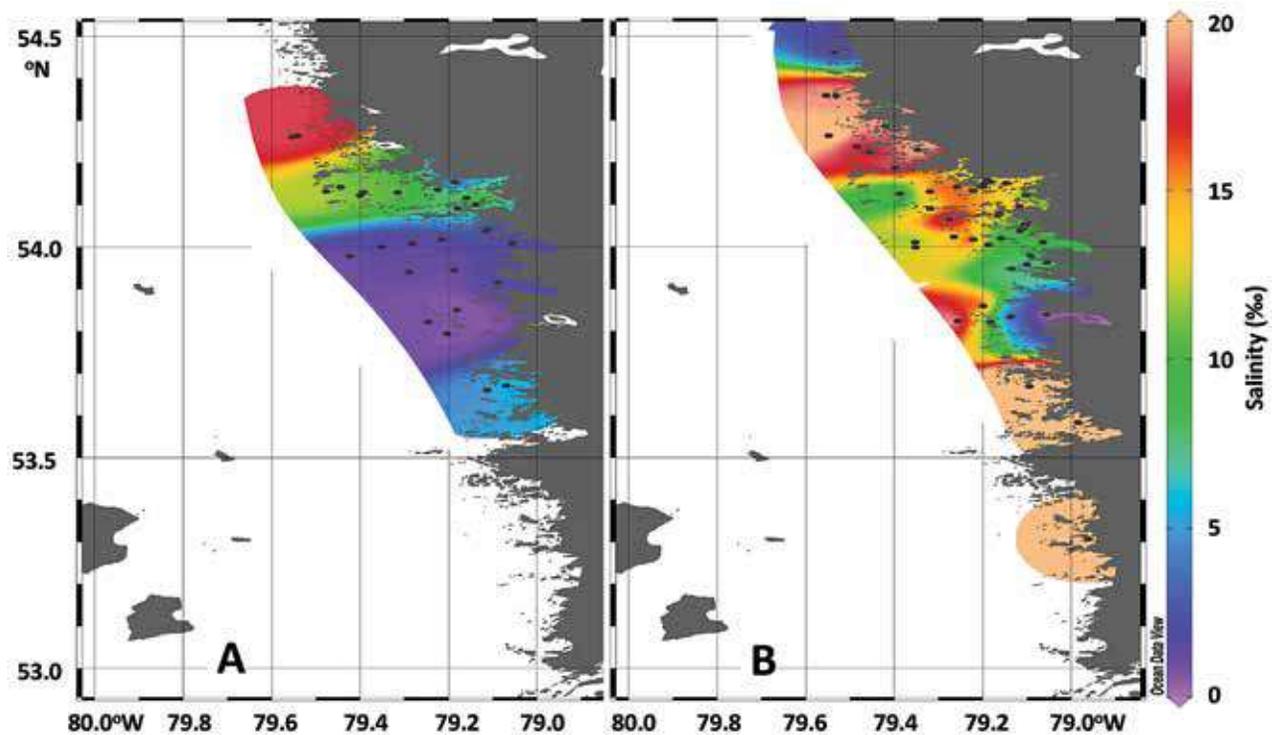


**FIGURE 16.** Salinity of northeast James Bay surface waters under the ice cover in February 1993 (Messier 2002).

20‰ isohaline extended 60 km south and 50 km north of the mouth (Messier 2002). In 1993, with discharge of  $4600 \text{ m}^3\text{s}^{-1}$ , the area of the plume (salinity = 20‰) varied from 3200 to 3500  $\text{km}^2$  (Table 5, Figure 16). In 1995, under similar discharge to 1993 ( $4400 \text{ m}^3\text{s}^{-1}$ ), the plume was smaller (2100–2800  $\text{km}^2$ ) at the time of the field survey, which Messier (2002) interpreted as being caused by wind opening up the lead beyond the outer limit of the landfast ice and driving vertical mixing. Indeed, the

two-layer vertical structure of the plume under the landfast ice cover (i.e., a surface layer of less than 5‰ and a second layer of 22‰, with the pycnocline located between 4 m and 6 m water depth) is not generally found beyond the limit of the landfast ice (Messier 2002).

There have been few observations of summer oceanographic conditions in James Bay since the 1980s. As part of eelgrass follow-up monitoring along the northeast coast



**FIGURE 17.** Salinity of northeast James Bay surface waters in 2016–2017 in (A) January–April under the ice cover and (B) Aug–September, during the open-water period.

(Consortium GENIVAR-Waska, 2017), temperature, salinity and turbidity have been recorded at 88 subtidal ‘verification’ points together with condition of the eelgrass beds (Consortium GENIVAR-Waska, 2017). The observations were made in August on one or more occasions between 1999 and 2011. Kuzyk and Ehn (2017) and Peck et al. (2017) presented preliminary data comparing the horizontal and vertical features of La Grande Rivière plume in summer and winter, which helps link properties at the inshore areas that host eelgrass with offshore conditions (Figure 17). Hydro Quebec collected oceanographic data in the estuarine system of Rupert Bay during the 2008–2017 period as part of the Eastmain-1-A and Sarcelle Powerhouses and Rupert Diversion project’s monitoring program, as required in the project’s conditions of authorization by Québec’s Ministère du Développement durable, de l’Environnement, de la Faune et des Parcs and by Fisheries and Oceans Canada (Environnement illimité, 2011; Hydro Quebec, 2014). The results showed that the ~50% decrease in the Rupert’s discharge, which corresponds to an 18% decrease in the total annual river inflow to Rupert Bay, has led to, in summer, the intrusion of saltwater to a limit of approximately 4 to 6 kilometres upstream from its position before the diversion of the Rupert River. The upstream limit of saltwater intrusion is less in winter.

### 8.3. Hudson Bay

Most river discharge flows into Hudson Bay either through James Bay (45%) or from rivers along the southwest coast, from Churchill to the mouth of James Bay (30%). Most of this remains in coastal waters, although with some injection into deep water (Granskog et al. 2011) or advection into the interior (St. Laurent et al. 2011).

Losses from the surface mixed layers to deep water occur where sufficient brine is rejected from growing ice into the relatively fresh, buoyant river water to cause it to sink; the process is most effective in flaw or other leads, and polynyas, where new ice formation occurs throughout the winter. Granskog et al. (2011) estimated that although as little as 10% of the area of Hudson Bay actively contributes, as much as 6–16% of the annual river water load is injected into deep water by this process. The process removes both salt (in the brine) and freshwater (entrained in the sinking flow of brine) from the surface mixed layer, so that the net effect on salinity in the surface mixed layers may be small relative to the freshening by inflowing river water.

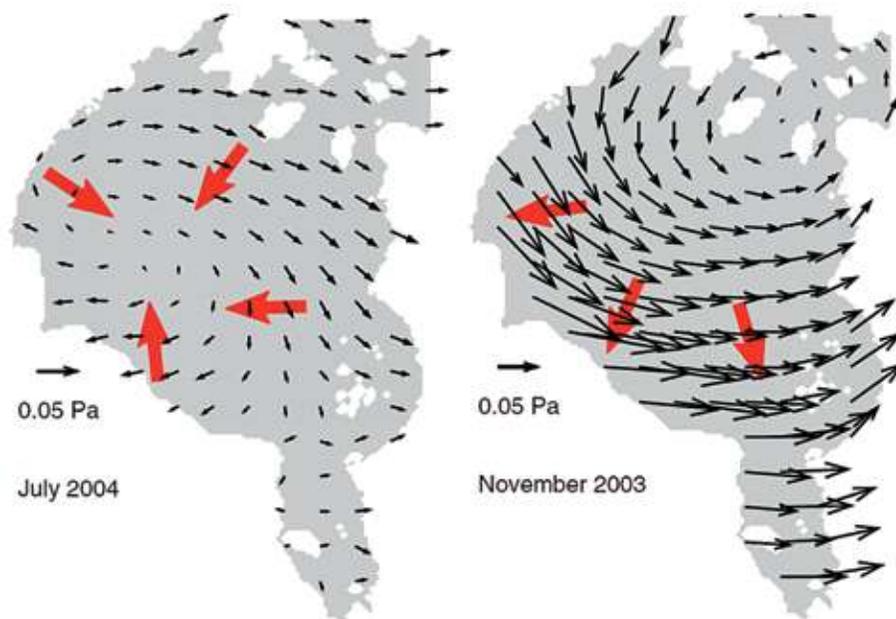
The flow in the coastal zone is generally counterclockwise around the bay, with most of the volume transport confined within 50–100 km of the coast. Freshwater from Foxe Basin flows around Southampton Island (through channels 1 and 2

in Figure 1), picks up river water as it passes around the coast (mostly along the southern coast and out of James Bay) and finally flows out into Hudson Strait through channels between Coates and Mansel Islands, and between Mansel Island and the east coast ( $14$  and  $802 \text{ km}^3 \text{ y}^{-1}$  respectively, through channels 3 and 4 in Figure 2; volume discharges estimated by numeric simulations, St. Laurent et al. 2011). Prinsenberg (1994) estimated that surface water followed this coastal pathway at an average speed of  $0.04 \text{ m s}^{-1}$ , in which case it would pass from Roes Welcome Sound around to Hudson Strait in just under 2 years.

Evidence from numerical models indicates a divergence from this general pattern in spring and early summer, associated with the peak fluvial discharge into James Bay (Saucier et al. 2004, Ridenour et al. in review(a)). Freshwater flowing out of James Bay increases the local dynamic height of the sea surface, inducing clockwise circulation in southeastern Hudson Bay and effectively, causing bay-wide circulation to form a double gyre (Ridenour et al. in review(a))—and a considerable divergence from the traditionally accepted coastal circulation. St. Laurent (2011) reported a quite different mechanism that also effectively diverts circulation from the periphery of the bay. They used tracer experiments in a numerical model to identify a pattern of freshwater transfers between the preferred coastal pathway and the interior of the bay, mostly inwards in early summer and again in early winter, and outwards in autumn. The

forcing mechanism for inward advection is Ekman transport associated with atmospheric circulation patterns over the bay, predominantly anticyclonic (clockwise) in early summer and early winter, and cyclonic in autumn (Figure 18). From the ratio of river water in the SSML to the total inventory of river water in the interior of Hudson Bay, Granskog et al. (2011) calculated that the residence time of freshwater there is of the order of 5 years. St. Laurent et al. (2011) concluded that these cyclic transfers slow the advance of freshwater to the outlet in Hudson Strait, increasing the average transit time from 2.2 years (following a strictly coastal path) to 3 years (with cycling).

Nonetheless, three-quarters of the river water in Hudson Bay never escapes the coastal pathway before flowing out of the bay into Hudson Strait (St. Laurent et al. 2011). Some of this passes into Hudson Strait in months, not years. Barber (1967) noted that near the outlet of Hudson Bay the freshwater in the water column nearly doubled from August to October, and concluded that river water reached Hudson Strait in the same season as it had discharged into James Bay. Data from moorings deployed in Hudson Strait support this conclusion, where freshwater discharge peaks in October–November, 4–6 months after the snowmelt runoff peak in the southern HBMR Drainage Basin and the sea ice melt in the Marine Region (Figure 13 in Straneo and Saucier 2008b). Other investigators (e.g., Sutcliffe et al. 1983; Myers et al. 1990) postulated that the



**FIGURE 18.** Mean stress (black arrows) at the ocean surface for two contrasting periods. Ekman transport (red arrows) is directed toward the right of the stress. The wind stress is taken from the model forcing (clockwise and counterclockwise atmospheric circulation centred over parts of the Hudson Bay Marine Region). Source: St-Laurent et al. 2011).



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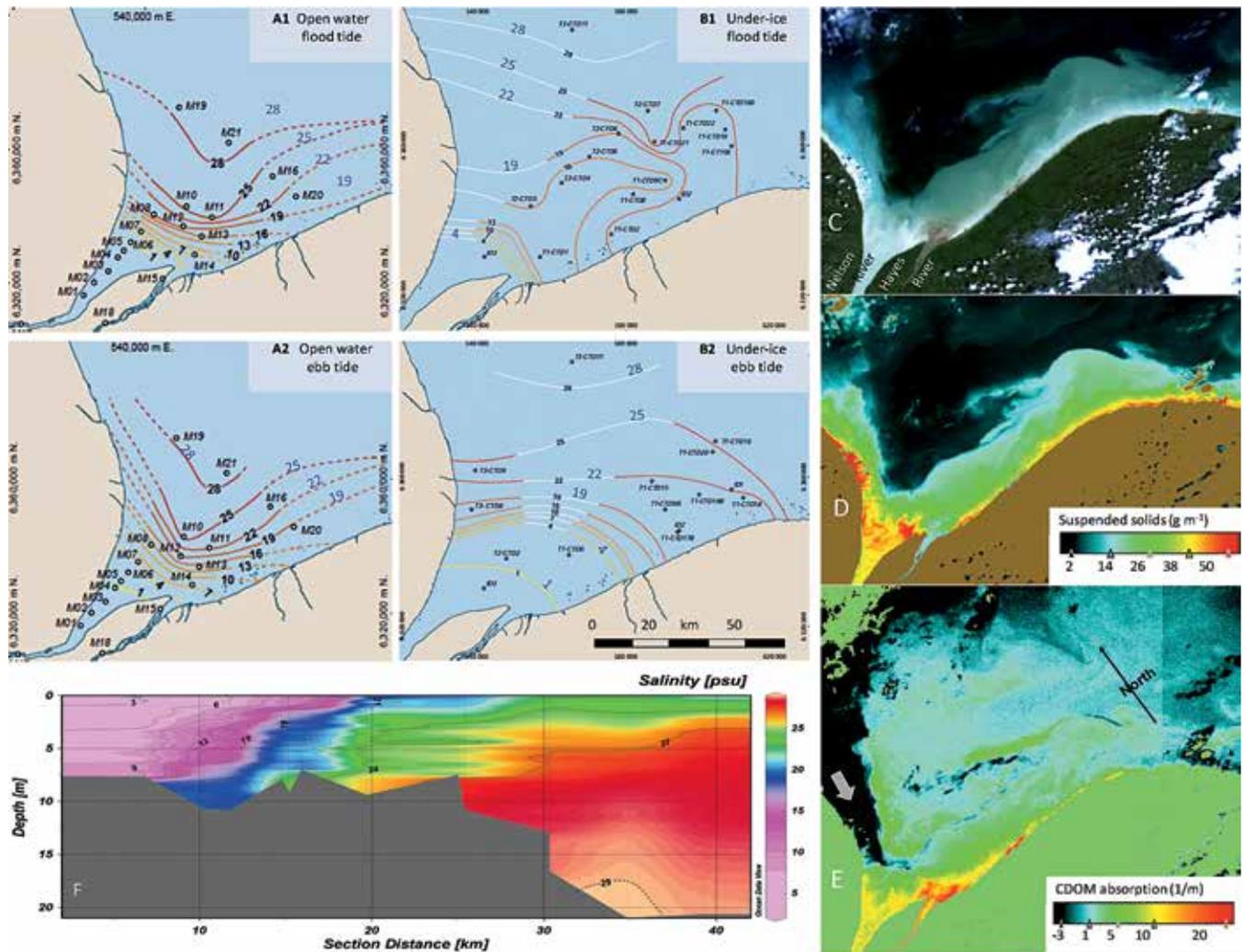
signal of freshwater discharge from the Marine Region could be detected in Labrador Current waters even further downstream. Myers et al. (1990) presented evidence that it reaches as far as the Newfoundland Shelf each year, nine months after snow-melt discharge peaks in the southern Hudson Bay and James Bay watersheds.

Interestingly, contrary to the conventional view of a continuous coastal current outflow from Hudson Bay, recent results suggest that the freshwater outflow involves discrete pulses. Mooring records obtained in fall/winter 2005–2006 showed the pulses occurring once every 4.4 days on average and associated with anticyclonic, surface-trapped eddies propagated through the strait by the mean outflow (Sutherland et al. 2011). The occurrence of the freshwater-rich eddies was related to the passage of storms across Hudson Bay that force low-salinity boundary current waters out of the bay near Mansel Island. The eddies were responsible for approximately 40% of the mean volume transport and 50% of the mean freshwater transport out of the strait during the period of record. It is not known whether

the inflow of freshwater to Hudson Bay is influenced by similar processes but if a different mechanism is involved, one could envision scenarios in which inflow and outflow of freshwater from Hudson Bay become uncoupled, allowing freshwater to accumulate temporarily in the bay for later release. The process could drive inter-annual variability in salinity and other properties, the potential for which has not yet been assessed.

### **8.3.1. Nelson River estuary**

The Nelson and Hayes River share an outer estuary where flow from each is mixed. (The initial separation is apparent in Panel C in figure 19, where a distinct brown plume of water relatively rich in dissolved organic matter, and low in suspended sediment reaches several kilometers eastward from the mouth of the Hayes River.) However, most of the dynamics of freshwater-saltwater mixing described below occur in the inner and middle estuary of the much larger Nelson River. Interaction between tides and river flow in this estuary has been described by Wang et al. (2012). The inner estuary is marked by extensive



**FIGURE 19.** The Nelson–Hayes surface plume in southwestern Hudson Bay. A1, A2: open water conditions at high and ebb tide. B1, B2: Same, under ice (March). All represent spring tide conditions. Isohalines are at 3‰ intervals (with 19–28‰ marked in larger font). Source: Manitoba Hydro 2006. C: Natural colour rendition of MERIS satellite data recorded over the Nelson–Hayes estuary. D, E: Suspended solids and CDOM concentrations derived from D by regression on in situ data collected in the summer of 2006. F: Salinity profiles through the tidal mixing zone, in a section recorded near high tide (from 0 km near M04 to 40 km near M10 on Panel A1). Source (E–F): Unpublished data (Greg McCullough).

mud flats, partially exposed at low tide. Daily mean discharge measured 150 km upstream of the river mouth averages 3400 m<sup>3</sup> s<sup>-1</sup> but has varied from < 500 to > 7000 m<sup>3</sup> s<sup>-1</sup> (1987–2013). Tides are amplified to as much as 5 m (ranging from 2–5 m between spring and neap, summer and winter tides) where currents converge in the funnel-shaped inner estuary. In surveys undertaken in 2005–2007, currents of 0.5–1 m s<sup>-1</sup> directed upstream were measured during flood tide, and from 1.5–2 m s<sup>-1</sup> downstream during ebb tides (Figures 4.10 and 4.11 in Manitoba Hydro 2114).

The Nelson estuary may be described as a partially mixed estuary; that is, during flood tide, heavier salt water flows into the river mouth under lighter, fresh river water until constrictions force the two to mix vertically. It is this mixed, brackish water that spreads into the outer estuary, only a few meters thick over the surface of saltier water below (Panel F in Figure 19). Nowhere seaward of the inner estuary is the plume as fresh as plume of La Grande Rivière under the landfast ice (described above). In the open water season, full vertical mixing occurs in the middle estuary—roughly between the 1–25‰ isohalines

shown in Figure 19, that is, roughly, over a 10 km distance during flood tide, stretching to 20 km during ebb tide—before the surface plume becomes fully developed in the outer estuary. In winter, although the freshwater plume still spreads predominantly eastward, it also reaches further seaward than in summer, so that the 22‰ and 25‰ isohalines are 10–20 km further offshore in winter than in summer.

The isohalines shown in Figure 19, determined by *in situ* sampling, do not represent the full, measurable extent of the influence of Nelson and Hayes waters in southwestern Hudson Bay. Their water is marked by the high concentrations of coloured dissolved organic material (CDOM) in both rivers<sup>16</sup>. Elevated CDOM indicates that the freshwater plume from these rivers is identifiable out to more than 100 km to the east along the coast, and seaward in gyres reaching out almost as far to the north (Panel E). The bright coastal plume apparent in visible imagery and identified as a suspended sediment plume in Panel D is not everywhere coincident with this larger plume of river water and its dissolved load; rather, the suspended sediment plume is created mostly by erosion and resuspension of littoral sediments and only partly from the Nelson and Hayes rivers, and this material is coarse enough that much of it is lost by sedimentation far short of the full extent of the brackish plume. To the north of the river mouth, the very high suspended solids load along the coast is apparently derived entirely from the littoral bottom and mud flats, since the lack of CDOM indicates Hudson Bay water flowing southward into the estuary region (grey arrow in Panel E) and not river water flowing northward. This interpretation is in general agreement with information from the *in situ* survey; although the isohalines do indicate limited northward spread of the freshwater plume, they agree with the remote sensing interpretation that most Nelson and Hayes water spreads eastward along the coast (Panels A1 and A2).

#### 8.4. Hudson Strait

The freshwater circulation in Hudson Strait has been described in section 7.4. In brief, northwestward currents flow along the north side as far into the Marine Region as southeastern Foxe Basin and southeastward currents flow along the south side into the Labrador Sea. Part way into Hudson Strait, most of the marine inflow is turned southward into the flow along the Quebec coast, and back into the Labrador Sea. The freshwater flow out of the Marine Region is also carried in

<sup>16</sup> CDOM provides a strong optical signal readily distinguished in satellite imagery (Panel E in Figure 19). In the Nelson-Hayes combined estuary, it is highly correlated with salinity (Gueguen et al. 2011, Granskog et al. 2007). Both rivers are rich in CDOM, although in satellite imagery, it is somewhat masked in the Nelson River waters by suspended sediments. Since these two rivers supply most of the river water identifiable in a region out to at least 100 km from their mouths, the CDOM plume is an indicator of distributary patterns of Nelson-Hayes water in the region.

this southeastward current, in a shallow wedge of relatively freshwater (above the 32.5‰ halocline, Figure 5) derived from the surface mixed layers in Hudson Bay. The more saline water below carries a smaller, but still significant load of river-sourced water mixed into the deep water in Hudson Bay by entrainment in brine. The circulation in Ungava Bay is not well known but, because many large rivers empty into the bay, it presumably contributes substantially to the freshwater-rich eastwardly flow along the south coast of the strait.

## 9. Conclusions and recommendations for future work

While general aspects of freshwater flow through the Greater Hudson Bay Marine Region are reasonably well understood, many questions remain. At the level of the overall input/output budget, only river discharge from the watershed is well-enough documented to describe precision, variability (at least at the inter-decadal scale) and long term trends.

Net transfers from the atmosphere (precipitation minus evaporation) may account for a third as much freshwater input as river discharge, or they may not. Given the harsh conditions, it is not likely that this uncertainty will be improved using *in situ* data over the Marine Region. A paucity of *in situ* data over water also hinders error analysis of simulated precipitation and evaporation, so that the accuracy and precision of modeled atmospheric transfers of freshwater is hard to evaluate. Satellite microwave remote sensing offers some potential for improved precipitation (e.g., Berg et al. 2010; Tapiador et al. 2018) and evaporation (e.g., Boisvert et al. 2013) estimates over the oceans, and these methods should be tested for their utility in the Hudson Bay Marine Region.

The *in situ* data available to quantify freshwater inflow through Fury and Hecla Strait is particularly rudimentary. It appears that this inlet supplies less than 10% of the freshwater loading to the Marine Region so that it is of lesser concern than the large uncertainty in net transfers from the atmosphere (uncertainty larger than the estimated total freshwater inflow through Fury and Hecla Strait) or compared to potential inter-annual or inter-decadal variability in the much larger freshwater outflow through Hudson Strait. The spatial resolution of the current implementation of the NEMO model implemented under the BaySys project is too coarse to improve on current estimates (Ridenour et al. in review (b)). Deployment of salinity and current velocity instruments on an annual mooring (at least) will be necessary if we are to narrow the current uncertainty in freshwater inflow through the strait; such measurements would also serve to calibrate a future higher resolution numerical model.



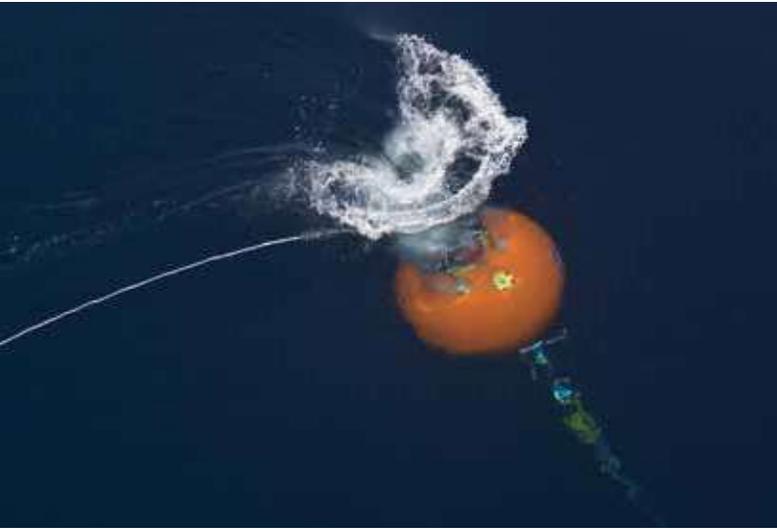
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The current estimate of annual freshwater transfers through Hudson Strait is also limited by less than optimal moorings records (Straneo and Saucier 2008a)—although the underlying data seem more dependable than that for Fury and Hecla Strait. It may be that the ideal program to better quantify seasonal and annual freshwater budgets of the Hudson Bay Marine Region, then, would consist of simultaneous, year-long mooring deployments, one in Fury and Hecla Strait and an array in Hudson Strait. However, as it is, the freshwater outflow through Hudson Strait is reasonably well known. It and fluvial discharge from the watershed are together the best quantified elements of the freshwater input/output budget of the Hudson Bay Marine Region. The freshwater flow through Fury and Hecla Strait is probably the more tractable of the two remaining elements; if it were better known, the residual of the budget would serve as perhaps the best test of available estimates of the least tractable element, that is, freshwater transfers from the atmosphere.

To the previous recommendation, we add that transport of freshwater in solid form can and should be determined. It

has long been possible to measure ice velocities using various remote sensing techniques. Landy et al. (2018) demonstrated that other remote sensing techniques allow us to estimate sea ice thickness with useful precision. Taken together, these methods should support an improved estimate of net exchange of freshwater in solid form between Hudson Strait and the Baffin/Labrador currents feeding into the northern Labrador Sea. The same combination of tools should also be used to quantify circulation of solid freshwater within the major basins of the Marine Region, and in particular, to confirm (or reject) and quantify the long-assumed advection of freshwater by ice drifting from northwest to southeast across Hudson Bay.

Inter-basin circulation within the Greater Hudson Bay Marine Region remains poorly understood. Some Arctic water from the Baffin Current may penetrate westward in Hudson Strait as far as Foxe Basin, but this remains conjectural, and Jones and Anderson (1994) concluded that the waters in Foxe Basin are only marginally affected by this inflow. There is good evidence that Hudson Bay deep water is derived at least in part



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from 'overflow' of Foxe Basin deep water, but it is likely that it is further altered within its own basin by injections of river water entrained in sinking brine. In the same monograph, Jones and Anderson (1994) also concluded that salinity-alkalinity relationships in Hudson Bay's surface and intermediate waters can be explained by mixing discharge from the watershed with Arctic water flowing in through Hudson Strait (with additional freshwater supplied to the shallowest waters by sea ice melt). However, these mixing processes are not quantitatively well known. Source waters associated with inter-basin transfers can be investigated using the current implementation of the NEMO model, but it is likely that data moorings data will be necessary to confirm them.

Salinity and oxygen isotope profiles similar to those used by Granskog et al. (2009, 2011) to trace horizontal and vertical circulation of river and sea ice melt water have been collected on three ArcticNet expeditions (2005, 2007, 2010) as well as the BaySys expedition (2018); the latter data set also includes the first profiles recorded during the sea ice breakup period. Hopefully, when fully analyzed, they will provide spatial, seasonal and inter-annual context for horizontal and vertical circulation determined from the single-survey, single-season, south-half of Hudson Bay study that we relied on for this review.

Granskog et al. (2011) speculated that the amount of river water identified in Hudson Bay deep water depends on processes occurring over less than 10% of the bay—meaning intermittent freezing/opening of the pack, whether in local leads spread throughout the pack, or the larger circum-bay flaw lead around the coast of the Marine Region, or in the even larger polynyas, such as the northwest polynya. The process would be the same as has been demonstrated in

Foxe Basin, where the salinity of deep waters in the south is maintained by sinking brine rejected from ice formed polynyas in the north. Other than Defossez et al.'s (2008) study of the relationship between polynyas and Foxe Basin deep water, and Gunn's thesis (2014) describing spatio-temporal aspects of polynyas in Hudson Bay, there is little published literature relating to leads and polynyas in the region. Here, our focus is on physical oceanographic processes that affect the distribution of freshwater in the system, but the reader should be aware that such mid-winter open water areas are well known for their significance to many physical processes (e.g., downslope flow of cold saline waters; enhanced water column turbulence that supports vertical mixing, nutrient upwelling and sediment resuspension; heat and gas exchange with the atmosphere—including the greenhouse gas, carbon dioxide) and biological processes (e.g., seeding spring phytoplankton/zooplankton blooms; supporting marine life ranging from benthic populations to overwintering marine mammals and birds) (e.g., Morales Maqueda et al. 2004). Leads and polynyas in the Hudson Bay Marine Region deserve greater attention from the scientific community.

The direct effect of climate (air temperature and wind) on the sea ice regime of the region has been reported by various authors, as well as the sensitivity of the regime through teleconnections to major oceanic indices of global climate (e.g., the El Niño-Southern Oscillation, the North Atlantic Oscillation and others). To date, authors have considered links with sea ice conditions during either freeze-up or breakup, in particular linking air temperature to the timing of freeze-up, and temperature and wind together to the timing and progress of breakup. There can be no doubt that a warming climate will lead to continued lengthening of the ice-free season and to less sea-ice production and hence, meltwater production during the ice-covered season, with implications for physical and biological processes, and human activities, throughout the Hudson Bay Marine Region.

As to more particular ice-related phenomena like polynyas, there is little published information relating mid-winter open water frequency, extent and duration to winds or other causal mechanisms (e.g., mixing of warmer freshwater with cooler saline seawater, as in the Nelson estuary) to support sound prediction. We have little more than inferences from data recorded during open water season surveys and general knowledge of polynya functioning in the Arctic to guide us on the importance of these polynyas to the ecosystem—their effect on vertical mixing, deep water formation, nutrient upwelling and biological productivity. The BaySys spring survey of 2018 may provide us with better insight into the significance of the polynya in northwestern Hudson Bay, but we will need local, annual or longer term moorings data and observations

to truly understand their place in the physical and biological system that is the Greater Hudson Bay Marine Region.

More indirect impacts of climate on sea ice remain matters of speculation. In particular, changes to precipitation may affect sea ice formation through seasonal or annual variability of river discharge from the watershed. This is almost certainly the case in estuarine waters, where freshwater raises the freezing point of surface waters. The significance of this effect is of particular concern in James Bay and southeastern Hudson Bay, where river regulation has both increased the total discharge (into James Bay) and dramatically increased the winter discharge (Figure A4 in Appendix A). Based on observations of unusually thick ice, possibly freshwater in origin, encountered along the southern coast during the BaySys expedition in the spring of 2018, we suspect that water discharged from large rivers may affect ice thickness for tens or hundreds of miles downstream (Barber et al. In prep.). Whether the impact of multiyear variability in discharge affects ice formation far seaward of the landfast ice edge is unknown.

We have not commented in any detail on potential impacts of future additional regulation of rivers to optimize discharge for hydro-electric production, or on the likely effects of climate change, whether on ice formation or on river discharge from the watershed. These are the subject of BaySys, a major multi-institution study currently tasked with the overarching objectives of describing and discriminating between the two (BaySys 2015). Regulation of La Grande Rivière hydroelectric complex in Quebec, and the Nelson-Churchill system in the western provinces may be largely complete, but in the latter, at least, if changing climate leads to increased drought frequency, there is still potential for discharge reductions due to consumptive uses—mainly dry land irrigation. Moreover, the need to shift energy production away from carbon-based sources will surely lead to increasing pressure to develop the hydro-electric capacity of unregulated watersheds, including those flowing into southern James Bay and along the Ontario coast of Hudson Bay. Eventually, it is likely that Nunavut and Quebec will seek to develop the hydro-electric potential of rivers along the north-western and eastern coast of Hudson Bay. And if climate change leads to worsening, more persistent drought conditions in the United States mid-west and southwest, we should not discount eventual renewed pressure to build the vast GRAND Canal project which would convert James Bay into a vast lake from which water would be transferred through the Laurentian Great Lakes to irrigate agricultural land to the south (Kierans 1988; Stewart and Lockhart 2005). We are able to present here but a baseline of knowledge at a particular juncture in a region that will likely be altered dramatically in the next century.

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## APPENDIX A.

### Regulation of rivers in the watershed

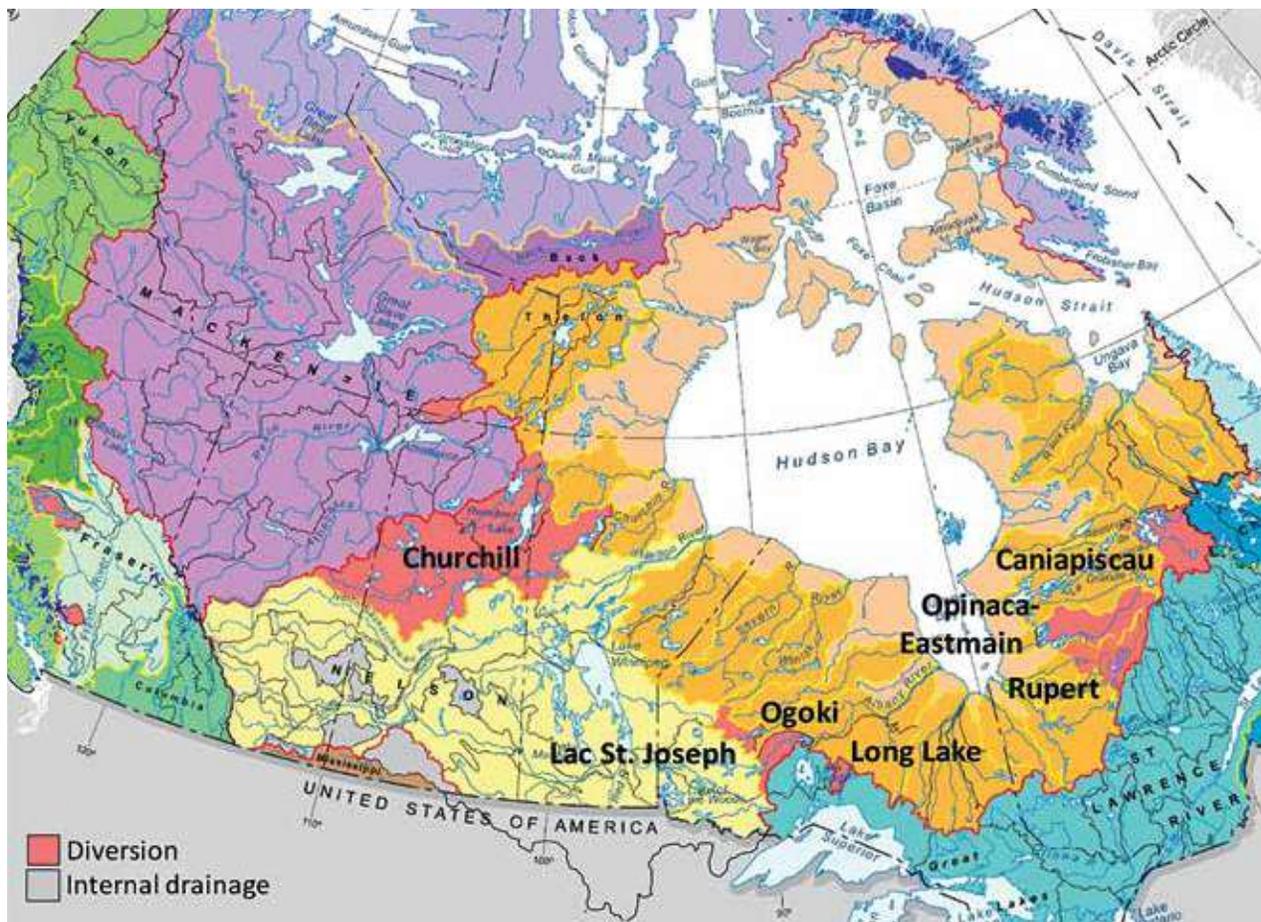
This appendix describes major features of river regulation in the watershed of the Hudson Bay System. Watersheds upstream of major diversions in the region are shown in Figure A1.

#### River diversions

Diversion discharges are not publicly reported on an annual basis for most diversions in the Hudson Bay Marine Region. For diversions within La Grande Rivière hydroelectric complex, we rely on average discharges reported in the first few years of operation, mostly in the 1980s. The Churchill River diversion is not continuously monitored at the point of diversion, so that we rely on model estimates (supplied by Manitoba Hydro) and inferences from flow records at downstream stations. Where

possible, we refer to discharge records retrieved from WSC's HYDAT database, available online. Gap-filled monthly records based on the observational data were supplied for use in this appendix by S. Déry (University of Northern British Columbia. Methods are reported by Déry et al., 2011). Additional discharge records for the Nelson River were supplied by Manitoba Hydro. For the most part, we compare discharges averaged over the 30-year period 1984–2013, approximately the same as used for oceanographic parameters discussed elsewhere in this report. However, flow in diversions out of the upper Albany watershed has not been monitored continuously by the WSC since the early 1990s; hence, we refer to an earlier averaging period for these records.

From these records, it can be estimated that about  $96 \text{ km}^3 \text{ y}^{-1}$  of water is redirected by diversions among major tributary rivers in the Greater Hudson Bay Marine Region Drainage Basin (HBMR Drainage Basin). Together, diversions in the HBMR



**FIGURE A1.** Major river diversion in the Hudson Bay Marine Region. Major rivers and watersheds are indicated in yellow-to-orange tones, with U.S. portion of the Nelson watershed outlined in black. Diverted watersheds are indicated in pink. Source: Natural Resources Canada.

Drainage Basin account for 60% of all diverted river discharge in Canada (Quinn, 2007).

Only two projects, the Long Lake and Ogoki Diversions (opened 1938 and 1943 respectively) direct water out of the HBMR Drainage Basin. Both are on tributaries of the upper Albany River, and redirect flow into the Laurentian Great Lakes basin to supplement flow through hydroelectric generating stations in the St. Laurence system. From 1973–1989, the most recent long period of gap-free records reported by the WSC, they carried 4.4 km<sup>3</sup> (s.d. = 0.8 km<sup>3</sup>) out of the Marine Region annually. The Ogoki River upstream of the Ogoki diversion has been monitored nearly continuously from 1972 to the present day (at WSC station 04GB004, including 82% of the drainage area above the diversion). Compared to the climate period 1984–2013 discussed elsewhere in this report, discharge from this contributing basin was 25% higher than from 1973–1989; it is likely that discharges diverted out of the HBMR Drainage Basin have been proportionately higher in the more recent period.

Two projects divert water from one region of the HBMR Drainage Basin to another. One of these, the Lac St. Joseph diversion, redirects about 2.4 km<sup>3</sup> y<sup>-1</sup> (s.d. = 0.7 km<sup>3</sup>) of water from Lac St. Joseph, a headwater lake in at the western extremity of the Albany River watershed, which drains into western James Bay, westward into the Nelson River basin and ultimately into southwestern Hudson Bay. The diversion was commissioned in 1935.

Together, the Long Lake, Ogoki and Lac St. Joseph diversions removed 6.8 km<sup>3</sup> y<sup>-1</sup> flow from the Albany River, reducing discharge near its mouth by an average of 18% over the period

1973–1989. The diverted discharge is roughly 2% of the total discharge into James Bay. The 4.4 km<sup>3</sup> y<sup>-1</sup> diverted into the St. Laurence watershed amounts to only about half of one percent of annual discharge into the Hudson Bay Marine Region.

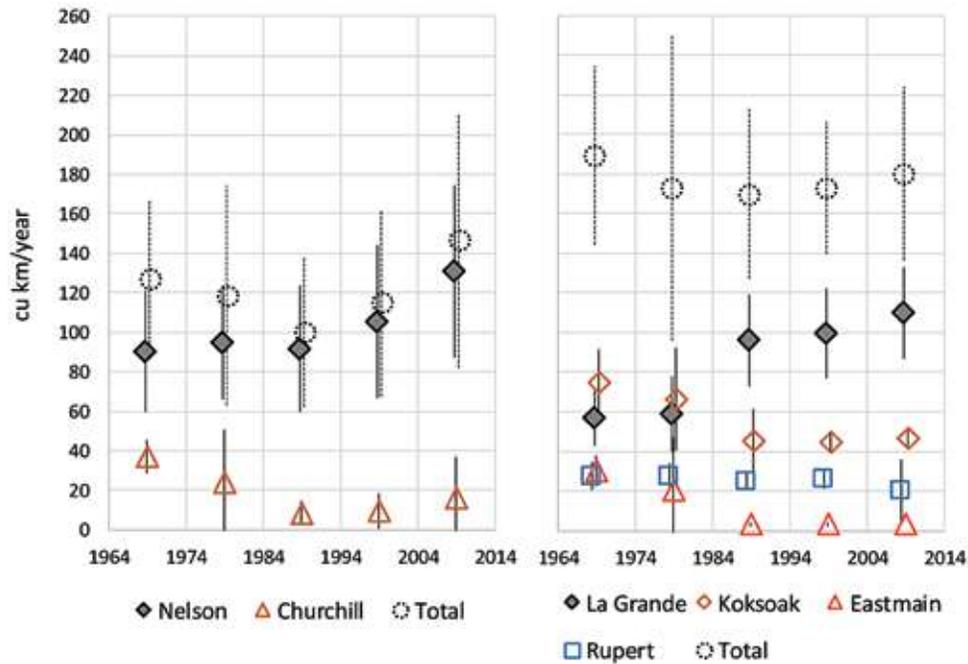
A more substantial project, the diversion of the upper Caniapiscau River redirects part of the discharge of the Koksoak River, which flows into Ungava Bay in Hudson Strait, via La Grande Rivière into James Bay (Table A1). Impoundment of the Caniapiscau reservoir began in 1981, and the diversion was fully operational by 1984. Roy and Messier (1989) reported that 24 km<sup>3</sup> y<sup>-1</sup> (about 32% of the flow of the Koksoak River near its mouth) were diverted from the Caniapiscau. This reported value is supported by WSC records at stations in the Koksoak watershed downstream of the diversion. By comparison of decadal mean flows before and after diversion, discharge near the mouth of the Koksoak River was immediately reduced by 26 km<sup>3</sup> y<sup>-1</sup>. On average, the total discharge into Hudson Strait was reduced by 14% and into James Bay, increased by 8%. The Caniapiscau diversion traverses a headwater tributary basin of the Great Whale River, where it captures an additional 1 km<sup>3</sup> y<sup>-1</sup> (SEBJ 1988) diverting this from southeastern Hudson Bay into James Bay.

The Caniapiscau is one of several diversions in Hydro Quebec's Grande Rivière hydroelectric complex. The others redirect flow entirely within the James Bay watershed. The Boyd-Sakami diversion, opened in 1980, redirected 26 km<sup>3</sup> y<sup>-1</sup> of from the Eastmain and Opinaca watersheds (Roy and Messier 1989) and beginning in 2009, a further 14 km<sup>3</sup> y<sup>-1</sup> from the Rupert basin (Hydro Quebec 2012) into the Robert Bourassa reservoir in the lower reaches of La Grande Rivière. These reported diversion flows, totalling 51 km<sup>3</sup> y<sup>-1</sup>, would have nearly

**TABLE A1.** Water diversions in the HBMR Drainage Basin. The tributary from which water was diverted is reported in Column 2. The value in parentheses in column 1 indicates the year when each diversion was opened. Sources are identified in the note below; note that in most cases, the discharge data rely on data recorded more than 20–30 years ago.

Diversion	Tributary river	Discharge (km <sup>3</sup> y <sup>-1</sup> )	Flow diverted from	Flow redirected to
Long Lake (1938)	Albany R.	1.2	James Bay	St. Laurence watershed
Ogoki (1943)	Albany R.	3.2	James Bay	
Lake St. Joseph (1935)	Albany R.	2.4	James Bay	Nelson R., SW. Hudson Bay
Churchill (1976)	Churchill R.	24	W. Hudson Bay	
Boyd-Sakami (1980)	Eastmain-Opinaca R.	26	James Bay	La Grande R., James Bay
Caniapiscau (1984)	Koksoak R.	24	Hudson Strait	
Caniapiscau (La Forge reach; 1984)	Grande R. de la Baleine	0.9	E. Hudson Bay	
Rupert (2009)	Rupert R.	14	James Bay	

Sources: Long Lake, Ogoki and Lake St. Joseph diversions: WSC records for 1973–1989. The International Joint Commission reported a mean flow of 5 km<sup>3</sup> y<sup>-1</sup> for the Long Lake and Ogoki diversions through the period 1943–1975 (IJC 1985). Churchill diversion: Manitoba Hydro (2015; discharge was computed by subtracting modeled, natural discharge from recorded, regulated discharge). This estimate matches the 24 km<sup>3</sup> y<sup>-1</sup> increase in recorded discharge along the diversion route, comparing the mean discharges reported by WSC for the Burntwood River at Thompson (i.e., the Churchill River diversion) for 1962–1971, immediately before construction began, and the first decade after diversion, 1978–1987. Caniapiscau and Boyd-Sakami diversions: Roy and Messier (1989). These reported values refer to the first few years of regulation; more recent data are not publicly available. Rupert diversion: Hydro Quebec (2012).



**FIGURE A2.** Decadal mean discharge of rivers in the Nelson-Churchill system and La Grande Rivière hydroelectric complex. Vertical bars indicate  $\pm 2$  standard deviations from the means. Prepared using data reported by Déry et al. 2016 (Table 3).

doubled the discharge at the mouth of La Grande Rivière compared to the prediversion discharge of  $56 \text{ km}^3 \text{ y}^{-1}$  (1964–1978 mean; WSC data). In fact, mean discharge near the mouth of La Grande Rivière was only  $96 \text{ km}^3 \text{ y}^{-1}$  in the first decade after diversion (Figure A2). That these diversions did not immediately double the discharge near the mouth of La Grande Rivière, is explained by a regional, presumably climatically-driven decrease in river discharge from the 1960s/70s through to the 1980s/90s. (See “Total” discharge in Figure A2). In fact, regional river discharge has not yet recovered fully to the levels recorded in the 1960s/70s. At a mean discharge of  $110 \text{ km}^3 \text{ y}^{-1}$  over the decade from 2004–2013 (Déry et al. 2016) the discharge of La Grande Rivière has still not realized the potential one may infer from diversion volumes published soon after those diversions were first commissioned.

The combined discharge of the Opinaca and Eastmain Rivers into James Bay averaged  $29 \text{ km}^3 \text{ y}^{-1}$  in the last decade before diversion (WSC records at station 03CC001, on the Eastmain below its confluence with the Opinaca). Over the first years after the diversion was commissioned, discharge at the mouth averaged about  $4 \text{ km}^3 \text{ y}^{-1}$  (Roy and Messier, 1989); that is, flow in the lower reaches was reduced by 85–90%. Through the last decade of the WSC record, the mean flow of Rupert River

was about  $28 \text{ km}^3 \text{ y}^{-1}$  into James Bay<sup>17</sup>. Diversion of  $14 \text{ km}^3 \text{ y}^{-1}$  has reduced flow in the lower reaches by about half.

Over the period 1978–2014, the Churchill River diversion redirected an average  $24 \text{ km}^3 \text{ y}^{-1}$  from the Churchill River into the lower Nelson River, both in the southwestern HBMR Drainage Basin (Manitoba Hydro 2015). On average, diverted Churchill River water accounted for 22% of the  $109 \text{ km}^3 \text{ y}^{-1}$  annual mean discharge at the mouth of the Nelson River over the period 1984–2013. Over the same period, the discharge at the mouth of the Churchill River averaged  $11 \text{ km}^3 \text{ y}^{-1}$ , or 69% less than without diversion<sup>18</sup>. However, these averages obscure both high inter-annual variability and long term trends in discharge in the Nelson-Churchill system. From 1984–2013, the decadal mean discharge of the system increased from 100 to  $147 \text{ km}^3 \text{ y}^{-1}$  (Figure A2). Annual mean discharges ranged from 69 to  $166 \text{ km}^3 \text{ y}^{-1}$  and 4 to  $39 \text{ km}^3 \text{ y}^{-1}$  in the Nelson and Churchill rivers respectively. The extremes were recorded in 2003 (low) and 2005 (high)—that is, within a three-year period.

<sup>17</sup> Discharge at the mouth of the Rupert River is estimated as the discharge recorded at a WSC station 110 km upstream of the mouth (03BC002) multiplied by the ratio of total to gauged watershed area. The most recent decade of continuous records at this station was from 1984–1993.

<sup>18</sup> Discharge at the mouth of the Churchill River is based on records at WSC stations upstream of the mouth (06FD001 and 06FD002) with gaps filled as described in Déry et al. (2011) multiplied by the ratio of total to gauged watershed area.

Discharge at Notigi dam along the diversion route is restricted by provincial licence (Province of Manitoba 1973 & 2017) so that in very wet years most flow from the upper Churchill watershed is released into the lower Churchill River. In 2005, for example, the annual discharge near the mouth of the Churchill River,  $39 \text{ km}^3 \text{ y}^{-1}$ , was equal to the 5<sup>th</sup> highest value in the prediversion record.

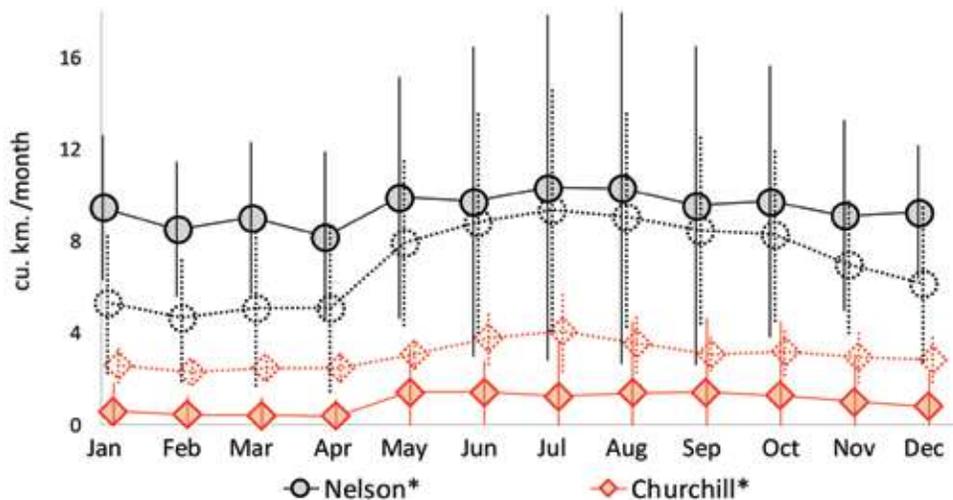
### Seasonal flow regimes

In addition to diversions, river discharge in the HBMR Drainage Basin is affected by several hundred large and small dams built to facilitate storage or diversion for downstream flood control, municipal water supply, agricultural irrigation, mine tailings management, transport, recreation and hydro-electric production. The largest reservoirs impounded by these dams are in the watersheds of the Nelson-Churchill system in western Canada, La Grande Rivière hydroelectric complex in Quebec, and the Albany and Moose Rivers in Ontario. (For locations of major dams, see Figure 9 in Theme I. Chapter iv.) Only a very few operate with sufficient active storage to alter seasonal or multi-year discharge patterns significantly.

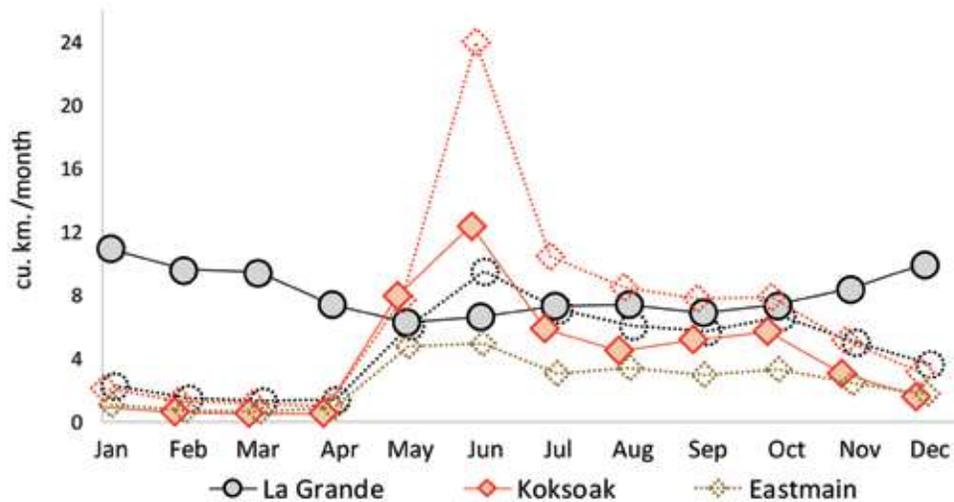
Dams in the upper Albany watershed function mainly to facilitate diversion. Although in most years the entire snowmelt runoff peak upstream of each dam is diverted, so too is most of the winter discharge. Near the mouth of the Albany River, only

about 10% of annual discharge occurs from December through March, compared to an average of 18% for four nearby, unregulated rivers, based on WSC records. Four reservoirs on the lower reaches of the Mattagami tributary of the Moose River have insufficient live storage to hold back flow for winter release. The most upstream reservoir on the Abitibi tributary (Twin Falls dam which controls the outflow of Lake Abitibi) does store spring peak flows for release in the winter (Metcalfé et al. 2005) but the total volume shifted is less than  $1 \text{ km}^3$ , so that winter flows of the Moose River near its mouth are not much altered (with only 13% of annual discharge occurring from December through March). Likewise, the annual flow regime near the mouth of the Koksoak River is not significantly altered by diversion of the upper Caniapiscau. Although the mean annual discharge is reduced by about a third, the annual pattern remains nival—May–June runoff continues to contribute an average of 40% of annual discharge, and December–March only about 8%.

The annual flow regimes of the Nelson River and La Grande Rivière are, however, much altered by storage of snowmelt runoff for release to meet higher hydroelectric demand in winter (Figures 20 and 21). Reservoir storage is used to store part of peak runoff developed by snowmelt and spring rains in the upper watersheds of the Nelson River in Manitoba and La Grande Rivière in Quebec, and (in both basins) in tributaries captured by diversion, for later release to supply energy to



**FIGURE A3.** Monthly discharges of the Nelson and Churchill rivers for the prediversion (1960–1971 mean; dotted lines) and postdiversion, augmented flow regimes (1984–2013 mean; solid lines) periods. Dashed lines indicate the range of monthly discharges over the respective periods. Sources: For the Nelson River, monthly discharges at Limestone dam, supplied by Manitoba Hydro, plus WSC records for three small tributaries downstream of the Nelson River station (WSC stations 05UH001, 05UG001, 05UH002). For the Churchill River, WSC records at the most downstream station (06FD001) plus one downstream tributary (06FD002). Where necessary, gaps in the hydrometric records were filled as per Déry et al. (2011)



**FIGURE A4.** Monthly discharge of La Grande Rivière, and of the Eastmain and Koksoak rivers, showing prediversion (1960–1971 mean; dotted lines) and postdiversion flow regimes (1984–2004 mean; solid lines) periods. Prediversion discharges of La Grande and Eastmain rivers derive from hydrometric records at stations near the mouths of each river (WSC stations 03CC001 and 03DF001 respectively). Pre- and postdiversion discharges of the Koksoak River were estimated as the sum of discharges of the Melezes and Caniapiscaw rivers above their confluence (WSC stations 03LF002 and 03KC004) multiplied by the ratio of the watershed area at the river mouth to the contributing area above the two stations. For the post diversion regime of La Grande Rivière, the monthly discharge record was reconstructed from percents of annual discharge as reported in Hernández-Henriquez (2011, Figure 6) and decadal mean discharges reported in Déry et al. (2016, Table 3). Monthly data were not available for determination of interannual variance as shown for the Churchill and Nelson rivers in Figure A3. Nor were annual postdiversion discharges available for the lower Eastmain River, but it is unlikely to have exceeded  $1 \text{ km}^3 \text{ y}^{-1}$  in any given month.

meet higher demand in the winter. This has flattened (in the case of the Nelson) or reversed (in La Grande Rivière) the annual hydrographs of the two rivers and increased winter discharge as a proportion of the annual discharge (Table A2).

The change in relative open-water and ice-cover seasonal discharge between pre- and postdevelopment conditions gives some indication of the scale of seasonal shifts in the two systems. In the decade before commissioning the first reservoirs in La Grande Rivière system, only 12% of annual discharge occurred from December through March; in the first three decades since, 31% occurred in the same months (Table A2). On average, April through November discharge was reduced, and December through March discharge increased by about  $25 \text{ km}^3 \text{ y}^{-1}$ . Here, we refer to the total river discharge in the system—of La Grande Rivière, Koksoak and Opinaca-Eastmain, so that we compare runoff from the same watershed before and after development. By inspection of the annual hydrographs in Figure A4, most of this shift was achieved by truncating the snowmelt peak of the Koksoak, and only a very

small part by reduced spring flows in La Grande Rivière itself. However, all flow transferred into the winter period passed into James Bay via the lower Grande. The increase due to regulation makes up 32% of the  $77 \text{ km}^3 \text{ y}^{-1}$  winter discharge into James Bay (December through March, averaged through 1984–2013) and 39% of the winter discharge into the eastern side alone. December through March discharge into Ungava Bay via the Koksoak River was not changed by regulation.

The effect of added storage in the Nelson system has been much less dramatic. Even in the decade before opening the Churchill River diversion and commissioning of the largest reservoirs in the Nelson system, December through March discharge accounted for one-quarter of the annual discharge from the two rivers. In part this may be due to the enormous natural storage in the watershed, which contains six of the 25 largest lakes in Canada. It may also reflect some earlier reservoir development. Reindeer Lake and Lac Seul have both been regulated since the 1940s, and the Gardiner and Grand Rapids dams on the Saskatchewan River were commissioned during

**TABLE A2.** Changes in seasonal and annual mean discharges of the Nelson-Churchill system and La Grande Rivière hydroelectric complex, comparing the regulated period, 1984–2013, with the pre-regulated period of record, 1960–1970. Units are km<sup>3</sup> y<sup>-1</sup>, with % of annual discharge shown in parentheses. Data sources are as described in Figures 20 and 21.

	Apr-Nov	Dec-Mar	Annual
<b>Nelson-Churchill system</b>			
1961–1970	89 (74%)	31 (26%)	120
1984–2013	86 (69%)	38 (31%)	124
Difference	–3	7	4
<b>Grande Rivière hydroelectric complex</b>			
1961–1970	142 (88%)	20 (12%)	162
1984–2013	117 (69%)	45 (31%)	162
Difference	–25	26	0

the 1960s, so that the earliest discharge records available for this calculation already reflect some artificial storage in the system.

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# THEME II ECOSYSTEMS AND WILDLIFE

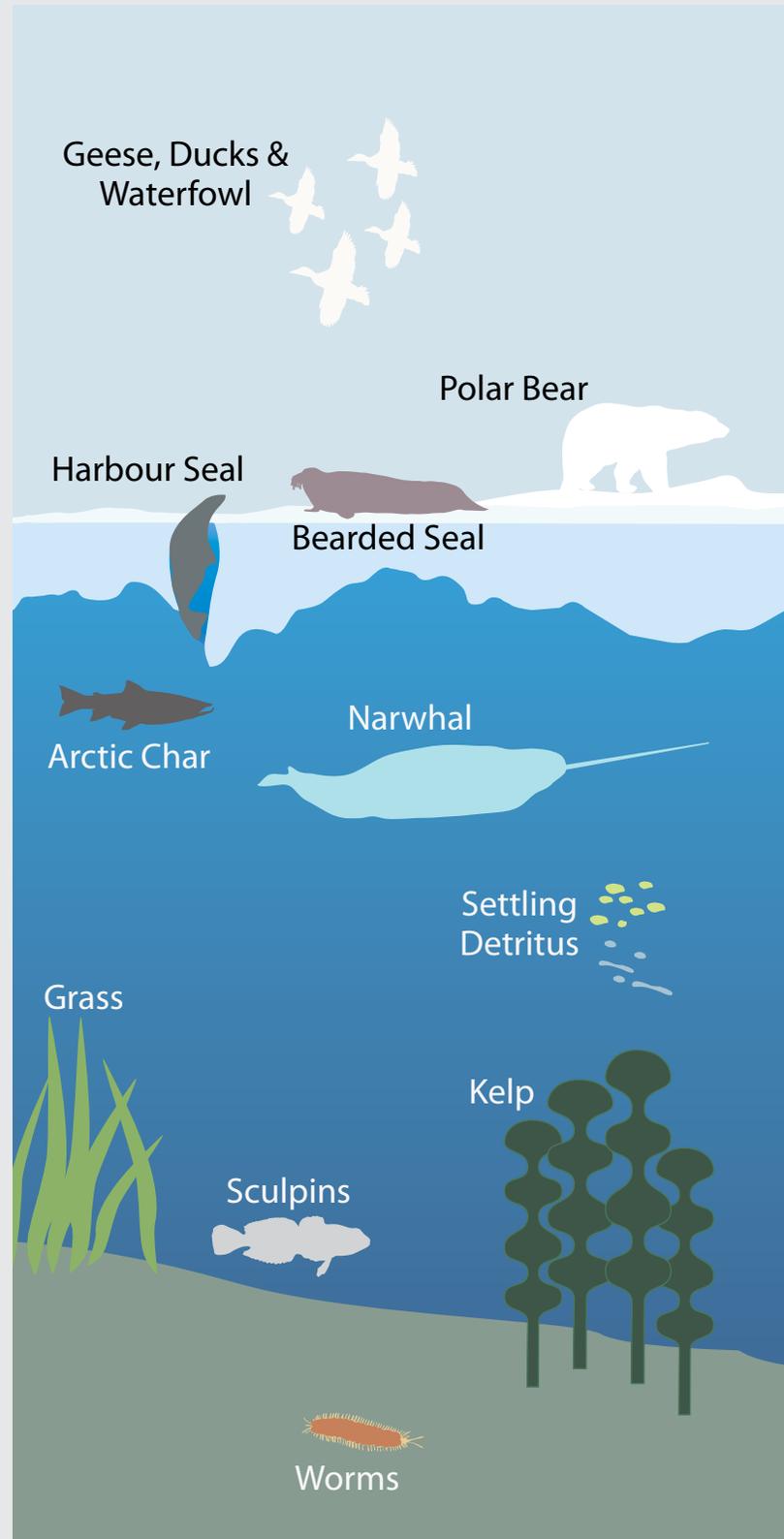
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The Greater Hudson Bay Marine Region encompasses a wide range of sub-Arctic and Arctic marine ecosystem types from coastal estuaries strongly influenced by river runoff and polynyas to open ocean environment. Wildlife *hotspots* are found throughout the Marine Region, supporting both high arctic and low latitude fish species (e.g., Arctic cod versus capelin), significant bird colonies (e.g., Coats Island and La Pérouse Bay), and populations of a number of marine mammals including beluga, bowhead whales, narwhal, and walrus. Subsistence harvesting of fish and wildlife for food and materials is interwoven into the lives and culture of Inuit and Cree who live along the coastlines of the Region. Impacts from a changing climate, including a longer open-water season, have been associated with observed ecosystem shifts (e.g., capelin replacing Arctic cod in the diet of thick-billed murres) and raise concerns about the future security of country foods. Regional approaches to management, with continuing monitoring programs and cooperation at high levels are essential to long-term success.

The following chapters describe the ecosystems, fish and wildlife in the Greater Hudson Bay Marine Region. We begin with the carbon system then go to the base of the food chain by providing an in-depth overview of the nutrient dynamics and biological productivity of the Marine Region, followed by benthic communities, fishes and fisheries, seabirds, and finally whales, seals, and walrus.



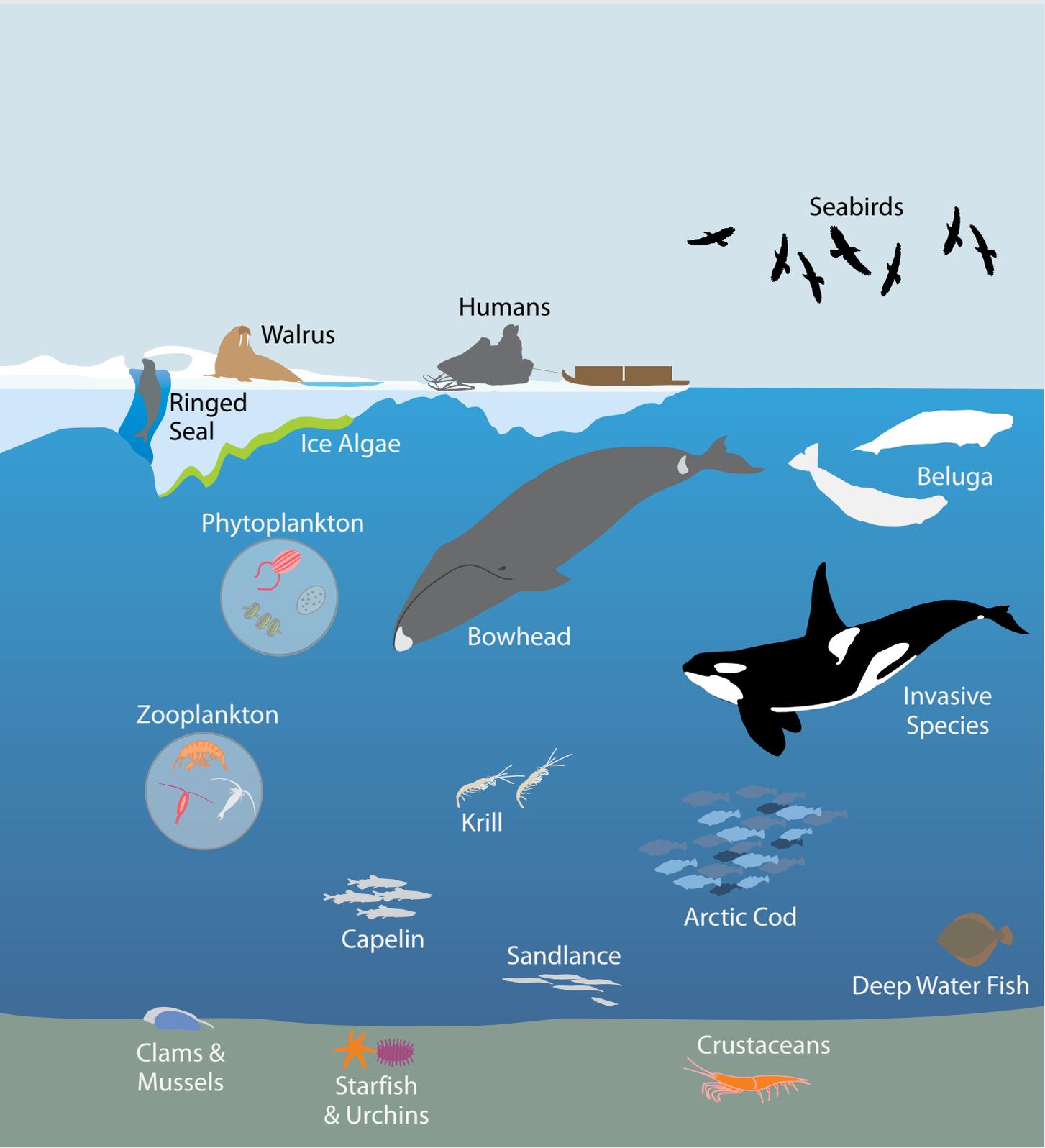


FIGURE MODIFIED BY P. KIMBER AND L. CANDLISH FROM SKETCHES CREATED BY H. HINAM





## II.i

# Carbon Cycling in the Greater Hudson Bay Marine System

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### Summary

The *carbon cycle* describes the exchanges of carbon among the lithosphere (solid outer layer of the earth), hydrosphere (oceans, seas, lakes, ponds, rivers and streams), atmosphere, and biosphere (living things) and the transformations within each sphere. Many physical, biological, and chemical processes drive the carbon cycle across space and time scales ranging from very coarse (e.g., global, thousands of years) to very fine (e.g., individual cell, plant, or community, months or days). Oceans play a major role in global carbon cycling, both as a temporary store for CO<sub>2</sub> emitted to the atmosphere and as a long-term sink for carbon buried in seafloor sediments. Oceans have slowed climate change by absorbing a portion of the CO<sub>2</sub> emitted by human activities. However, dissolved CO<sub>2</sub> forms a weak acid in oceans, which leads to ocean acidification that may threaten ecosystems and alter biogeochemical cycles. High-latitude, river-dominated systems like Hudson Bay are among the most vulnerable to carbon loading and associated ocean acidification, and this may be exacerbated by climate change and human activities in the Hudson Bay watershed. In this chapter, we provide an overview of our current understanding of the carbon cycle of Hudson Bay, the best studied of the water bodies in the Greater Hudson Bay Marine Region.

### Key Messages

- Rivers deliver large quantities of terrigenous organic carbon (OC) to Hudson Bay, very little of which is buried. Remineralization of terrigenous OC releases CO<sub>2</sub> in Hudson Bay waters, promoting the release of CO<sub>2</sub> to the atmosphere and ocean acidification.
- Parts of Hudson Bay are already experiencing some of the strongest ocean acidification among all arctic and subarctic areas, giving rise to conditions under which calcium carbonate would tend to dissolve. The effects on shell-forming organisms and other parts of the ecosystem need investigation.
- We have scarcely any knowledge of carbon cycling in Foxe Basin, James Bay, Hudson Strait, and Ungava Bay. The fate of the vast carbon stores associated with permafrost in the Hudson Bay Lowlands is a potential key driver of future change and largely unknown.

## 1. Introduction

Carbon is the essential building block for life on Earth. It is a key component of the greenhouse gases carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ), which regulate the Earth's climate, and it is involved in chemical reactions that control the pH (acidity/alkalinity) of the oceans.  $\text{CO}_2$  emissions from fossil fuel burning have changed the Earth's carbon balance, generating great concern about climate change and its effect on global ecosystems. By absorbing much of the gaseous  $\text{CO}_2$  emitted by humans, oceans have slowed climate change, however, dissolved  $\text{CO}_2$  forms a weak acid in oceans (carbonic acid or  $\text{H}_2\text{CO}_3$ ), which leads to ocean acidification – what has been called “the other  $\text{CO}_2$  problem” (Doney et al., 2009). Major scientific effort during

the past two decades has intensified focus on the role of the global ocean in removing  $\text{CO}_2$  from the atmosphere and the extent of ocean acidification resulting from that uptake. It has become apparent that individual ocean basins display large differences in their ability to absorb atmospheric  $\text{CO}_2$  and in their vulnerability to ocean acidification, but the drivers of this variability are not always well understood.

In the Greater Hudson Bay Marine Region, significant advances have been made in our understanding of carbon cycling during the last 15 years; mostly through oceanographic cruises conducted through programs such as ArcticNet and MERICA-nord (pour études des MERs Intérieures du Canada). These programs have employed advanced geophysical and geochemical techniques to study many independent



Z. KUZNYK

components of the marine carbon system in this region. Less work has been conducted in coastal areas (due to their limited accessibility by ship) and during the winter season. Thus our understanding is limited for these aspects of the Hudson Bay carbon cycle to mostly models and extrapolation.

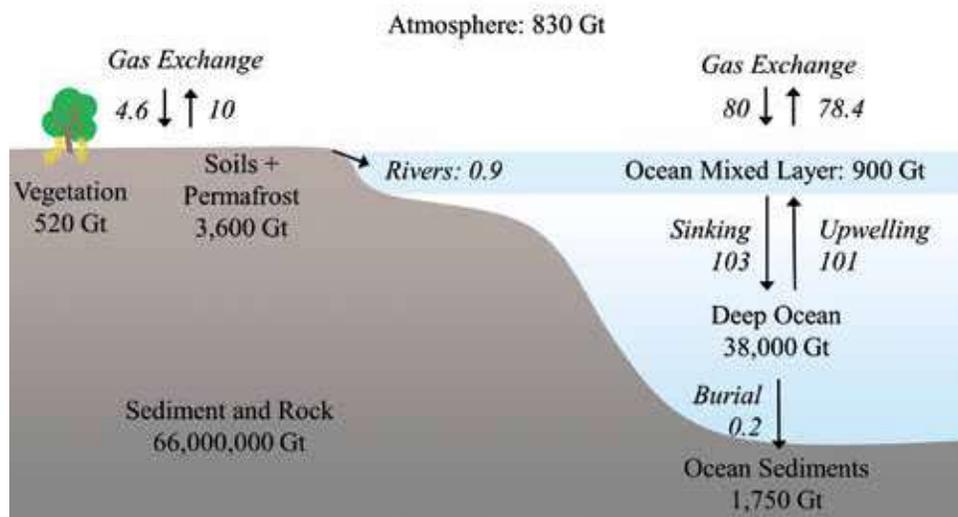
In this chapter, we first provide a general overview of the marine carbon cycle and the processes that influence carbon cycling in Hudson Bay. We focus on Hudson Bay because it is the largest single body of water within the Greater Hudson Bay Marine region ( $\sim 0.83 \times 10^6$  km<sup>2</sup>) and the best studied; with extremely limited carbon system measurements available from James Bay, Foxe Basin, or Ungava Bay. We summarize the current knowledge of discrete aspects of the Hudson Bay carbon system, and interpret this in the context of the overall carbon cycle and its implications for air-sea CO<sub>2</sub> exchange and ocean acidification in Hudson Bay. We then consider the sensitivities in the carbon cycle and project how they may respond to future change (e.g. climate change and human activity). Finally, we outline some key uncertainties that require further study.

## 2. Overview of the marine carbon cycle

Understanding how oceans process increasing CO<sub>2</sub> requires an in-depth understanding of aquatic biogeochemical cycles, which include dynamic exchanges of carbon between the atmosphere, hydrosphere, and lithosphere (Figure 1), and conversions between inorganic and organic carbon forms within the biosphere (Figure 2). In Figure 1 it can be seen that

the oceans receive carbon from rivers and exchange with the atmosphere, holding  $\sim 38,900$  gigatons (Gt) of carbon, which is  $\sim 45$  times that held by the atmosphere (830 Gt). Rapid increases in CO<sub>2</sub> emissions from fossil fuel burning, agriculture, deforestation, and industrial activities such as cement production have increased the atmospheric carbon (CO<sub>2</sub>) inventory from 589 Gt to  $\sim 830$  Gt over the past 250 years (Figure 1), with the atmospheric CO<sub>2</sub> inventory currently increasing by  $\sim 4$  Gt yr<sup>-1</sup>. Oceans have absorbed an estimated 39% ( $\sim 155$  Gt) of the total CO<sub>2</sub> released by industrial activity since 1750 ( $\sim 395$  Gt), making the CO<sub>2</sub> concentration in the oceans higher than at any time in the past 800,000 years (Luthi et al. 2008). The CO<sub>2</sub> added to the ocean has, so far, caused a 30% increase in surface ocean acidity (0.1 drop in pH; Caldeira and Wickett 2003), which is sufficient to stress CaCO<sub>3</sub>-shell producing organisms (Azevedo, De Schryver, Hendriks & Huijbregts, 2015), alter the speciation of trace metals (see section 2.4 in AMAP 2013), and influence the rates of important metabolic reactions (section 3.2 in AMAP 2013). The potential exists for ocean acidification to impact everything from microbial species abundance to commercial fisheries.

The main factors controlling carbon in high-latitude coastal oceans like Hudson Bay are sketched in Figure 2. Terrigenous organic carbon (OC<sub>terr</sub>) from rivers consists of dissolved (DOC) and particulate (POC) organic carbon. Some forms of DOC are light-sensitive (i.e. chromophoric dissolved organic matter – CDOM) and can thus break down to CO<sub>2</sub> when exposed to sunlight (Amon 2004), in a process termed “photo-remineralization”. Heterotrophic organisms such as microbes and zooplankton also “remineralize” organic carbon to CO<sub>2</sub>. Because it is associated with inorganic sediments, a



**FIGURE 1.** Simplified schematic of the global carbon cycle, inventories are in gigatons (Gt) of carbon, and fluxes are in gigatons of carbon per year. (Adapted from Ruddiman 2014 and IPCC 2013.)

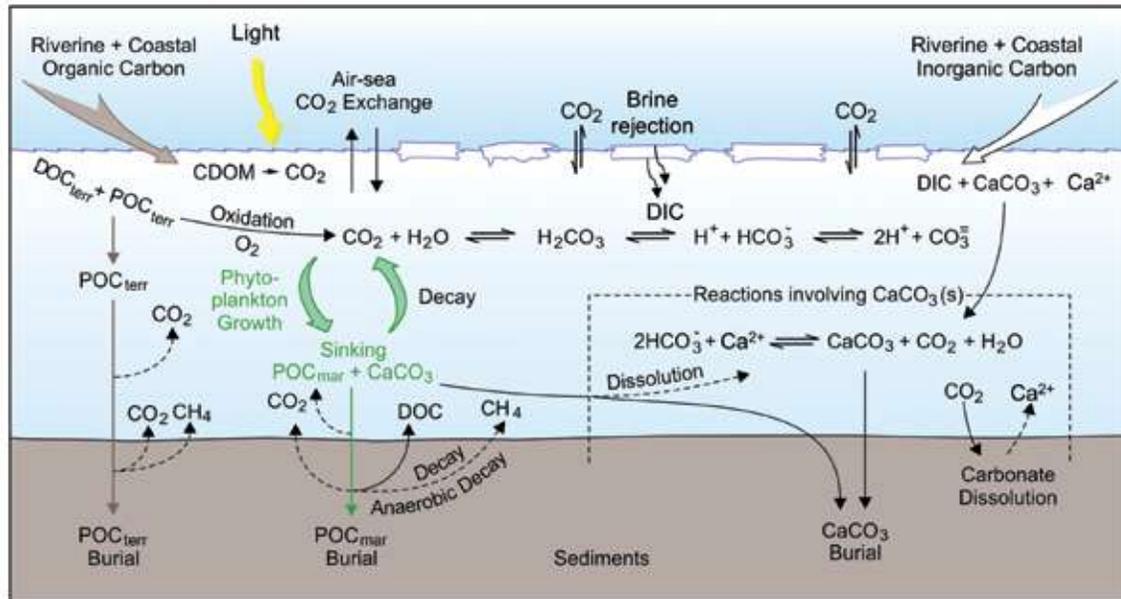


FIGURE 2. Key pathways for delivery, transport, modification, and removal of carbon in high-latitude coastal oceans.

large fraction of the POC<sub>terr</sub> discharged by rivers sinks down to the bottom (seabed), where it may be further remineralized to CO<sub>2</sub> if oxygen is present or methane (CH<sub>4</sub>) if sediments are anoxic (usually below the sediment surface in high-latitude coastal oceans). The remaining POC<sub>terr</sub> that is not remineralized is buried, which removes (sequesters) carbon from the atmosphere for thousands of years.

Particulate inorganic carbon (PIC; i.e. CaCO<sub>3</sub>) is derived from weathering of carbonate-bearing rocks in watersheds and delivered to the coastal ocean via rivers (Figure 2), or produced in the water column by shell-producing marine organisms (e.g. some phytoplankton, clams, mussels). CaCO<sub>3</sub> is produced through the reaction between bicarbonate (HCO<sub>3</sub><sup>-</sup>) and dissolved calcium ions (Ca<sup>2+</sup>), which produces CO<sub>2</sub> and water as by-products. Thus, CaCO<sub>3</sub> formation by marine organisms adds CO<sub>2</sub> to seawater that can contribute to the process of ocean acidification and CO<sub>2</sub> evasion to the atmosphere. Conversely, the addition of CO<sub>2</sub> to water promotes the dissolution of CaCO<sub>3</sub>, which is one of the main concerns about ocean acidification, as it stresses shell-producing organisms.

Dissolved CO<sub>2</sub> reacts with water to form carbonic acid (H<sub>2</sub>CO<sub>3</sub>), bicarbonate (HCO<sub>3</sub><sup>-</sup>) and carbonate (CO<sub>3</sub><sup>2-</sup>), as well as hydrogen ions (H<sup>+</sup>). Thus, the CO<sub>2</sub> produced during remineralization of OC<sub>terr</sub> increases the total dissolved inorganic carbon (DIC) of the water column, and the addition of H<sup>+</sup> ions lowers the pH (i.e., promotes ocean acidification). Some of the CO<sub>2</sub> produced during remineralization may evade to the atmosphere, if the waters are or become “super-saturated” in CO<sub>2</sub> with respect to the atmosphere. However, primary

producers (phytoplankton) growing in the sunlit water layers can consume CO<sub>2</sub> during photosynthesis, potentially making the waters “under-saturated”, and promoting the uptake of atmospheric CO<sub>2</sub>. Other processes such as water mass mixing, seasonal changes in temperature and salinity, depth or pressure, and the sea-ice formation/melt cycle can all also alter the CO<sub>2</sub> “saturation state” of surface waters. For a detailed summary of air-sea CO<sub>2</sub> exchange processes, the inorganic carbon system and how they relate to ocean acidification, see Box 1.

Several characteristics distinguish the carbon cycle in high-latitude coastal seas from that in other parts of the world’s oceans. Cold surface water has an enhanced capacity to absorb CO<sub>2</sub>, which means northern seas are especially vulnerable to increasing CO<sub>2</sub> concentrations in the atmosphere. The high CO<sub>2</sub> uptake means that these oceans are among the first to show signs of acidification (AMAP 2013).

Sea ice affects the carbon cycle in high-latitude seas in many different ways. Drifting sea ice can act as a transporter for particulate organic and inorganic matter together with sediments. Sea-ice cover impedes direct air-sea CO<sub>2</sub> exchange but despite this a complicated carbonate system within the ice can drive an exchange of CO<sub>2</sub> between sea ice and the atmosphere and affect underlying waters during ice growth and melt. The specific carbon cycling processes within sea ice are complicated and this remains an area of on-going research (e.g. Brown et al. 2015; Else et al. 2012; Geilfus et al. 2014; Rysgaard et al. 2011b; Vancoppenolle et al. 2013). Ice formation distills surface water, rejecting salts and other impurities, including carbon, into dense brines that transport dissolved and particulate forms

### Box 1. Primer on the seawater carbon system

By absorbing atmospheric carbon dioxide (CO<sub>2</sub>) and exchanging carbon with land, the oceans have an important role in dictating how global climate will respond to rising CO<sub>2</sub> concentrations. Below, we summarize the technical aspects of air-sea CO<sub>2</sub> exchange, the marine carbonate system and ocean acidification, and some of the ways these exchanges are influenced by rivers, sea ice, and vertical mixing.

#### Air-sea CO<sub>2</sub> flux

Air-sea CO<sub>2</sub> exchange is determined by the difference in CO<sub>2</sub> concentration (units mass volume<sup>-1</sup>) between the atmosphere and dissolved in surface seawater ([CO<sub>2</sub>]<sub>air</sub> and [CO<sub>2</sub>]<sub>sw</sub>, respectively). On a regional to global scale the flux can be represented using the following bulk formulation: [Liss and Slater 1974; Liss and Merlivat 1986; Wanninkhof et al. 2009]:

$$F_{CO_2} = k ([CO_2]_{sw} - \Lambda [CO_2]_{air}) \quad (1)$$

where F is the flux (units mass area<sup>-1</sup> time<sup>-1</sup>) (k; units length time<sup>-1</sup>) is the gas transfer velocity, and where *sw* and *air* represent the sea surface and atmosphere respectively. The product of the Ostwald solubility ( $\Lambda$ ) and [CO<sub>2</sub>]<sub>air</sub> is the equilibrium concentration of CO<sub>2</sub> in the surface water (i.e., [CO<sub>2</sub>]<sub>eq</sub>). The concentration difference (i.e.  $\Delta[CO_2] = [CO_2]_{sw} - [CO_2]_{eq}$ ), determines the potential magnitude and direction of the gas exchange. The transfer velocity determines the rate at which the exchange can occur. Equation (1) can be restated in terms of partial pressures (units of atmospheres) of CO<sub>2</sub>:

$$F_{CO_2} = k K_o (pCO_{2sw} - pCO_{2eq}) \quad (2)$$

through the application of Henry's Law, which states that the partial pressure of a gas overlying a liquid with which it is thermodynamic equilibrium is directly proportional to the concentration of that gas in the liquid. Therefore, for CO<sub>2</sub>, [CO<sub>2</sub>] = K<sub>o</sub>pCO<sub>2</sub>, where K<sub>o</sub> is Henry's Constant (units, mass volume<sup>-1</sup> atmospheres<sup>-1</sup>), which is also the solubility of the gas in seawater.

#### Seawater Carbonate System

When CO<sub>2</sub> is dissolved in seawater it reacts with seawater forming carbonate CO<sub>3</sub><sup>2-</sup> and bicarbonate HCO<sub>3</sub><sup>-</sup>, while releasing protons [H<sup>+</sup>]:



In the above H<sub>2</sub>CO<sub>3</sub> is carbonic acid and as mentioned, the reaction of CO<sub>2sw</sub> dissociation (termed carbonate equilibria) releases protons [H<sup>+</sup>] in seawater, which lowers pH (increases acidity). The result of the reaction is that most of the CO<sub>2</sub> introduced to the modern ocean is converted to bicarbonate. This is because the H<sup>+</sup> ions released during the reaction have a tendency to combine with [CO<sub>3</sub><sup>2-</sup>] to also produce [HCO<sub>3</sub><sup>-</sup>], thus slowing both a lowering of pH and accumulation of [CO<sub>3</sub><sup>2-</sup>].

The sum of the carbonate species: CO<sub>2</sub>, bicarbonate [HCO<sub>3</sub><sup>-</sup>], and carbonate [CO<sub>3</sub><sup>2-</sup>] is considered total dissolved inorganic carbon (DIC). Another important quantity is the total alkalinity of seawater (TA), which is mostly made up by:

$$TA \approx [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4] + [OH^-] - [H^+] \quad (4)$$

Alkalinity refers to acid neutralizing capacity (buffering capacity) of water, and in Equation (4) TA represents the buffering capacity of seawater in terms of dissolved CO<sub>2</sub> (or carbonic acid) [Zeebe and Wolf-Gladrow 2001]. The addition of DIC to seawater will decrease pH, however the consequence of high TA in seawater allows the seawater to resist the decrease in pH more effectively than in freshwater (AMAP 2013). Hence the pH in seawater is typically higher (less acidic) than in freshwater despite having higher concentrations of DIC (AMAP 2013).

The mineral calcium carbonate (CaCO<sub>3</sub>) generally forms in water super-saturated in calcium (Ca<sup>2+</sup>) and carbonate [CO<sub>3</sub><sup>2-</sup>]. An impact of seawater acidification is to reduce [CO<sub>3</sub><sup>2-</sup>] and therefore increase the solubility of CaCO<sub>3</sub> minerals, allowing the mineral to dissolve. The tendency for the mineral to resist dissolution is represented by the saturation state ( $\Omega$ ), which is proportional to the product of concentrations of calcium ion [Ca<sup>2+</sup>] and [CO<sub>3</sub><sup>2-</sup>], and in general, the carbonate mineral will be vulnerable to dissolution in waters where  $\Omega$  is less than 1, and stable when greater than 1 (AMAP 2013). There are many calcium carbonate minerals, and the two most common biologically important forms in the ocean are aragonite and calcite. The saturation state for these minerals is denoted with the subscript AR and Ca, i.e.,  $\Omega_{AR}$  and  $\Omega_{Ca}$ , with aragonite being slightly more soluble at a given pH than calcite due to its mineral structure. Hence, together a lowering pH and  $\Omega_{AR \text{ and } Ca}$  contribute to "ocean acidification" (OA).

of carbon down and away from the surface and in some cases to deep waters (Figure 2; Rysgaard et al. 2011a). The water-mass sinking caused by sea-ice formation can literally ‘pump’ carbon out of the surface layer. It is thought that the release of CO<sub>2</sub> into sea ice brines resulting from the production of carbonate minerals (ikaite) can augment this carbon transport process (Rysgaard et al. 2013). In the absence of deep mixing or bottom water formation, the DIC in deep waters can remain isolated from the surface layer and atmosphere for decades (Hudson Bay) to hundreds of years (Arctic Ocean).

High-latitude coastal seas are also uniquely sensitive to changes occurring in northern watersheds because of their long coastlines, relatively large shelf seas, and large river inflows. Coastal erosion is an important source of terrigenous sediment and carbon to many northern coastal areas, particularly those with ice-rich coastal bluffs that are rapidly eroding due to permafrost thaw, sea-level rise and increasing storm-driven wave activity (Couture et al. 2018; Lantuit et al. 2018; Vonk et al. 2015). Both the Arctic Ocean and Hudson Bay receive more river-water input per unit area than any other major ocean area. River inflow delivers organic carbon in dissolved and particulate forms as well as particulate inorganic carbon from the weathering of rocks. CDOM carried by river water can alter the clarity of coastal waters, affecting water temperatures and light availability for primary producers. Fluvial sediment delivery can also affect the clarity of coastal waters while providing sediment that supports carbon burial on the seafloor. Rivers deliver essential nutrients needed by phytoplankton and



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other primary producers. In estuarine settings, river plumes can entrain subsurface waters, bringing carbon and nutrients associated with deep waters up to the surface (Kuzyk et al. 2010). River water has a lower total alkalinity than seawater, thus reducing the buffering capacity of coastal marine waters and making them more vulnerable to ocean acidification (AMAP 2013). In terms of physical effects, river water is an important source of freshwater that will ‘float’ on top of seawater and thus promote stratification (layering).

Water column stability, induced by the addition of river water and other freshwater sources such as sea-ice melt, inhibits mixing between the surface and deeper waters. Stratification effectively isolates subsurface waters from the atmosphere, preventing the release of CO<sub>2</sub> produced in deeper waters to the atmosphere. Both high pCO<sub>2</sub> and low seawater pH can develop in subsurface waters as a result of this isolation. Stratification also affects primary production, on the one hand allowing autotrophs to remain in the photic zone and on the other hand setting a limit to the biomass they can produce by preventing the upwelling of nutrient-rich water to the surface. In high-latitude coastal ocean areas, stratification experiences a seasonal cycle. In spring and summer, stratification is enhanced by freshwater delivery from sea-ice melt and river water, and by surface warming. In the fall and winter, vertical mixing is enhanced surface cooling and strong winds. In winter, the surface mixed layer is further deepened by the sinking of dense brines produced during sea-ice formation.

Figure 2 emphasizes that the total inventories and exchanges of carbon between the various compartments of a high-latitude coastal ocean system are dynamic and driven by a combination of physical, chemical and biological processes, all of which may vary regionally in space, and seasonally, annually or on longer time scales. In addition, the Arctic is showing many signs of climate-related change, including warming, reduced sea-ice cover (Kwok et al. 2009; Stroeve and Serreze



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2008) and changing freshwater flux from rivers, which may enhance or mitigate rates of air-sea  $\text{CO}_2$  flux and acidification.

### 3. Recent progress on understanding the Hudson Bay carbon system

Recent advances in understanding the Hudson Bay carbon system have been made in the following areas: 3.1) particulate organic carbon pathways as inferred from sedimentary proxies; 3.2) patterns and rates of marine primary production; 3.3) dissolved organic carbon pathways as inferred from CDOM; 3.4) gaseous  $\text{CO}_2$  and exchanges with the atmosphere; and 3.5) dissolved inorganic carbon distribution and calcium carbonate saturation state.

#### 3.1. Particulate organic carbon pathways as inferred from sedimentary proxies

Hudson Bay receives particulate organic carbon (POC) partly by conversion of  $\text{CO}_2$  to organic carbon (OC) through marine primary production and partly by importing OC from land via rivers or coastal erosion. The amount of terrigenous POC ( $\text{POC}_{\text{terr}}$ ) imported to the bay is small when compared to marine productivity, but because much of marine OC is recycled back to DIC, the  $\text{POC}_{\text{terr}}$  becomes an important component of the OC accumulating in sediments (Kuzyk et al. 2009). On areal basis, the amount of  $\text{POC}_{\text{terr}}$  impinging on Hudson Bay is comparable to the amount estimated for the Arctic Ocean ( $0.6 \text{ g m}^{-2}$  compared to  $1.1 \text{ g m}^{-2}$ ; Stein and Macdonald 2004), with the result that bottom sediments from both areas are noticeably “terrigenous” in their organic matter. However, not all of the  $\text{POC}_{\text{terr}}$  survives transport in the ocean. Vonk et al. (2012) estimate that over the Siberian Shelves as much as two-thirds of  $\text{POC}_{\text{terr}}$  introduced to the marine system is oxidized and escapes to the atmosphere as  $\text{CO}_2$ . The question of how much  $\text{OC}_{\text{terr}}$  becomes metabolized is crucial to understanding the role of Hudson Bay in the global atmospheric cycle: is the Bay taking up atmospheric  $\text{CO}_2$  (autotrophic) or releasing it (heterotrophic)?

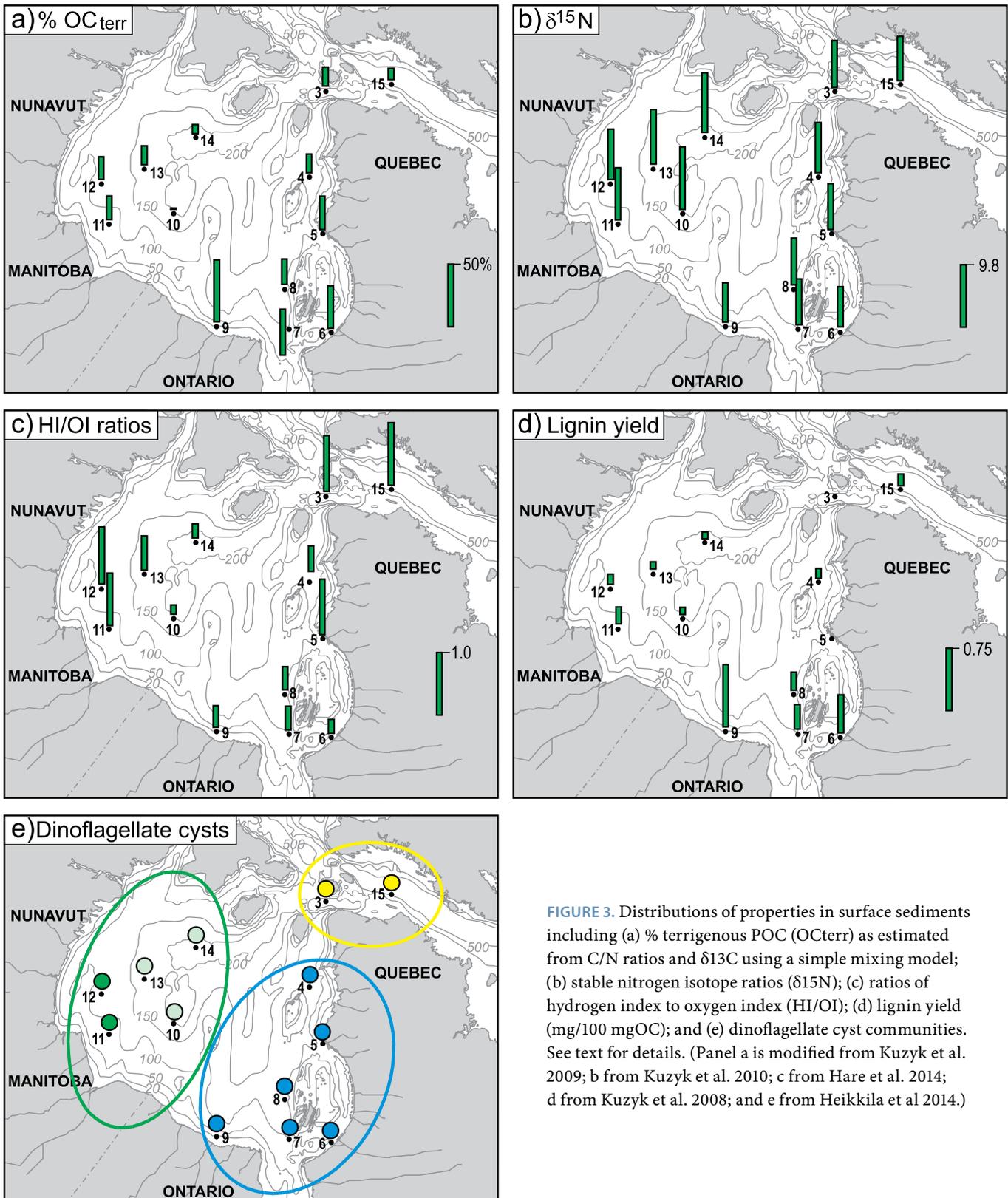
To understand how the OC cycle in Hudson Bay contributes to the Bay’s overall carbon budget, including the deposition of OC, the net removal of  $\text{CO}_2$  through exported primary production (autotrophy), and the addition of  $\text{CO}_2$  through OC metabolism, it is essential to distinguish between terrigenous and marine OC. Organic biomarkers have become the method of choice for tackling this problem (see Box 2). Many of these techniques were applied in Hudson Bay for the first time using marine sediment and suspended particulate matter samples collected during ArcticNet missions.

#### *Inferences from bulk measurements*

Organic carbon (OC) carried by the numerous Hudson Bay rivers is generally nitrogen (N) poor (high C/N) and isotopically depleted (low  $\delta^{13}\text{C}$ ) compared to marine OC, and is buried in sediments with little or no modification. This permits the application of simple mixing models to estimate the relative amounts of  $\text{POC}_{\text{terr}}$  and  $\text{POC}_{\text{mar}}$  in Hudson Bay sediments (Figure 3a). As can be seen, the proportion of  $\text{OC}_{\text{terr}} : \text{OC}_{\text{mar}}$  in sediments decreases with distance away from shore, and from south to north, suggesting that  $\text{OC}_{\text{terr}}$  is primarily deposited close to major rivers (Churchill/Nelson, James Bay rivers) in the southern part of the Bay.

Unlike the C/N and  $\delta^{13}\text{C}$  proxies,  $\delta^{15}\text{N}$  distributions cannot be viewed as simple mixing between terrigenous organic matter ( $\text{OM}_{\text{terr}}$ ) and marine organic matter ( $\text{OM}_{\text{mar}}$ ) (Figure 3b). This is because the  $\delta^{15}\text{N}$  composition of particulate organic matter (POM) may be affected by fractionation processes that occur between trophic levels within food webs, including by depletion of dissolved inorganic nitrogen (DIN) concentration in the water as algae blooms progress, and through other processes associated with decay, including denitrification (cf., Codispoti et al. 2005). The distribution of  $\delta^{15}\text{N}$  seen in Hudson Bay surface sediments (Figure 3b) indicates upwelling of deep water replete in DIN in the coastal zone, likely driven partially by estuarine circulation, while DIN-depletion in offshore surface waters is likely due to stratification by freshwater (Kuzyk et al. 2010). The river water itself is but a minor contributor to DIN for Hudson Bay although organic forms of nitrogen are supplied with terrigenous dissolved organic matter (DOM) at an average carbon:nitrogen (atomic) ratio of about 29:1 (Kuzyk unpublished data). It is noteworthy that the low  $\delta^{15}\text{N}$  values seen in sediments near Hudson Strait (Figure 3b; Stn 15) indicate primary production sustained by high DIN supply, probably produced by a combination of upwelling and high-light penetration levels due to relatively clear water. This pattern is consistent with previous findings of increasing export production in northern Hudson Bay, near Hudson Strait (Lapoussi re et al. 2013).

Rock Eval pyrolysis (see Box 2) results show that Hudson Bay surface sediments generally have HI/OI  $\leq 1$  (Figure 3c), indicating the predominance of highly degraded material compared to other Arctic shelves (Hare et al. 2014). This may be due to sediment reworking through resuspension in shallow, coastal regions and eventual transport into the deeper basins, as this repeatedly exposes the organic matter to oxygenated bottom water. Manganese surface enrichments in the interior basin sediments (Kuzyk et al. 2011) indicate low in-situ metabolic rates (e.g., see Macdonald and Gobeil 2012), implying that much of the organic matter likely arrives at its final destination in a highly degraded state.



**FIGURE 3.** Distributions of properties in surface sediments including (a) % terrigenous POC ( $\text{OC}_{\text{terr}}$ ) as estimated from C/N ratios and  $\delta^{13}\text{C}$  using a simple mixing model; (b) stable nitrogen isotope ratios ( $\delta^{15}\text{N}$ ); (c) ratios of hydrogen index to oxygen index (HI/OI); (d) lignin yield (mg/100 mgOC); and (e) dinoflagellate cyst communities. See text for details. (Panel a is modified from Kuzyk et al. 2009; b from Kuzyk et al. 2010; c from Hare et al. 2014; d from Kuzyk et al. 2008; and e from Heikkila et al 2014.)

### ***Inferences from biomarkers and other bio-proxies***

Like the bulk proxies discussed above, lignin phenol (see Box 2) yields determined by CuO oxidation of Hudson Bay sediments reveal coastal sediments containing relatively high amounts of lignin compared to interior basin sediments (Kuzyk et al. 2008; Figure 3d). At this level of interpretation, the lignin data confirm the transport of  $OM_{terr}$  to the interior as inferred from bulk proxies. Perhaps of greater significance, the lignin compositional patterns in the sediments reveal regional sources, with woody gymnosperm compounds having greater prevalence in the south and non-woody angiosperm compounds having greater prevalence in the north, consistent with dominance of boreal forests in the southern regions and tundra in the north (Godin et al. 2017). Although the database is small, the sediment-core lignin data fit the general pattern of a coastal anti-cyclonic current transporting fine sediments and  $OM_{terr}$  around the margin of the Bay. A relatively small leakage of this particulate transport into the Bay's interior must occur, but this likely consists of older material, such that the basin sediments reflect a different history than do the coastal sediments. Coastal zones very near river mouths generally trap much of the terrigenous plant debris, with the exception of the southwest inner shelf, where such debris may be found at distances >30 km offshore (Kuzyk et al. 2008).

Recent counting and identification of dinoflagellate cysts (see Box 2) in sediment and sediment trap samples from Hudson Bay provide insight on marine carbon sources (Heikkilä et al. 2016, 2014). These results have revealed cyst species compositional patterns that reflect regional differences in productivity. There is an eastern domain characterized by strong freshwater stratification and an ample supply of nutrients due to estuarine entrainment, which favours a spring-blooming autotroph (*P. dalei*), an autotrophic species. The central and western regions have longer periods of sea-ice cover and a limited supply of nutrients (oligotrophy), which favours both autotrophic and heterotrophic cysts (Heikkilä et al. 2014; Figure 3e). Hudson Strait, in contrast, is well supplied with nutrients and light, provides a good setting for diatom production. This ready source of food then favours heterotrophic cysts (Heikkilä et al. 2014; Figure 3e). Interestingly, sea ice appears to play a negligible role in controlling primary production as reflected by cyst assemblages. Rather, the two domains evident in Hudson Bay and the Hudson Strait are controlled by nutrient availability, which itself is controlled by stratification.

### **3.2. Marine primary production patterns and rates**

Hudson Bay has long been considered an oligotrophic system (an environment that offers very low levels of nutrients) (cf., Dunbar 1993). Studies completed during the last decade support this conclusion, although the main spring

phytoplankton bloom has yet to be assessed (see Theme II, Chapter ii). There is variance of about one order of magnitude in the estimates of annual primary production in Hudson Bay from the available work (10-100 gC m<sup>-2</sup> yr<sup>-1</sup>), but the bulk of the evidence supports the lower end of the range. Both remote sensing studies (Bélanger et al. 2013) and field observations of surface chlorophyll *a* distribution (Anderson and Roff 1980; Drinkwater and Jones 1987; Harvey et al. 1997) and primary production (Ferland et al. 2011) show Hudson Bay to be much less productive than neighbouring Hudson Strait.

Within Hudson Bay, in situ observations of spatial patterns of phytoplankton biomass and primary production generally agree with the inferences from sediment proxy studies. There is high spatial heterogeneity but a general decline in productivity and biomass from the coast to the interior, and from northeast to southwest. Somewhat disparate results were generated by a 3D physical-biogeochemical model (Sibert et al., 2011), which showed enhanced primary production throughout the NW half of Hudson Bay, including part of the central offshore sector, with no indication of elevated primary production inshore. The relatively low productivity simulated by the model in the nearshore zone was attributed to light limitation due to particulate and dissolved organic matter loadings from rivers (Sibert et al. 2011). The models provide the advantage of vertically-integrated primary production estimates, which take into account the deep chlorophyll maximum that is widespread through Hudson Bay (Ferland et al. 2011; Granskog et al. 2007), whereas satellite-based estimates and *in-situ* chlorophyll data require the extrapolation of surface values and may not fully capture the euphotic (or sunlight) zone as a whole. To date, field observations fail to capture under-ice productivity or the spring bloom, which may account for a significant portion of the annual primary production. It has been suggested that Hudson Bay probably has a long period for ice algal growth because of favourable spring light conditions (Cota et al. 1991) and similarly may host productive benthic vascular plant or algae communities, but measurements of these types of primary production remain scarce.

### **3.3. Dissolved organic carbon sources and pathways**

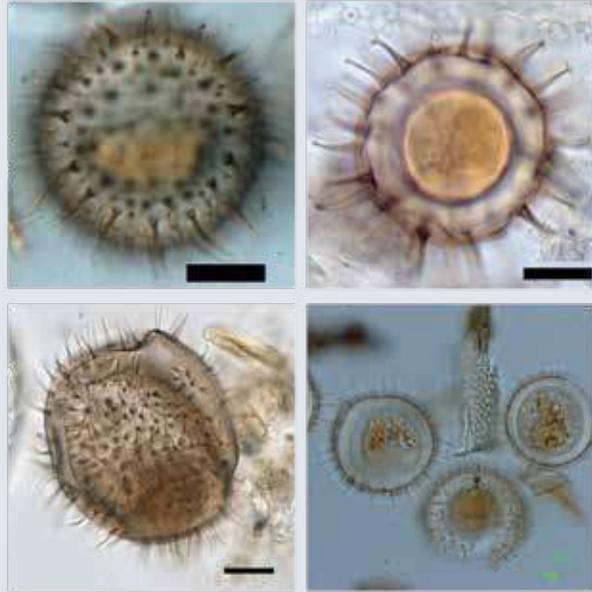
Similar to POC, Hudson Bay receives a large amount of dissolved organic carbon (DOC) from rivers and coastal erosion, as well as by autochthonous processes (marine primary production). In the Arctic Ocean, surface waters have higher concentrations of DOC than other ocean basins because of the large contribution of terrigenous DOC from Arctic rivers (Benner et al. 2005). Similarly, Hudson Bay surface waters also contain relatively high DOC concentrations (median 10<sup>9</sup> mmol L<sup>-1</sup>), which accumulates in coastal waters as they circulate counter-clockwise around the bay (Mundy et al. 2010).

**Box 2. Primer on organic carbon proxies (biomarkers)**

Biomarkers have been used widely in ocean settings to determine sources of OC including marine ice algae, marine phytoplankton, terrigenous carbon from land plants, ancient petrogenic carbon from weathering of rocks, carbon from forest fires (Belt et al. 2007; Dittmar and Kattner 2003; Eglinton and Repeta 2006; Hörner et al. 2018; Meyers 1997; Peters and Moldowan 1993; R. Stein and Macdonald 2004; Xiao et al. 2013; Yunker and Macdonald 1995). Generally, biomarkers can be applied as *bulk* measurements (e.g., C/N,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ; Rock Eval pyrolysis), which provide quantitative information on the overall composition of an OC sample, or *biomarkers and other bio-proxies*, such as organic compounds (n-alkanes, PAHs, sterols, lignin phenols) or visual microscopic evidence (macerals, pollen, cysts), which provide quantitative or qualitative evidence of specific sources (e.g., woody material, bacterial products, specific types of algae).

Bulk measures have a long history of application to the determination of the fractional contribution of terrigenous and marine OC to samples from global and arctic marine settings. Rock Eval pyrolysis, which is a technique borrowed from geology, involves gradually raising the temperature of a given sample and measuring the sequential release of organic compounds and provides confirmation and amplification of the picture derived from the other bulk proxies. As organic compounds weather and age, they tend to lose hydrogen, gain oxygen, and accumulate recalcitrant organic matter/carbon which is indicated by greater fractions of residual carbon surviving high temperatures. The status of degradation of an OM sample is, therefore, frequently assessed based on the relative amounts of H compared to O as indicated by the hydrogen index (HI) divided by the oxygen index (OI) in a given sample (see Hare et al. 2014, and references therein).

Specific biomarker compounds, which generally comprise but a small component of the total OC, have been less commonly used, but both bulk measures and individual biomarkers are beginning to be widely applied in the Arctic (see Stein and Macdonald 2004 for a review of the application of these markers in the Arctic Ocean). Among the biomarkers, lignin phenols have proven especially useful for understanding carbon cycling in coastal zones that receive large inputs of organic matter from land. Lignin derives from vascular plants growing on land but has essentially no marine sources (Hedges and Mann 1979). Because these compounds are preserved reasonably well in marine sediments, they have the potential to indicate transport pathways and the history of terrestrial inputs. Furthermore, different lignin compounds are produced



in different land plant types (i.e., angiosperms vs. gymnosperms) and tissues (woody vs. non-woody), enabling us to estimate the characteristics and in some cases location, of the drainage basin in which they were produced. This has a special relevance to Hudson Bay, given that its river basins span a wide range of plant ecosystems, including Arctic domains above the tree line, and boreal settings below the treeline (Godin et al. 2017; Kuzyk et al. 2008).

One of the microscopic techniques applied to the study of organic carbon deposition in Arctic seas is identification and enumeration of dinoflagellate cysts in marine sediments. Dinoflagellates are single-celled planktonic organisms that play important roles in the ocean, both as primary producers (fixing carbon) and as grazers. Like most plankton, dinoflagellates do not preserve well in sediments; however many species produce an organic, highly resistant, resting-stage cyst that does preserve, and whose species can be identified through microscopy.

DOC concentrations in ocean waters depend not only on inputs, but also on photo-mineralization, which occurs near the ocean surface (Timko et al. 2015), and on bacterial remineralization (Catalá et al. 2015; Gueguen et al. 2014; Walker et al. 2016). Marine DOC is highly labile (Holding et al. 2017; Retelletti Brogi et al. 2018) and thus rapidly remineralized in the ocean (within hours to days; Hansell 2013). Traditionally,  $\text{DOC}_{\text{terr}}$  was believed to be much more recalcitrant in the ocean, because it represents very highly degraded vascular plant materials (Ertel et al. 1986; Hedges et al. 1994; Ittekkot 1988), with remineralization occurring over months-years in the surface ocean, and up to 40,000 years in the deep ocean (Hansell 2013). However, all indications (e.g., from bulk proxy data and biomarkers) are that  $\text{DOC}_{\text{terr}}$  is significantly degraded in the ocean, leaving behind a residual that makes up at most a few percent of the total DOM in seawater (Hernes and Benner 2002). Thus, although DOC in the ocean is, on average, thousands of years old, there is a portion of the DOC (including  $\text{DOC}_{\text{terr}}$ ) that cycles on much shorter time scales (days to decades) (Druffel et al. 2017).

Recent biomarker studies of the DOC supplied by the six largest Arctic rivers (none discharging to Hudson Bay) showed that  $\text{DOC}_{\text{terr}}$  concentrations and compositions varied over seasonal cycles and from river to river (Amon et al. 2012). The first biomarker study of DOC from Hudson Bay rivers examined samples collected near the mouths of 17 rivers, which incorporated basins to the south with no permafrost, basins in the north with continuous permafrost, and four different ecozones (Boreal Forest, the Hudson Plains, Taiga Shield, and Tundra) (Godin et al. 2017). The results were intriguing in that most of the Hudson Bay rivers displayed higher acid to aldehyde lignin phenol ratios compared to the large Arctic rivers (Amon et al. 2012), suggesting Hudson Bay  $\text{DOC}_{\text{terr}}$  is highly degraded and/or altered by sorptive/desorptive processes. Radiocarbon isotope data showed that most of the DOC carried by Hudson Bay rivers was relatively young, with the exception of several northern rivers, suggesting the release of old DOC from permafrost and/or that older DOC survives river transport in these rivers. The observation that both riverine fluxes and degradability of  $\text{DOC}_{\text{terr}}$  vary widely within the Hudson Bay system underscores the need for additional research.

While biomarkers have not yet been employed to trace DOC within Hudson Bay waters, one approach that has been used successfully is the optically active fraction of DOC, i.e., chromophoric and fluorescent dissolved organic matter (CDOM and FDOM, respectively; Granskog et al. 2009, 2007, Guéguen et al. 2016, 2011). CDOM constitutes an important fraction of all dissolved organic matter in both open ocean (~20%) and coastal areas (~70%) (Coble 2007). Guéguen et al. (2011) found that the optically active fraction of DOC (both absorbing and fluorescing) was very high in Hudson Bay (up to 89%),

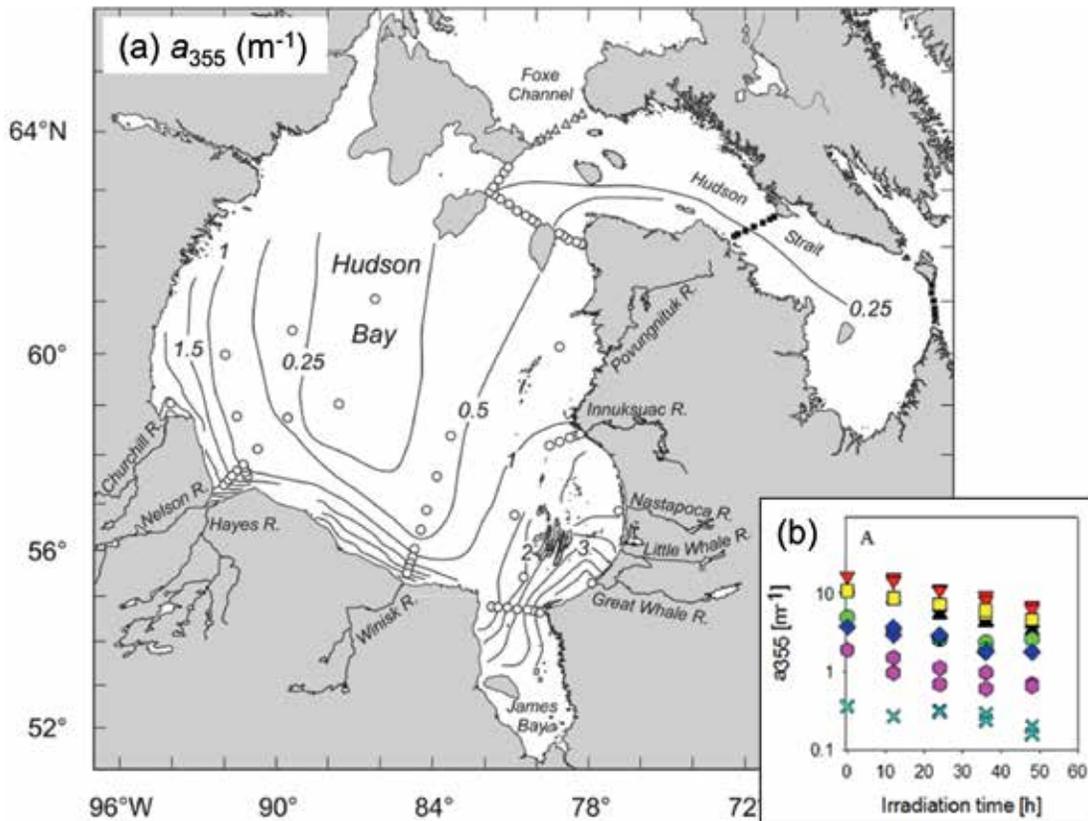


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suggesting that fluorescence and absorbance could be used effectively as proxies of DOC concentration in this system.

A large dataset comprising 470 discrete water samples in offshore, coastal, estuarine and river waters was collected in Hudson Bay and surrounding regions during September and October 2005 to study the distribution and characteristics of CDOM in this marine system (Granskog et al. 2007). For the rivers, CDOM and DOC concentrations varied considerably, with low levels in the northern rivers and higher levels in the southern and western rivers draining the Hudson Bay Lowlands (peatlands). DOC concentrations varied from  $114 \mu\text{mol L}^{-1}$  to  $1175 \mu\text{mol L}^{-1}$ , as did the absorption coefficient at 355 nm ( $a_{355}$ ; from  $1.4 - 44.4 \text{ m}^{-1}$ ), which is commonly used to represent the terrigenous CDOM concentration in a sample (Granskog et al. 2007). Within Hudson Bay, the CDOM levels in surface mixed layer waters were similar or higher than the Beaufort Sea or Mackenzie River delta and considerably higher than the Greenland Sea or central Arctic Ocean (Pegau 2002; Stedmon and Markager 2001). The observations of pronounced inshore-offshore gradients in  $a_{355}$  (Figure 4) suggest the dominance of CDOM-rich river water in the coastal waters, which circulate around the bay in an anti-clockwise direction (Granskog et al. 2007). Based on generally strong relationships between salinity and  $a_{355}$  in Hudson Bay, these workers concluded that CDOM was behaving quasi-conservatively (at least regionally), implying limited degradation.

Subsequent work used both the absorbing and fluorescing components of CDOM to study DOC behaviour and fate within Hudson Bay (Guéguen et al. 2016). This approach

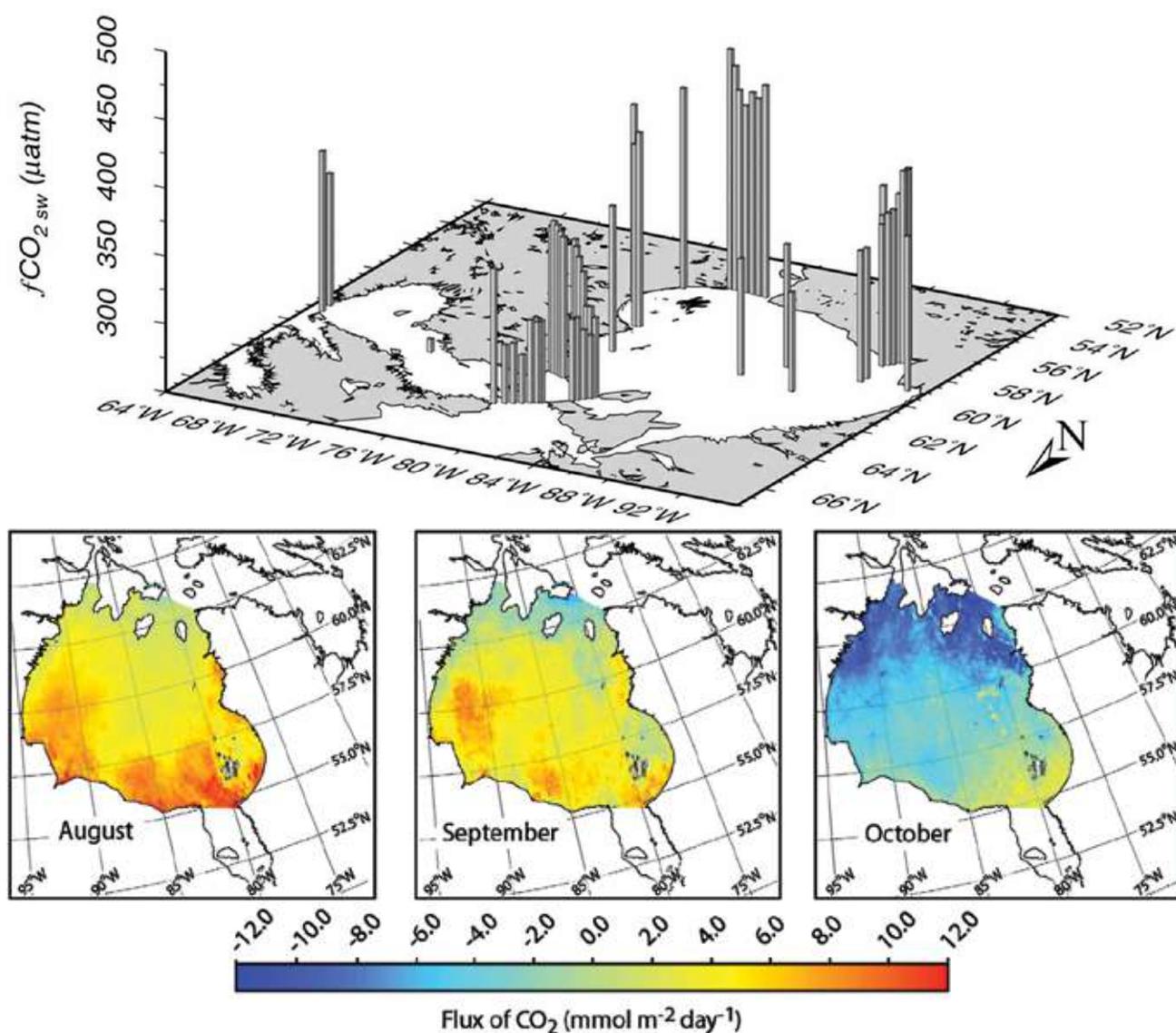


**FIGURE 4.** Distribution of CDOM (as  $a_{355}$  ( $m^{-1}$ )) in the surface mixed layer of Hudson Bay (a modified from Granskog et al., 2009) and loss of CDOM from Nelson River estuary samples subjected to light exposure (b from Gueguen et al., 2016).

allowed identification of three components: one humic-like component that represented  $DOC_{terr}$ ; a second humic-like component that originated both on land and in the marine environment; and a third component that was protein-like and appeared to be plankton-derived. The optically active DOC was inversely correlated with salinity, indicating conservative behaviour, but some non-conservative variations were observed for both  $a_{355}$  and the humic-like component, particularly at low to mid salinities, and may be explained by either DOM adsorption to particles or degradation. To identify whether the DOM was vulnerable to photochemical degradation, Guéguen et al. (2016) conducted light exposure experiments and found that the  $DOC_{terr}$  was particularly light-sensitive, with losses of  $a_{355}$  over two-day light exposures of 61-68%, 49-56% and 52% for river, estuarine, and offshore bay samples, respectively (Figure 4b) (Guéguen et al. 2016). Further work is needed to determine how much of the photochemically degraded  $DOC_{terr}$  is converted to  $CO_2$ .

### 3.4. Gaseous $CO_2$ and observations of air-sea exchange

Air-sea  $CO_2$  flux can be estimated based on surface water  $CO_2$  saturation levels and wind-speed (see Box 1). Else et al. (2008a, 2008b) used this approach to make the first discrete field measurements of air-sea  $CO_2$  flux in Hudson Bay during September and October 2005 (Figure 5a). They found a strong correlation ( $r^2 = 0.89$ ) between sea-surface temperature and surface water  $CO_2$  concentrations (Else et al. 2008b), which allowed them to infer surface water  $CO_2$  concentrations across the bay based on satellite-derived measures of sea surface temperature (MODIS Aqua). This was combined with satellite-derived wind-speed estimates (QuickSCAT/SeaWinds imagery) to derive air-sea fluxes (Fig 6b). Their results indicated that Hudson Bay was a net source of  $CO_2$  to the atmosphere during the ice-free season. Regionally, Hudson Bay waters ranged from strong  $CO_2$  evasion to the atmosphere in the nearshore (particularly south-eastern Hudson Bay and James Bay), to  $CO_2$  sinks in the offshore and northern Hudson Bay, including Foxe Basin (Figure 5; Else



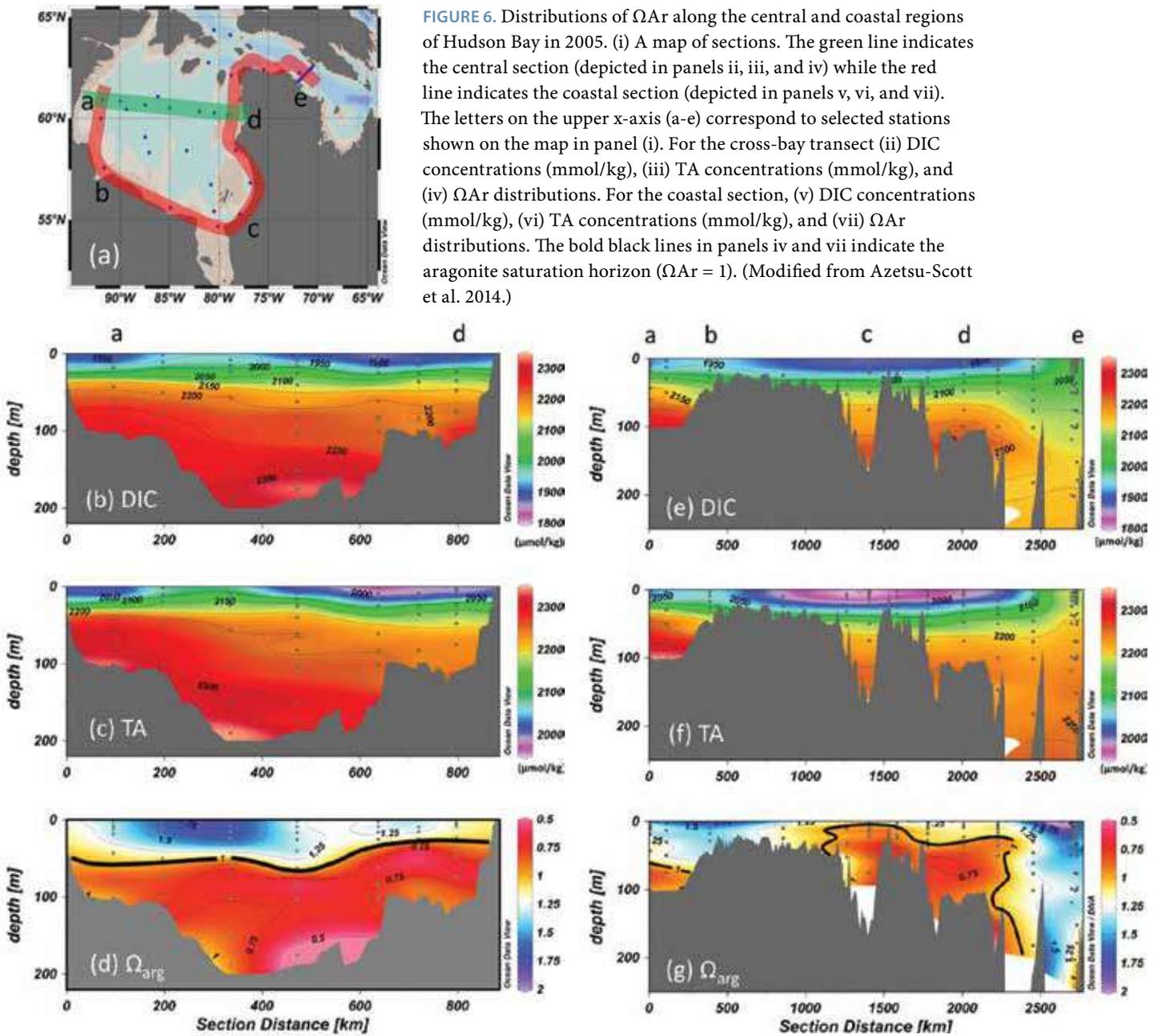
**FIGURE 5.** Instantaneous discrete  $\text{CO}_2$  flux measurements from fall 2005. Panel a, black bars denote net  $\text{CO}_2$  emission to the atmosphere, and light bars denote  $\text{CO}_2$  uptake by the surface ocean. (Panel a from Else et al., 2008a) Panel b, extrapolated  $\text{CO}_2$  flux during August, September and October 2005. (Panel b from Else et al., 2008b.)

et al. 2008a, 2008b). Maximum rates of emission and uptake were  $+16.5 \text{ mmol m}^{-2} \text{ d}^{-1}$  and  $-20 \text{ mmol m}^{-2} \text{ d}^{-1}$ , respectively, in James Bay and northern Hudson Bay/Foxe Basin. Strong relationships were observed between excess surface  $\text{pCO}_2$  and temperature, salinity, and CDOM, suggesting  $\text{CO}_2$  fluxes were driven primarily by remineralization of terrigenous organic matter (Else et al. 2008a). The authors speculated that the near- and offshore dichotomy in air-sea flux was strongly influenced by river input during the open water season. Estuaries transitioned from a strong  $\text{CO}_2$  source in the upper estuary (near the river mouth) to a net  $\text{CO}_2$  sink just 150 km downstream in

outer estuary waters (Else et al. 2008a). Seasonally, the Bay was a net source of  $\text{CO}_2$  during the months August and September, reverting to a sink during fall (October) (Figure 5b) with the cooling of the sea surface (Else et al. 2008b).

### 3.5. Dissolved inorganic carbon and evidence of ocean acidification

Two recent studies have examined the distribution of elements of the inorganic carbon system in Hudson Bay including the distribution of DIC, total alkalinity (TA), pH, and the saturation states of the calcium-carbonate minerals calcite and aragonite



**FIGURE 6.** Distributions of  $\Omega_{Ar}$  along the central and coastal regions of Hudson Bay in 2005. (i) A map of sections. The green line indicates the central section (depicted in panels ii, iii, and iv) while the red line indicates the coastal section (depicted in panels v, vi, and vii). The letters on the upper x-axis (a-e) correspond to selected stations shown on the map in panel (i). For the cross-bay transect (ii) DIC concentrations (mmol/kg), (iii) TA concentrations (mmol/kg), and (iv)  $\Omega_{Ar}$  distributions. For the coastal section, (v) DIC concentrations (mmol/kg), (vi) TA concentrations (mmol/kg), and (vii)  $\Omega_{Ar}$  distributions. The bold black lines in panels iv and vii indicate the aragonite saturation horizon ( $\Omega_{Ar} = 1$ ). (Modified from Azetsu-Scott et al. 2014.)

(see Box 1 for more details). The first study was conducted from August to October 2005 as a part of the MERICA-nord and ArcticNet programs (Azetsu-Scott et al. 2014). The second study was conducted in July 2010 as a part of ArcticNet (Burt et al. 2016).

Both studies found a strong relationship between fresh-water distributions and inorganic carbon system components (DIC and TA) and calcite and aragonite saturation states ( $\Omega_{cal}$

and  $\Omega_{arg}$ , respectively). Rivers and sea-ice melt contain less DIC and TA per volume than inflowing marine waters, leading to a strong relationship between salinity and  $\Omega_{Ar/Ca}$  (Azetsu-Scott et al. 2014; Burt et al. 2016). Figure 6 shows the DIC, TA, and aragonite saturation states in 2005 along two sections, one east-west across the middle of the bay, and one along-shore that follows the path of water in the near-shore as it circulates counter-clockwise around the bay and out into Hudson Strait

(Azetsu-Scott et al. 2014). Aragonite under-saturation (i.e.,  $\Omega_{Ar} < 1$ ) was pronounced in surface waters with >10% freshwater composition, i.e. southeastern Hudson Bay (Figure 6g; Azetsu-Scott et al. 2014).

The delivery of DIC and TA by rivers is strongly influenced by drainage basin geology (Azetsu-Scott et al. 2014; Burt et al. 2016; Tank et al. 2012). River water from the limestone-rich basins in southwestern Hudson Bay have relatively high DIC and TA compared to the eastern rivers (Tank et al. 2012), leading to aragonite super-saturation ( $\Omega_{Ar} > 1$ ) in southwestern Hudson Bay coastal waters despite the abundance of freshwater in this region (Figure 6; Azetsu-Scott et al. 2014; Burt et al. 2016).

Seawater with  $\Omega_{Ar} < 1$  (i.e. where aragonite is unstable) was more widespread in deep waters than at the surface, which can be attributed to remineralization of organic matter at depth and export of DIC to depth due to brine rejection during ice formation (Azetsu-Scott et al. 2014). Burt et al. (2016) estimated that the DIC in subsurface waters circulating around the Bay increased by  $\sim 100 \mu\text{mol L}^{-1}$  from the time they enter Hudson Bay in the northwest until the time they exit in the northeast. The authors attribute this observed increase to remineralization of organic matter in deep waters. As a result, the saturation horizon for  $\Omega_{Ar}$  shoaled to within 20 m of the surface in the southeast of Hudson Bay. We remain uncertain on the relative importance of marine versus terrigenous organic material in fuelling the respiration that is presumably responsible for the accumulation of DIC in deep waters.

Little is known about particulate inorganic carbon (PIC) in Hudson Bay, despite its potential effect on pH and  $\text{pCO}_2$ . Limited measurements of river PIC concentrations indicate terrigenous PIC concentrations are much lower than DIC. Water samples collected from the Nelson River in August 2016/17 contained on average  $1.0 \pm 0.5 \text{ mg PIC/L}$  ( $n=7$ ) (Stainton unpublished). However, PIC represents a significant portion (15%) of the total sinking particulate carbon flux collected in sediment traps around Hudson Bay (Lapoussière et al. 2009). If this PIC is autochthonous (formed by biota in the water column), it would increase surface  $\text{pCO}_2$  and affect pH, whereas if it is allochthonous (undissolved PIC imported from land) it would imply an opposite effect.

#### 4. Discussion and synthesis of Hudson Bay carbon cycle research

The condensed reviews of the Hudson Bay carbon cycle above highlight the significance of terrigenous OC ( $\text{OC}_{\text{terr}}$ ) delivery by rivers, in addition to marine OC ( $\text{OC}_{\text{mar}}$ ) produced within Hudson Bay itself. Assuming particulate carbon is not exported from the Hudson Bay system (Kuzyk et al. 2009) there are three possible

fates for the  $\text{OC}_{\text{terr}}$  which dictate the overall balance of the system with respect to air-sea  $\text{CO}_2$  flux and ocean acidification: i)  $\text{OC}_{\text{terr}}$  is buried with sediments on the seafloor; ii)  $\text{OC}_{\text{terr}}$  is remineralized in deep waters; or iii)  $\text{OC}_{\text{terr}}$  is remineralized in surface waters. The first of these loss processes – burial – will tend to promote the role of Hudson Bay as a carbon sink, without altering acidity or air-sea  $\text{CO}_2$  flux. The second loss process - remineralization in deep waters - would tend to increase  $\text{CO}_2$  concentration and vulnerability of deep water to ocean acidification, with subsequent impact on surface waters via upwelling events. The third process – remineralization in surface waters – will increase surface water  $\text{CO}_2$  concentration, increasing vulnerability to ocean acidification in surface waters while also promoting  $\text{CO}_2$  evasion to the atmosphere. This seems quite straightforward until we consider that the fate of  $\text{OC}_{\text{terr}}$  in the system is only one-half of the equation for the total carbon budget of Hudson Bay. The other half of the equation is provided by  $\text{OC}_{\text{mar}}$ . Its fate may be considered similarly to that of  $\text{OC}_{\text{terr}}$  above, remineralization or burial. However, in comparison to  $\text{OC}_{\text{terr}}$ ,  $\text{OC}_{\text{mar}}$  is typically very prone to remineralization and unlikely to be buried (Hedges et al. 1997). Ultimately, it is only if Hudson Bay sediments bury carbon, removing it from active cycling for hundreds to thousands of years that we could expect this system to contribute as a net sink within the long-term global carbon cycle.

One might expect Hudson Bay to be a net carbon sink because most North American Arctic shelves are net sinks, including the Chukchi (Bates 2006) and Beaufort (Murata and Takizawa 2003) Seas. The Barents Sea is also a net carbon sink (Fransson et al. 2001; Kaltin et al. 2002; Kaltin and Anderson 2005). In contrast, the Siberian Seas appear to be net atmospheric  $\text{CO}_2$  sources (e.g., Anderson et al. 2011; Vonk et al. 2012). Hudson Bay is fundamentally different from other North American Arctic shelves. For example, Hudson Bay does not abutt the deep Arctic Ocean basin or other deep basins and Hudson Bay is not experiencing falling relative sea level due to isostatic rebound of the land. Despite the literature summarized in the previous section, we lack a synthesis that clarifies the net results of the Hudson Bay carbon cycle (i.e., net atmospheric  $\text{CO}_2$  source or sink) and how the  $\text{OC}_{\text{terr}}$  it receives contributes to  $\text{CO}_2$  exchange with the atmosphere or ocean acidification.

To determine how the various loss processes play out in balance against the sources, we can refer to a previously constructed budget that compares the supply of terrigenous OC to burial in a quantitative approach (Kuzyk et al. 2009). According to these workers, rivers and coastal erosion deliver 0.53 teragrams (Tg) of carbon per year as terrigenous POC, of which less than 50% ( $\sim 0.23 \text{ Tg C yr}^{-1}$ ) is buried (Kuzyk et al. 2009). This implies that the majority of particulate  $\text{OC}_{\text{terr}}$  is remineralized in the Hudson Bay water column. We may assume that much of this remineralization occurs in bottom waters, which

is consistent with the observations of widespread aragonite-undersaturation in these waters (Azetsu-Scott et al. 2014). This low burial rate of  $OC_{terr}$  is in line with a report by Vonk et al. (2012) that two-thirds of  $OC_{terr}$  released along the Siberian coast is remineralized in the water column. Those workers suggest that this carbon escapes to the atmosphere as  $CO_2$ . However, even if the entire 0.3 Tg of remineralized  $POC_{terr}$  were evaded to the atmosphere as  $CO_2$ , another 1.3 Tg would be required to support the 1.6 Tg  $C\ y^{-1}$  evasion by  $CO_2$  from Hudson Bay (Else et al. 2008b). This evasion could be supported by the remineralization of 30-50 % of the annual  $DOC_{terr}$  supply to Hudson Bay (3.6 - 5.5 Tg  $y^{-1}$ ; Kuzyk et al. 2009; Mundy et al. 2010). Indeed, Else et al. (2008a) suggested that  $DOC_{terr}$  remineralization likely contributed to the higher  $CO_2$  evasion observed in nearshore Hudson Bay waters, and evidence suggests that  $DOC_{terr}$  is rapidly remineralized in high-latitude coastal waters (Dainard et al. 2015; Guéguen et al. 2011). This preliminary budgeting exercise implies that high riverine supply of terrigenous organic matter and its remineralization to  $CO_2$  make Hudson Bay more similar to the shallow marine systems of the Siberian coast than to other North American Arctic shelf waters in terms of its carbon cycle,  $CO_2$  evasion to the atmosphere and high vulnerability to ocean acidification.

## 5. Impacts of human activity and climate change

Human activities such as hydroelectric and infrastructure development, as well as climate change have the potential to alter the Hudson Bay carbon system (cf., Macdonald et al. 2015) but these impacts are not well understood. It seems clear that factors which alter the delivery or burial rate of  $OC_{terr}$  will be dominant controls on the overall ability of the system to emit/absorb  $CO_2$  and maintain its calcium carbonate saturation state. Below, we discuss some of the anticipated impacts and key unknowns that should be addressed by future research.

A third of the total river discharge entering Hudson Bay is regulated for hydroelectricity generation, either by increasing winter flows at the expense of summer flows, or by diverting portions of their flows to other rivers to increase electric capacity (Déry et al. 2011). Changes in the timing of river discharge may alter the Hudson Bay carbon system directly by altering the timing, total flux, and distribution of  $POC_{terr}$  and  $DOC_{terr}$  in coastal Hudson Bay waters, and indirectly through changes in nutrient delivery, mixed-layer dynamics and thermodynamics, light availability and sea-ice (AMAP 2013; Granskog et al. 2007; Prinsenberg 1983). Land-use changes such as road building, urbanization and resource extraction could also alter the delivery of  $OC_{terr}$  to Hudson Bay. Studies have found positive

correlations between the degree of urbanization and organic carbon loads (e.g. Sickman et al. 2007), and the lability (i.e. degradability) of organic matter in runoff (Fouché et al. 2017), likely caused by wastewater discharge, increased runoff, and new sources of organic matter in urban environments.

Climate change is already apparent in Hudson Bay. A reduction in the length of the ice covered season (Hochheim and Barber 2010) may increase the upwelling of  $CO_2$  rich (and aragonite-under-saturated) water to the surface (Carmack and Chapman 2003), increase the photo-remineralization of  $DOC_{terr}$  (Bélangier et al. 2006), and accelerate the exchange of  $CO_2$  between the atmosphere and surface ocean (AMAP 2013; Bates 2006). In absence of sea ice, the cold, fresh surface water in Hudson Bay could be expected to take up additional  $CO_2$ . If the additional  $CO_2$  remained in the surface layer, it could just be emitted during the open-water season (Else et al. 2008b) but if it were transported to deeper layers, it would likely exacerbate ocean acidification (Azetsu-Scott et al. 2014). Warmer waters, increased heterotrophy, or enhanced upwelling would all modify those expected trends. Another possibility is that a prolonged open water season could increase primary production (Arrigo et al. 2010), assuming availability of nutrients. This scenario would see reducing ocean acidification and  $CO_2$  flux. Another important variable is sea surface temperatures (SST), which will affect microbial activity and remineralization rates as well as other processes. SST in August is closely related to average air temperature and percentage of open water from June to August (Galbraith and Larouche 2011). Thus, shortening of the ice-cover season drives warming of surface waters. There is evidence of a roughly 3°C increase in SST during recent decades, although high inter-annual variability and a relatively short period of satellite observations contribute to uncertainty in that estimate (Brand et al. 2014; Galbraith and Larouche 2011).

Vast permafrost and peat deposits exist along the southern coast of Hudson Bay and throughout the Hudson Bay and James Bay Lowlands. Models suggest that 50% or more of this permafrost could be degraded by 2050 due to climate change (Gough and Leung 2002), potentially releasing vast quantities of labile  $OC_{terr}$  to Hudson Bay coastal waters (Frey and McClelland 2009; Lawrence and Slater 2005; Letscher et al. 2011). Recent work suggests Arctic rivers are becoming more rich in  $DOC_{terr}$  (Monteith et al. 2007) and this will be exacerbated by a warmer, wetter climate (De Wit et al. 2016). Increased  $OC_{terr}$  delivery to Hudson Bay would likely promote ocean acidification and  $CO_2$  evasion in coastal surface waters, although increased particle loads in river water may help remove DOC from the water column in coastal regions, as DOC adsorbs to sinking terrigenous particles (Vonk et al. 2015). Increasing groundwater flow may also increase the delivery of calcium (which mitigates ocean acidification) and nitrate (which may

stimulate primary production and carbon uptake; Vonk et al. 2015b). Variations in volume of river discharge entering Hudson Bay occur on decadal and multi-decadal timescales (Déry et al. 2011), potentially altering the delivery and characteristics of  $OC_{terr}$  to Hudson Bay. Global climate model simulations consistently project increasing pan-Arctic river discharge for the 21<sup>st</sup> century (Arnell 2005; Holland et al. 2007; Milly et al. 2005), although regulation and climate interact to control river discharge to Hudson Bay (see Theme I. Chapter vi.), making it more difficult to predict future discharge trends. More rapid flushing of freshwater through streams and wetlands can result in various biogeochemical changes; one effect that has already been observed in northern Canada is a ‘browning’ of boreal rivers because of higher concentrations of iron complexed with DOC (Weyhenmeyer et al. 2014).

## 6. Conclusions and recommendations for future research

The review of existing Hudson Bay carbon studies reveals that Hudson Bay receives a large quantity of  $OC_{terr}$  relative to other North American Arctic shelves, much of which is remineralized in the water column promoting  $CO_2$  evasion and ocean acidification. It is likely that human activity and climate change over the past century have already altered the Hudson Bay carbon cycle, with even more pronounced changes likely to occur in the next century. However, the responses of the system to these changes are difficult to predict because of the dynamic exchanges of carbon among the atmosphere, ice and ocean systems, the watershed and the marine ecosystem, and the transformations among different carbon phases that depend on complex biogeochemical processes. We expect that ocean acidification in Hudson Bay will become more widespread in the future but additional study is needed to predict how rapidly this will occur and its effects on the ecosystems. It is also critical that future research efforts examine the carbon system in Foxe Basin, James Bay, and Hudson Strait, which are fundamentally different from Hudson Bay. The Hudson Bay carbon cycle cannot be properly understood in isolation from these other water bodies. Many of the studies in Hudson Bay have been restricted to the open water season, so another priority for future research is collecting discrete data during spring and under-ice during winter. Few rivers have been sampled during spring freshet despite the importance of this time period for carbon exports. Recently developed sensors for carbon system parameters should be incorporated into future ocean moorings to develop time series and allow study of processes. For example, we know very little about where and when deep water is formed in Hudson Bay and thus cannot assess the importance of this process in



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removing carbon from the surface layer. Apparent ‘hot spots’ of productivity in northwest Hudson Bay and west of the Belcher Islands may be related to upwelling and tidally-generated internal waves (Petrusevich et al. 2018) but these processes also remain unquantified. There are limited data on the contributions of ice-algae and benthic primary production by eelgrass and kelp on the Hudson Bay carbon cycle, although this kind of production can exceed water column production in some Arctic regions (Glud et al. 2009). Furthermore, no studies have investigated the methane concentrations or air-sea fluxes in Hudson Bay to date, despite the observations of high methane concentrations in rivers, lakes, and groundwater surrounding the Bay (e.g. Laurion et al. 2010). The permafrost deposits in the southern Hudson Bay and James Bay Lowlands provide a source of organic carbon and anoxic environments ideal for methane production unless the carbon undergoes translocation and is ultimately remineralized in coastal waters instead. Climate change-induced mobilization of old permafrost carbon is believed to be well underway in the Arctic (cf., Feng et al. 2013) and recent work points to mobilization of anomalously old DOC in some Hudson Bay rivers (Godin et al. 2017). Further investigation of the age and composition of OC are needed to confirm the rates of old carbon mobilization from the watershed to coastal Hudson Bay waters and its fate therein.

For a system as large and complex as Hudson Bay, biogeochemical modelling is essential for predicting the consequences of future environmental change. A bay-wide study on the effects of climate change and hydroelectric activity on the Hudson Bay system (BaySys) is currently underway and generating a more comprehensive data set as well as more sophisticated, predictive numerical models, which will be used to infer the carbon system status under a range of river discharge and climatic scenarios. To complement these efforts, a comprehensive carbon budget that includes inorganic and organic carbon should be constructed to help in assessing the capacity of various processes to induce change in the Hudson Bay carbon cycle and identifying sensitivities to change.

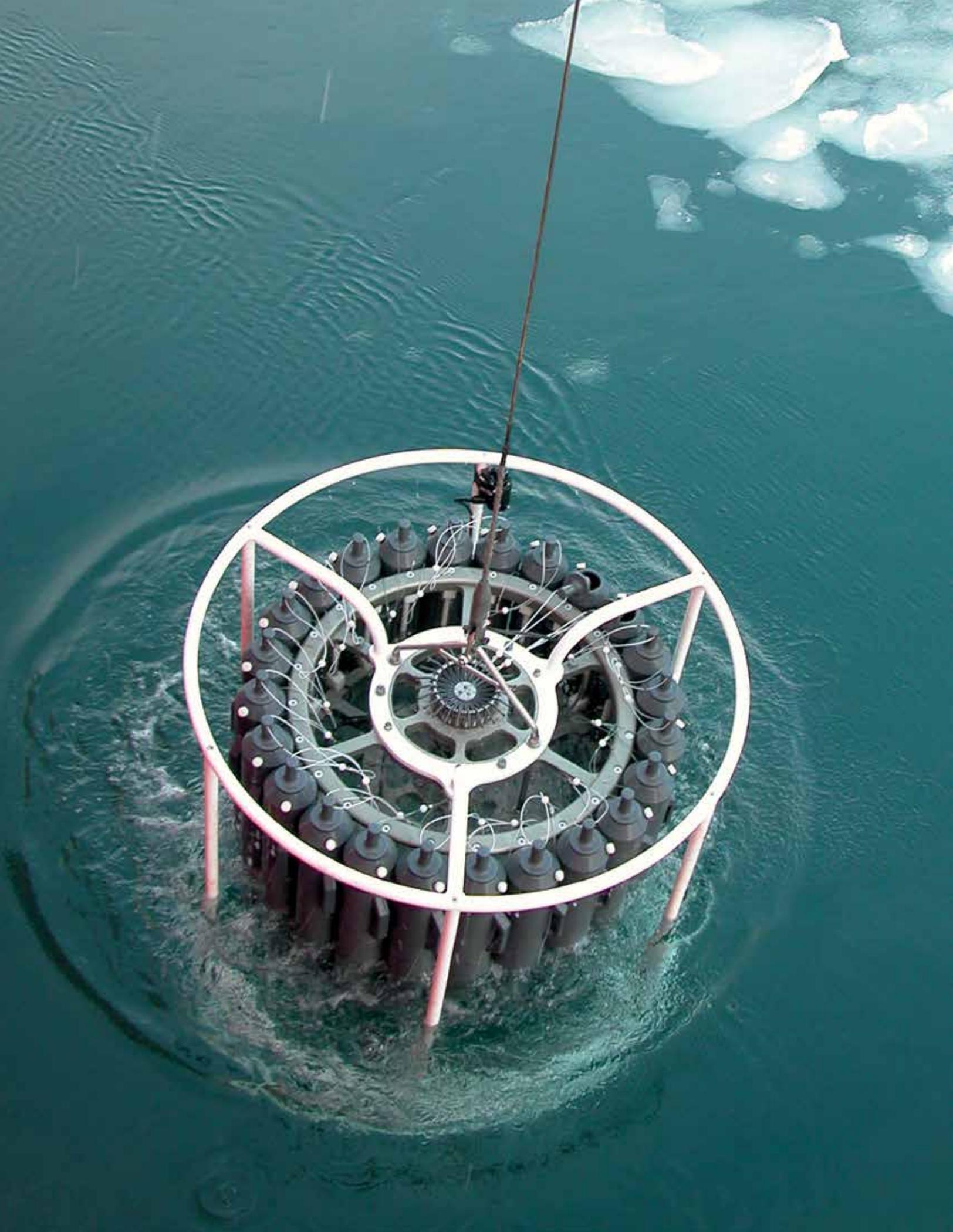
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## II.ii

# Nutrient Dynamics and Marine Biological Productivity in the Greater Hudson Bay Marine Region

### AUTHORS

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### Summary

**A**t the base of the marine and coastal food webs throughout the Greater Hudson Bay Marine Region are the photosynthetic organisms including phytoplankton (microscopic free-drifting algae), ice algae, macro-algae such as kelp, and coastal seagrasses (eelgrass). The production of organic matter by these various photosynthetic organisms – also called ‘primary producers’ – establishes the base of the food web, providing food to pelagic (open water) and benthic (sea-floor) organisms higher up the food web. As a result, the abundance and diversity of marine life including fish and marine mammals is a reflection of the primary production in that ecosystem. Generally speaking primary production is controlled by the availability of light and nutrients and modulated by other environmental factors such as temperature, salinity, pH and the availability of free carbon dioxide (CO<sub>2</sub>) in seawater.

### Key Messages

- **In the Greater Hudson Bay Marine Region, riverine nutrient inputs contribute to enhanced productivity in the nearshore zone of Hudson Bay, but the concurrent freshwater input favours high vertical stratification, which reduces the upward supply of nitrate and maintains low productivity away from estuarine transition zones. Indirect effects of river inflow, such as entrainment and upwelling may also make substantial contributions to nutrient supply and productivity in the coastal zone. Thus, the lower food web of Hudson Bay is generally unproductive and would be unable to support industrial fisheries at present.**
- **The situation is different in the northern part of the region (e.g., Foxe Basin and Hudson Strait), where upwelling and vertical mixing processes enhance nutrient deliveries into the sunlit layer where algae photosynthesize.**

- **Although the general trends are known, among the different methods used to estimate planktonic productivity, some converge and others diverge with respect to the spatial distribution of primary production. Available evidence suggests that the coastal intensification of primary production reported by the remote-sensing approach is realistic (except perhaps in James Bay) and consistent with the spatial distribution of the Ecologically and Biologically Significant Areas used by birds and marine mammals.**
- **Large knowledge gaps exist concerning the impact of climate change and river flow regulation on the riverine supply of inorganic and organic nutrients (especially nitrogen) and its consequences on primary production in Hudson Bay.**
- **A new analysis of nutrient ratios in the interior of Hudson Bay suggests that the direct transfer of riverine nutrients to deep waters (for example through winter convection) is minor relative to the sinking export of the organic matter synthesized by the primary producers that consume river nutrients in the coastal zone.**

## 1. Introduction

Marine ecosystems of the Greater Hudson Bay Region provide numerous benefits and services of economic, societal and ecological value, including the provision of food and the maintenance of the biodiversity of habitats and species that sustain the production of this food, coastal livelihoods and economies, culture and tradition, tourism, recreation and carbon storage. These benefits and services can either be enhanced or reduced by direct local impacts, including habitat modification, river runoff, harvest, navigation or the exploitation and transport of non-renewable resources, or indirectly through the cumulated impacts of human activities (i.e., climate change resulting from fossil fuel burning, energy production and land use). Climate-driven alterations of the marine environment are fastest and deepest at the periphery of the Arctic Ocean (IPCC 2014), notably in Hudson Bay, where the ecosystem is impacted in different concurrent ways by warming, acidification, reductions in the extent, thickness and seasonal persistence of sea ice, changes in upper ocean dynamics and increased freshwater loading from precipitation, rivers and melting sea ice.

At the base of the food web, the primary production (PP) of organic matter (OM) phytoplankton, ice algae and macroalgae in Hudson Bay is driven by the availability of light and nutrients and presumably modulated by other factors such as temperature, salinity, pH and the availability of free carbon dioxide (CO<sub>2</sub>). Changes in these drivers and growth factors

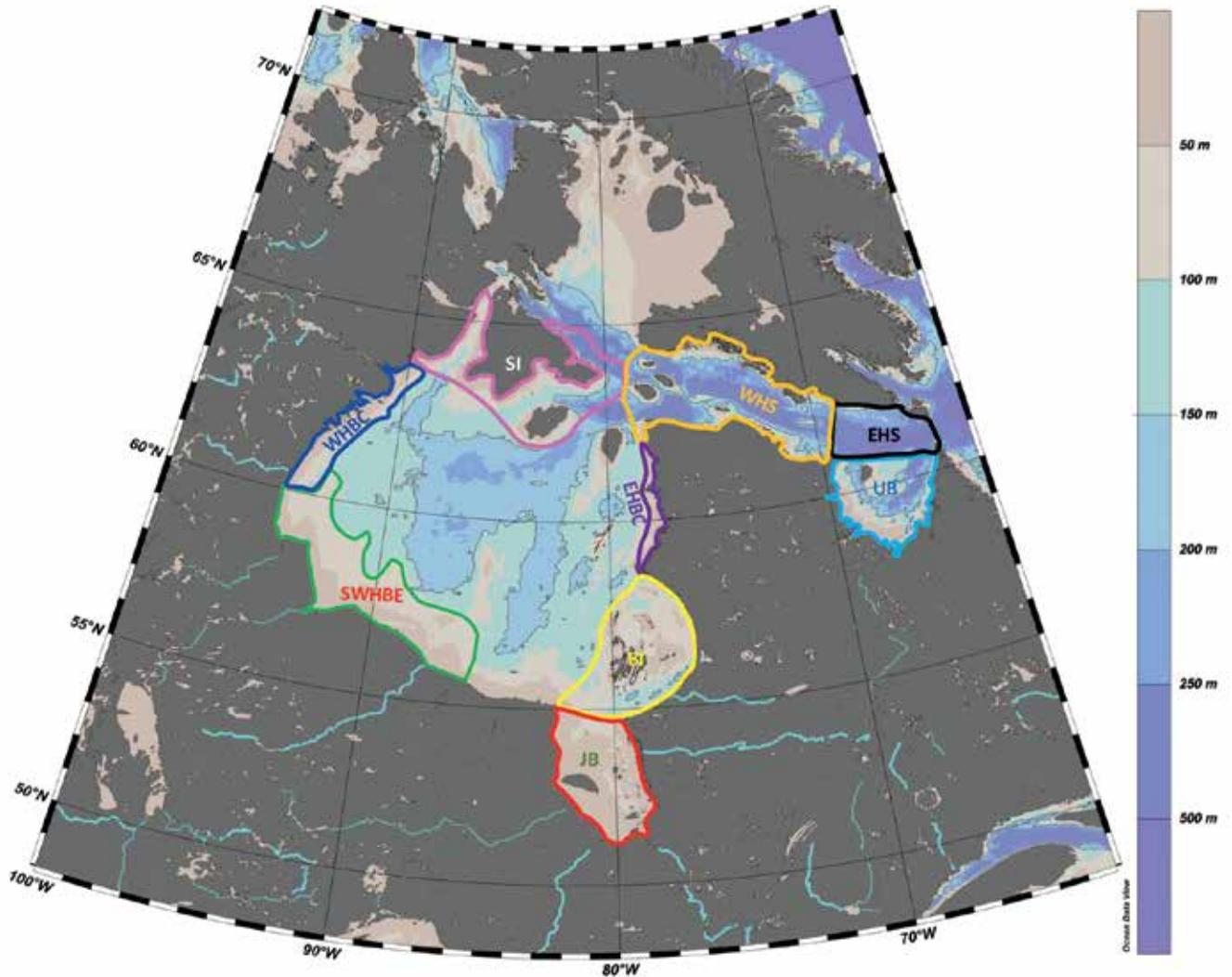
are expected to affect biodiversity (Witman et al. 2008; Vallina et al. 2014) and the productivity of harvestable resources since the intensity of PP by nutritious types of phytoplankton (e.g., diatoms as opposed to coccolithophores or harmful algae) sets an upper limit to the quantity of OM available to feed pelagic and benthic consumers higher up the food web (e.g., Bessière et al. 2007; Chassot et al. 2007). Indeed, different indices of marine food web productivity, ranging from zooplankton biomass to fish landings, correlate well with the magnitude of PP at regional (Ware and Thomson 2005) and global (Nixon and Thomas 2001; Irigoien et al. 2004; Chassot et al. 2010; Conti and Scardi 2010) scales.

When organic debris and animal carcasses sink from the surface, a portion of the OM originally produced by plants is mineralized in the water column by microbial decomposers, thereby recirculating essential nutrients. The rest reaches the seafloor, where it feeds living benthic resources (e.g., sea stars, mussels, shrimps, urchins) that are directly harvested by humans or serve as food source for diving seabirds, walrus and other consumers. The biomass of benthic animals is closely linked to the input of OM produced by sea-ice algae and may therefore be impacted by the expected switch to a predominantly planktonic PP in the future (e.g., Roy et al. 2015). In practice, the vertical settling of OM moves vital nutrients away from the ocean surface. The vertical movement of zooplankton and fish that feed at the surface and perform daily and/or seasonal migrations to deep waters also transports significant amounts of nutrients and carbon to depth (Benoit et al. 2010; Darnis and Fortier 2012).

This chapter highlights the importance of primary producers for the marine food webs and higher trophic levels of the region, providing a review and discussion of the current state of knowledge concerning the distribution of nutrients and primary production with respect to physical forcing processes in key sectors. This goal is achieved by comparing previously published studies and original data collected by the co-authors during ArcticNet. The chapter concludes with an analysis of possible trends in biological productivity and emphasize the numerous knowledge gaps that need to be addressed in order to improve our ability to understand and predict the response of the marine ecosystem to local and global anthropogenic disturbances.

## 2. Ecologically and Biologically Significant Areas (EBSAs)

In Hudson Bay and Hudson Strait, key animals that populate or transit through EBSAs depend on the primary production of OM by phytoplankton, ice algae and seagrasses at the base of the food web. Several EBSAs have been defined and each



**FIGURE 1.** Bathymetric map of Hudson Bay showing the boundaries of Ecologically and Biologically Significant areas (EBSA) as defined in DFO (2011). The boundaries were redrawn freely from DFO (2011) and delineate the Southampton Island (SI, white), Western Hudson Bay Coast (WHBC, dark blue), Southern Hudson Bay Estuaries (SHBE, red), James Bay (JB, green), Belcher Islands (BI, yellow), Eastern Hudson Bay Coast (EHBC), Western Hudson Strait (WHS, orange), Eastern Hudson Strait (EHS, black) and Ungava Bay (UB, light blue) EBSAs.

of these regions plays important roles for different species of marine mammals, fish and birds in the Hudson Bay system (Figure 1) (DFO 2011). Here we provide a very brief overview of these EBSAs since aggregations of higher trophic levels are generally indicative of enhanced prey availability and therefore provide an alternate means to assess the magnitude and spatial distribution of productivity in the lower food web.

Belugas aggregate at different sites during summer, including the western coastal areas and estuaries, notably the

Churchill Estuary, James Bay, the Belcher Islands and Ungava Bay (DFO 2011). The animals transit through the eastern coastal Hudson Bay area while migrating to overwintering areas in Hudson Strait. Other belugas overwinter in James Bay and possibly near the Belcher Islands. The latter serves as a feeding area for polar bears, which also use James Bay, Southampton Island and Southwestern estuaries to den and/or hunt. Walrus haul-out sites tend to be concentrated in the eastern part of the Hudson Bay/Hudson Strait complex, including James Bay,

where the animals also feed, the Belcher Islands, Southampton Island, as well as western and eastern Hudson Strait. The Belcher Islands host the entire world population of a subspecies of common eider, which rely heavily on the locally productive and diverse benthos for feeding. Other seabirds nest and forage in the area, as well as in James Bay, Ungava Bay and Hudson Strait (DFO 2011). It is noteworthy that central Hudson Bay does not appear to be a key area for any of the species generally considered to be important. Several of the key animal species and populations inhabiting the EBSAs of the Hudson Bay system are considered to be endangered or at least challenged (DFO 2011; Laidre et al. 2015), but it is unclear to what extent these situations arise directly from a change in the physical environment (e.g., sea ice dynamics, temperature) or indirectly via changes in the prey base, which ultimately depends on primary production at the bottom of the food web. The latter is addressed in the remaining sections.

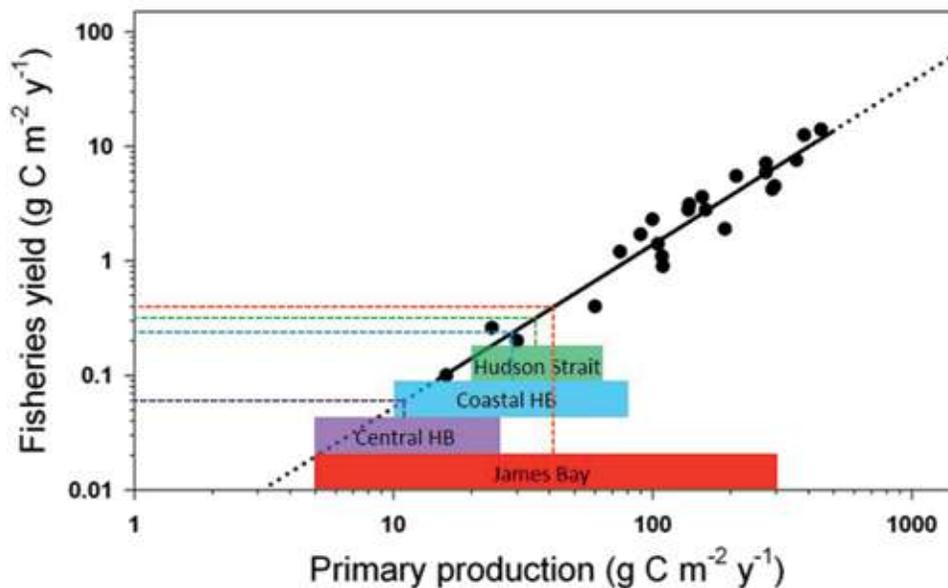
### 3. Magnitude and spatial distribution of primary production

In Hudson Bay, river runoff, sea ice dynamics and ocean physics (Ingram et al. 1996) influence the growth conditions of primary

producers. The relative importance of the different drivers and their interactions vary in space (locally, regionally) and time (seasonally, inter-annually) (Legendre et al. 1996; Kuzyk et al. 2010) and may differently affect the phytoplankton, ice algae and macro-algae (including kelp and seagrasses) that populate the water column, sea ice and nearshore benthic habitats, respectively. These three contributors to overall primary production play distinct roles in the ecosystem.

Ice algae develop relatively early in the growth season and are considered a key food source for the keystone herbivorous copepod, *Calanus glacialis*, and benthos in the Arctic in general. There has been no large-scale assessment of ice-algal productivity in Hudson Bay. Available data are based on limited regional surveys and a numerical ecosystem model.

Different estimates of planktonic primary production chlorophyll biomass or primary production, either based on direct measurements, remote sensing or modelling, all agree that Hudson Bay is generally oligotrophic, with low annual PP levels ranging from 10 to 80 g C m<sup>-2</sup> yr<sup>-1</sup> (Kuzyk et al. 2010 and 2011; Ferland et al. 2011; Lalande and Fortier 2011; Lapoussière et al. 2011; Sibert et al. 2011; Lapoussière et al. 2013; Bélanger et al. 2013) (Figure 2). According to the analysis of Nixon and Thomas (2011), this level of productivity would be unable to support significant industrial fisheries and may be adequate only for



**FIGURE 2.** Relationship between fish yield and annual primary production (adapted from Nixon and Thomas 2001 and Tremblay and Gosselin 2012) showing plausible ranges of annual productivity (boxes) for coastal and offshore waters of the Greater Hudson Bay Marine Region based on satellite climatology for the period 1998-2010 (Figure 3E). The dashed lines indicate potential fish yield based on the middle point of each productivity box.



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small-scale, localized subsistence or commercial fishing. While the PP estimates produced by different methods loosely agree on the overall trophic status of the Hudson Bay system, they show puzzling discrepancies in their magnitude and spatial distribution (Figure 3).

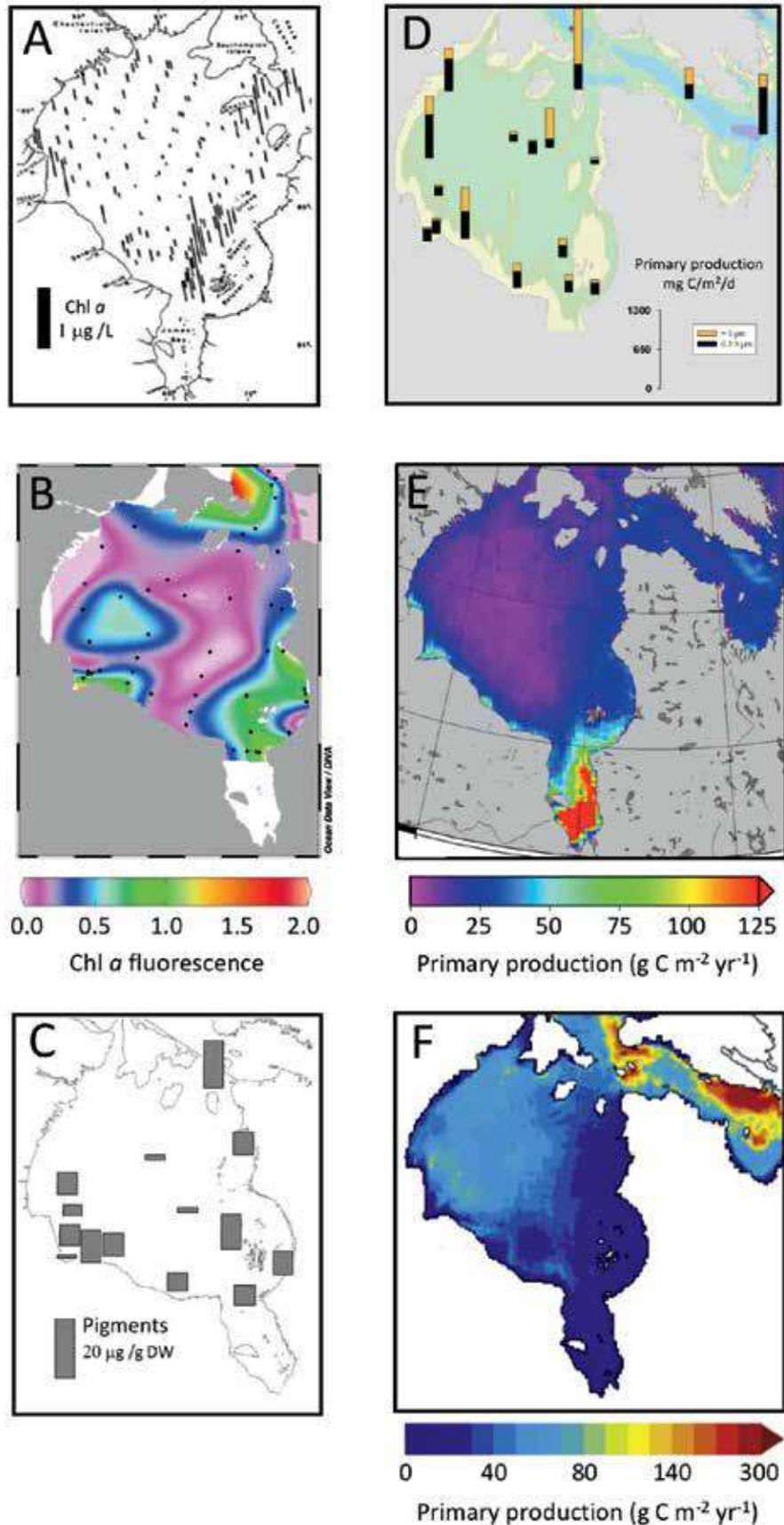
All the methods indicate high spatial heterogeneity across the Bay, but the patterns and details often differ strikingly from one method to the next. In-situ chlorophyll data taken at the surface during late summer 1975 showed very low concentrations throughout central Hudson Bay and a general intensification in coastal areas, especially in the Belcher Islands, Southwestern Estuaries and Western Hudson Strait EBSAs (Figure 3a). In general, the coastal areas located near the estuaries of dammed rivers (e.g., the Nelson and Great Whale Rivers) showed elevated chlorophyll *a* relative to other coastal areas receiving water from rivers that have not been dammed (Churchill, Severn, Winnisk, Naskapoka). When compared with the 1975 data, surface data obtained 35 years later show remarkably similar levels and spatial patterns of Chl *a*, with generally low values offshore and elevated concentrations near the Nelson River, the Belcher Islands and in the Northeast (Figure 3b). The patch of elevated Chl *a* east of the Churchill river was not seen in 1975 and may have resulted from a localized upwelling event. These coarse spatial patterns in surface Chl *a* are mirrored closely by the concentration of pigments in superficial sediments. The sediment integrates the vertical export of biological production at the seasonal time scale (Figure 3c), implying that the daily snapshots of Chl *a* in surface water (i.e., Figure 3a-b), despite their instantaneous nature, are possibly representative of annual productivity.

Short-term measurements of daily PP also exhibit a generally positive offshore-inshore gradient in productivity as well as elevated productivity in the northeast. Relatively low PP near the Belcher Islands suggests that the oceanographic processes

responsible for enhanced phytoplankton biomass there were relatively weak at the time of sampling (Figure 3d). This data set extends to Hudson Strait, where enhanced productivity also occurs. Satellite-based estimates of annual PP averaged for the period 1998-2010 are consistent with all the spatial patterns observed in situ. The conspicuously high levels of PP estimated for the southern and western portions of James Bay cannot yet be confirmed with in situ data available and it is unclear at this time whether these values are realistic or not. This small area is very shallow and highly impacted by the La Grande River, which suggests that colored dissolved organic matter (CDOM) and/or submerged eelgrass beds may substantially affect light reflectance (Figure 3e). While interference from CDOM could also explain why the satellite-based estimates show a coastal intensification elsewhere, the intensification often occurs well away from major rivers, especially in the Northwest, and is remarkably consistent with the in-situ data.

Annual PP estimates obtained from a 3-D ecosystem model of the Hudson Bay system are consistent with other estimates in showing elevated productivity in northern Hudson Strait, but otherwise depart from the spatial patterns discussed so far (Figure 3e). The model shows enhanced PP throughout the northwestern half of the Bay, even in the central offshore sector, with no indications of elevated PP levels inshore, near the Belcher Islands or in James Bay. The relatively low productivity simulated by the model in the nearshore zone has been ascribed to the negative impact of particulate and dissolved matter loading on photosynthesis due to the reduced penetration of sunlight into the water column (Sibert et al. 2012). Within Hudson Bay, the maximum simulated PP levels are observed offshore of the Churchill and Nelson River areas. While it may be tempting to discount these results based on the general agreement between other independent methods, the model generates vertically-integrated PP estimates, whereas the satellite-based estimates and in-situ chlorophyll data are partly based on the extrapolation of surface values and may not fully capture the euphotic or sunlight zone as a whole. In addition, the in-situ data are obtained late in the production season and do not capture under-ice productivity or the spring bloom, when a significant portion of the PP possibly occurs. This production should be captured by sedimentary pigment content, whose spatial distribution shows better agreement with in situ and satellite-based estimates than with the model. It is also possible that the sedimentary pigment load reflects spatial differences in the productivity of ice algae as well as the fact that the degradation of organic matter during its downward transit to the bottom is lesser in shallow coastal areas than offshore.

Given the lack of in-situ data for the springtime, current estimates of pelagic productivity must be considered as provisional. Nevertheless, we hypothesize that the model



**FIGURE 3.** Comparisons between various estimates of biological productivity in the Greater Hudson Bay Marine Region, including (A) surface chlorophyll-a measured during August-September 1975 (modified from Anderson and Roff 1980), (B) surface chlorophyll fluorescence during the ArcticNet expeditions of 2005 (October), 2007 (August) and 2010 (July), (C) sum of chlorophyll-a and phaeopigments in superficial sediments during the 2010 ArcticNet expedition (modified from Kenchington et al. 2011), (D) primary production during July 2010 (ArcticNet data, this study), (E) average satellite-based annual primary production for the period 1998-2010 (modified from Bélanger et al. 2013), and (F) annual primary production from an ecosystem model (modified from Sibert et al. 2011).

overestimates offshore productivity in the western and central portions of the Bay. It is also worth noting that the spatial coherence between the EBSAs where upper trophic levels congregate (Figure 1) and primary production hotspots that emerge from Figure 3a-e is generally good.

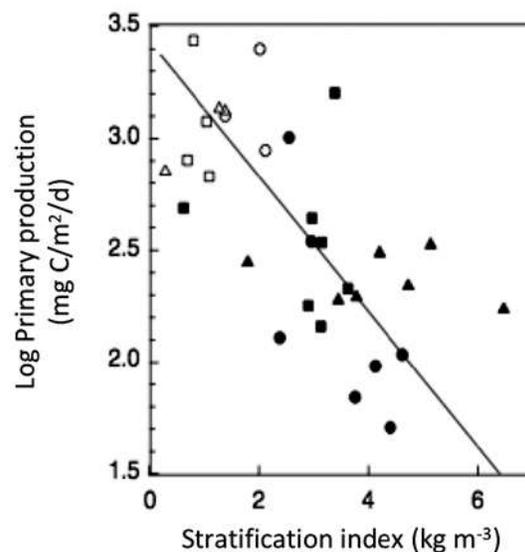
#### 4. Physico-chemical drivers of Primary Production (PP) in the Hudson Bay system

Overall, low productivity in the Hudson Bay system is linked in large part by the dynamics of freshwater-marine coupling. One of the main features of this coupling is the horizontal supply of nutrients and freshwater from the numerous rivers discharging into the Bay. While the nutrient supply may boost local productivity in estuaries and adjacent nearshore zones (Stewart and Lockhart 2005; Kuzyk et al. 2008), the freshwater propagates far beyond and combines with the seasonal freshwater input from sea ice melt (SIM). This combination of freshwater from SIM and river runoff reinforces the vertical stratification across all of the Hudson Bay system and its central portion in particular (Kuzyk et al. 2010; Lapoussière et al. 2013). This vertical stratification impedes the renewal of nutrients in the surface layer, and its adverse impact on biological productivity has been shown for the summer season, when daily rates of primary production are negatively correlated with the stratification index across the Hudson Bay system (Figure 4). Exceptions to the general pattern of high stratification and low surface nutrient availability and productivity offshore may be found in: 1) northwestern Hudson Bay, where the convective mixing associated with a winter polynya presumably brings deep nutrient to the surface; 2) in and near Hudson Strait, where vertical mixing and/or upwelling frequently occurs; 3) near the Belcher Islands, where a relatively cold temperature spot during summer months indicates the presence of upwelling (Galbraith and Larouche 2011); 4) along coastal slopes where entrainment and upwelling may be stimulated by the motion of river plumes (Kuzyk et al. 2010).

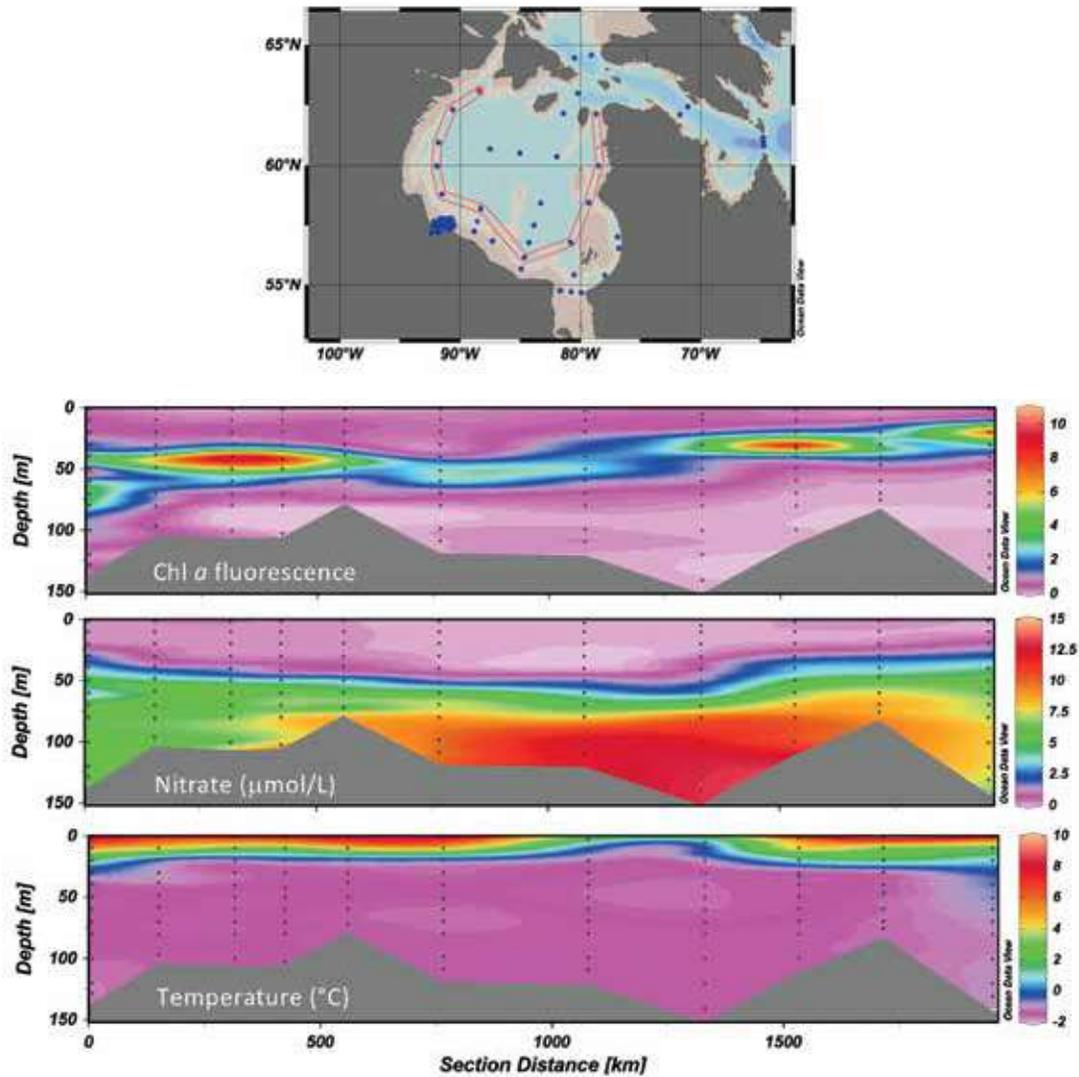
In areas of high vertical stratification and low nutrient concentration at the surface, especially offshore, Chl *a* is higher below the surface and forms what is termed a “subsurface Chl *a* maximum” or hereafter SCM. The SCM, which represents a compromise between the availability of sunlight at the surface and the availability of nutrients at depth, is nearly ubiquitous in the Bay during summer (Figure 5). It is generally associated with very cold temperatures and the nitracline, where the concentration of nitrate rapidly increases with depth. The depth of the SCM is also negatively correlated with water transparency, implying that greater light availability allows the phytoplankton to thrive deeper toward the nutrient-rich layer (Figure 6). The



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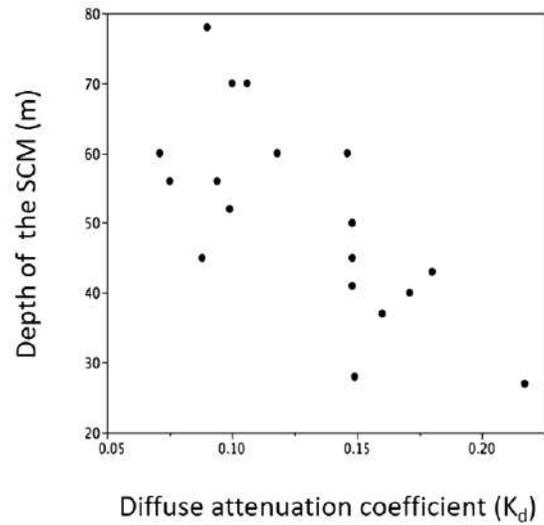
**FIGURE 4.** Relationship between the logarithm of daily primary production and the stratification index (density difference between 5 and 80 m; 0 = no stratification, 6 = strongly stratified) based on data obtained by the MERICA-NORD program during the summers of 2004 (circles), 2005 (triangles) and 2006 (squares) in Hudson Bay (black symbols) and Hudson Strait (open symbols) (modified from Ferland et al. 2011).



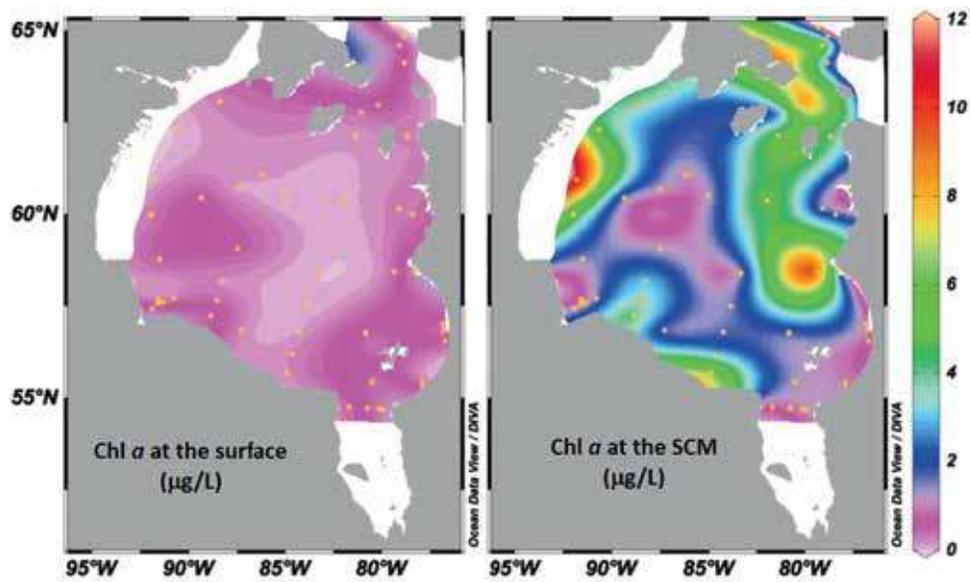
**FIGURE 5.** Vertical position and intensity of the subsurface chlorophyll maximum (SCM) in the interior of Hudson Bay during the 2010 ArcticNet expedition. Data follow a “horseshoe” track from the Northwest to the Northeast.

fact that a SCM is able to exist at 25-30 m in the most turbid locations included in Figure 6 shows that, earlier in the growth season, the phytoplankton have been able to deplete nutrients in the upper layer and suggests that the coastal amplification of primary production depicted in Figure 3a-e is realistic despite reduced water transparency inshore. The Chl *a* biomass attained in the SCM is also highest in relatively shallow peripheral areas (Figure 7). It is likely that the low Chl *a* biomass and deep position of the SCM offshore results from a co-limitation of phytoplankton growth rates by light and temperature, which is subzero and often nears the freezing point of seawater

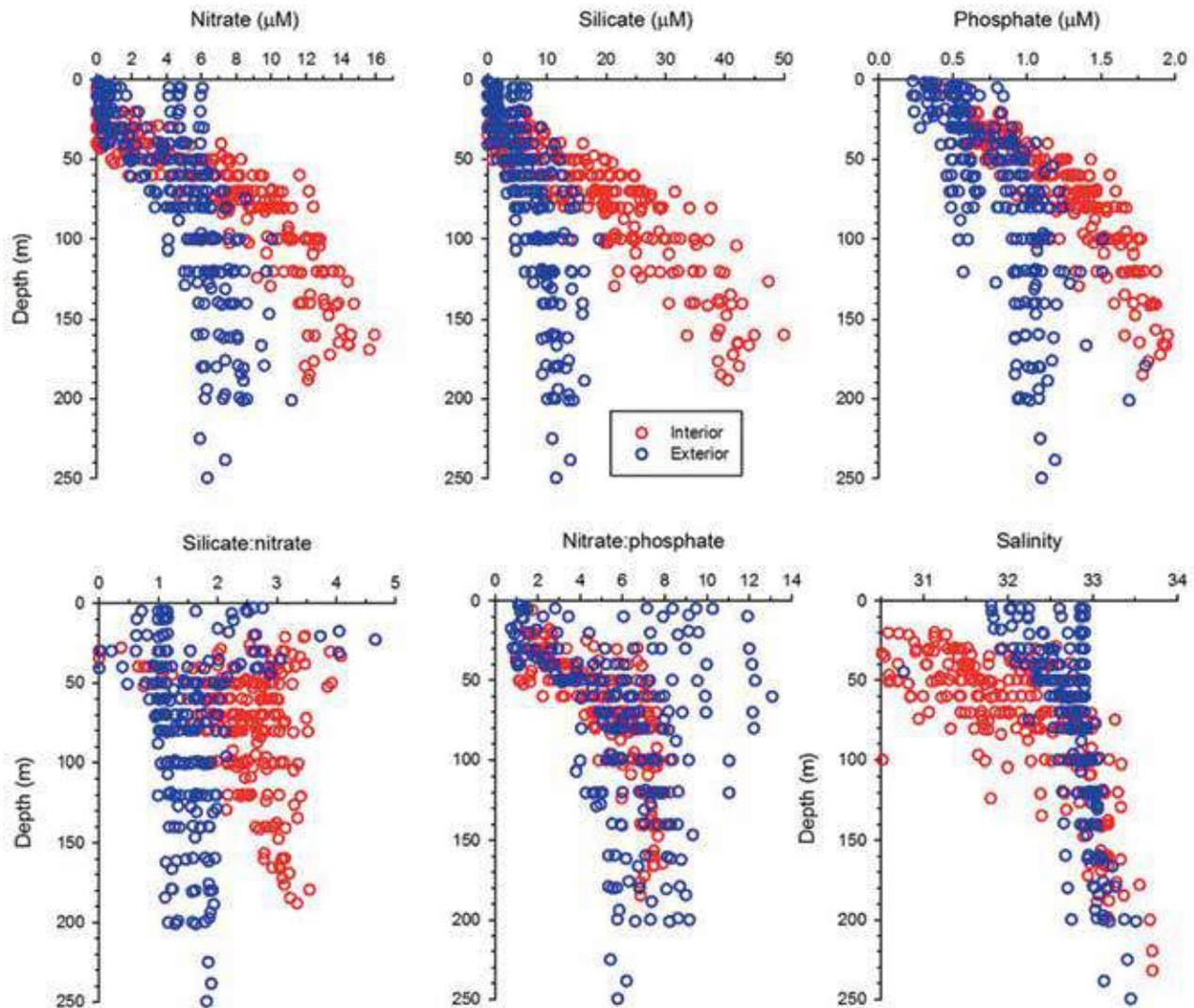
below 30 m. Despite the fact that a coastal intensification in Chl *a* is present both at the surface and in the SCM, the actual concentrations in the two layers are not correlated (Figure 7). This suggests that the coarse spatial patterns shown in Figure 3a and 3e capture the inshore-offshore gradient in depth-integrated primary production, but that using surface values to infer or estimate water-column productivity from in-situ or remote-sensing data entails large errors within the coastal domain.



**FIGURE 6.** Relationship between the diffuse attenuation of photosynthetically-available radiation (i.e., water transparency) and the vertical position of the SCM during July 2010 in Hudson Bay.



**FIGURE 7.** Comparison between the spatial distribution of chlorophyll fluorescence at the surface (same data as Figure 3B but on a different scale) and at the SCM using data from the ArcticNet expeditions of 2005, 2007 and 2010.

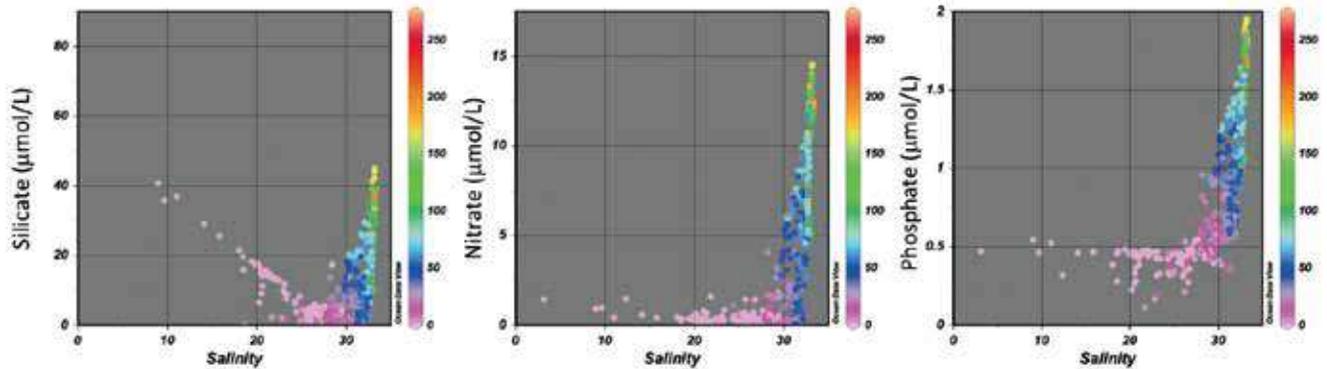


**FIGURE 8.** Vertical profiles of nitrate, silicate, phosphate, silicate:nitrate ratio, nitrate:phosphate ratio and salinity at all marine stations (surface salinity > 30.5) located in inner Hudson Bay (red circles) and outside in the adjacent waters of Foxe Basin and Hudson Strait (blue symbols) during the 2005, 2007 and 2010 ArcticNet expeditions.

## 5. Nutrient sources and dynamics

The particular setting of Hudson Bay in terms of nutrients clearly stands out when comparing the vertical distributions of salinity and nutrients between the marine waters of inner Hudson Bay and those of adjacent Foxe Basin and Hudson Strait, which provide the only possible source of marine waters for the Bay (Figure 8). For the purpose of this comparison, only the samples exhibiting salinities in excess of 30.5 were used to exclude the nearshore areas strongly impacted by rivers. The vertical gradients in salinity and nutrient concentrations are much steeper within the Bay, reflecting the stronger freshwater stratification and the chronic lack of nitrate and silicate in the upper 25 m.

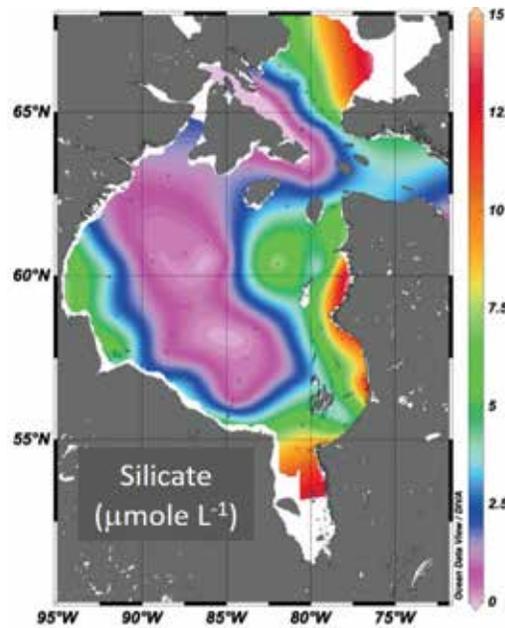
By contrast, several sites in Foxe Basin and Hudson Strait show relatively weak vertical gradients in nutrient concentrations along with elevated concentrations of nitrate and silicate near the surface. These sites in Foxe Basin and Hudson Strait are consistent with higher productivity levels and reduced stratification there (see Figure 4). It is also noteworthy that phosphate concentrations at the surface offshore are always present in excess throughout the Hudson Bay system, implying that nitrogen (primarily under the form of nitrate) is the element that limits overall biological productivity (Kuzyk et al. 2010; Ferland et al. 2011). Low silicate concentrations offshore are also potentially co-limiting for the production of diatoms, but would not affect overall productivity of other phytoplankton groups.



**FIGURE 9.** Relationships between surface salinity and the concentrations of silicate, nitrate and phosphate in the estuarine and marine waters (all salinities) during the 2005, 2007 and 2010 ArcticNet expeditions in Hudson Bay. The mean nutrient content and ratios of western rivers can be estimated by projecting to a salinity of zero the linear trends observed in the left-hand portion of each graph.

The relatively high nutrient concentrations in the subsurface waters of the Bay's interior imply that the rate of deep water exchange with adjacent marine source waters is slow enough to allow a deep accumulation of nutrients inside the Bay. Logically, this accumulation must be fuelled by internal processes through the physical injection of riverine nutrients by convection and/or the vertical export and decomposition of the organic matter produced at the Bay's surface or supplied by rivers. On the one hand, the relatively close match between interior and averaged exterior values for the nitrate:phosphate ratio suggest that a direct injection of riverine nutrients into the deep layer is not the dominant process (Figure 8). If that were the case, nitrate:phosphate ratios in deep Hudson Bay would be lower than outside the Bay (i.e., Foxe Basin and Hudson Strait) since western rivers deliver waters with N:P ratios < 4 (calculated using data from Figure 9). On the other hand, the relative high silicate:nitrate ratios are not inconsistent with a direct riverine source. The data shown in Figure 8 can be used to calculate the average nitrate and silicate increments between interior and exterior waters. The silicate:nitrate ratio of the increment is approximately 5, which is too high to reflect the decomposition of sinking diatoms with an average silicate:nitrate composition of 1 (Brzezinski 1985), yet much too low to reflect the silicate:nitrate ratios of western rivers (> 50).

A simple thought experiment assuming that the accumulation of nitrate and silicate in deep Hudson Bay waters is entirely fuelled by a combination of diatom export and physical river nutrient transfer shows that the latter can account for approximately 8% of the net accumulation. A consequence to this is that most of the river nutrients are eventually used by primary producers in surface waters. Because silicate is in large excess in the river outflows, it cannot be consumed as quickly as other nutrients and mixes in a semi-conservative manner with offshore marine waters. This situation makes silicate particularly



**FIGURE 10.** Average distribution of silicate at the surface of Hudson Bay for the 2005, 2007 and 2010 ArcticNet expeditions.

useful to track river water in the Bay. The silicate distributions shown in Figure 10 suggest that the coastal intensification in primary production discussed previously is driven by rivers, either through direct nutrient supply or entrainment and highlight differences in the nature of the eastern and western watersheds. Moreover, nutrient concentrations and ratios from river delivery are largely driven by the difference in watershed distribution. For example, the western and southern parts are composed of wetland complex whereas the eastern and northern parts are composed of sporadic or continuous permafrost (Vonk et al. 2015).

**Box 1. Eelgrass in Hudson Bay**

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**Eelgrass, *Zostera marina* L., is a true flowering plant** that lives submersed in the coastal ocean; it is the dominant seagrass of the Northern Hemisphere. It grows with a root and rhizome system in the sediments; its narrow green leaves extend into the water and reach toward the surface (Figure 1). Eelgrass flowers, pollinates, and sets seed under water. The plants reproduce both sexually from seed and vegetatively through extension of rhizomes beneath the sediment. Eelgrass occurs along the shores of the east coast of the USA and Canada as well as on the west coast of both countries and in Europe (Green and Short 2003). It is highly adaptable and is found from Baja, Mexico to Alaska on the west coast and from North Carolina to Greenland and Hudson Bay on the east coast



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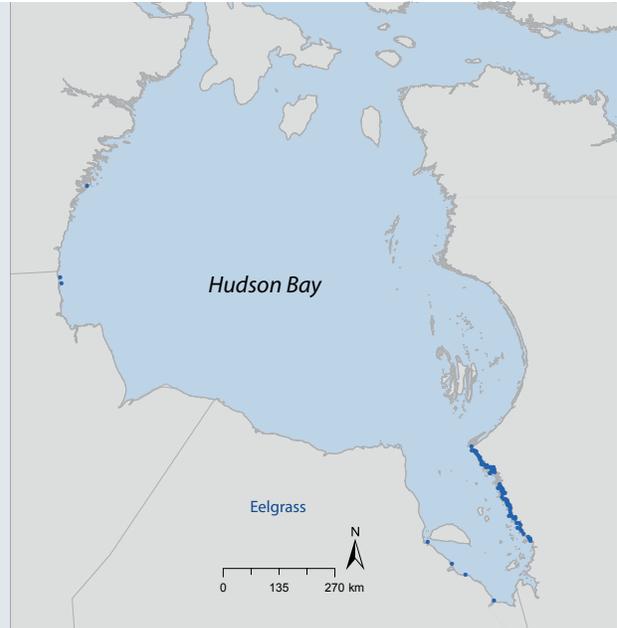
**FIGURE 1.** Eelgrass, *Zostera marina* L. in James Bay at Attikuan Point.

of North America. Eelgrass is known to occur sporadically around the coast of Hudson Bay (Figure 2), although observations are limited; in James Bay, part of southern Hudson Bay, dense and extensive eelgrass beds have been documented since the 1970s (Curtis 1975).

Eelgrass contributes many important functions and values to the coastal and estuarine areas where it grows (Green and Short 2003, Nordlund et al. 2016).

It provides a three-dimensional structure in the water column that is a nursery for fish and shellfish. Brant, ducks and geese all feed on parts of the eelgrass plant and eelgrass beds are way stations in these birds' migration. In James Bay, eelgrass is important in the life cycle of trout and cisco. Additionally, eelgrass filters the waters where it occurs, reducing suspended sediments and excess nutrients that flow to the coastal ocean from the watershed. It also damps waves along the shore.

Eelgrass is able to tolerate a wide range of growing conditions, both subtidal and intertidal (Moore and Short 2006). It can grow under Arctic winter ice as well as in near-semi-tropical conditions at the southern edge of its range, and it is able to



**FIGURE 2.** Eelgrass distribution in Hudson Bay, Canada as reported to date.

grow in fairly high currents. The plant is dependent on the light that reaches it through the water column and therefore requires clear water in order to thrive. Eelgrass tolerates salinity levels from 5 to 36; its temperature tolerances range from -2° to 28°C. Eelgrass typically grows in sandy, muddy substrates but is found in a wide range of sediments from very fine-grained muddy silt to coarse-grained gravel. Typically, it grows in mono-specific meadows which range in size from small patches of 1 m<sup>2</sup> or less to huge, multi-hectare expanses.

There are several threats to eelgrass habitat, which may impact the plants concurrently. The two greatest threats to eelgrass throughout its range are impacts which reduce water clarity: nutrient pollution and suspended sediments. Each of these threats decreases the amount of light reaching the plants, which has been shown to have a direct effect on plant photosynthesis and growth. Suspended sediments from runoff and resuspension cloud the water in which eelgrass grows and reduce the amount of light reaching the bottom. Nutrient pollution, both point and non-point source, encourages the growth of phytoplankton and macroalgae, and these plants interfere with the ability of eelgrass to receive light through the water column. Some macroalgae is free floating, other macroalgae may occur as epiphytes growing attached to eelgrass leaves. Low salinity also has an adverse impact on eelgrass growth, through metabolic stress at salinities lower than 10 (Short 2008). Eelgrass is also subject to direct

physical damage from boating and mooring practices, from coastal dredging, filling, and pier building, and from some fishing methods such as clam and mussel dragging as well as aquaculture practices, all of which have the potential to degrade or eliminate acres of eelgrass habitat. Sea level rise and climate change may also affect eelgrass growth (Short and Neckles 1999).

Another impact to eelgrass is a disease of the plant known as the “wasting disease,” caused by the protist *Labyrinthula zosterae* (Short et al. 1988). The wasting disease organism is endemic in eelgrass populations and can almost always be found growing at some level within eelgrass beds, occurring as black spots and patches on the leaves. During a severe outbreak of the disease, plants blacken and die and the leaves break off in large numbers. In the 1930s, eelgrass in the USA, Canada, and Europe was severely impacted by wasting disease and vast die-offs occurred throughout its range. Over several decades, the plants recovered, although in some locations eelgrass never regained its historic distribution. The wasting disease organism has been shown to be most virulent in higher salinity locations; the disease does not spread at low salinities (Burdick et al. 1993).

In Hudson Bay, at the more northerly end of the eelgrass range, eelgrass begins its spring growth under the ice (McRoy 1969) in May and June. Eelgrass grows rapidly during the long days of summer, especially in July, and reaches its maximum annual biomass in September when declining day length, waterfowl grazing, and eventually, new ice formation and lower temperatures, start to reduce plant biomass and slow the plants’ growth once again (Short et al. 1989, Lalumiere et al. 1994). The brief summer growing season is critical to eelgrass survival in James Bay. The plants flower and produce seed during the summer and expand vegetatively to maintain large eelgrass meadows (Lalumiere et al. 1994). Eelgrass habitat supports trout and cisco populations in James Bay. Ducks, brant and Canada geese stop over at eelgrass meadows during their migrations along the bay. Cree traditional practices include extensive goose hunting in both spring and fall on the Bay. Eelgrass supports the biodiversity of James Bay.

In recent years, there has been a documented decline in eelgrass in James Bay (Cree Traditional Knowledge, Pachano et al. 2015, Consortium Genivar-Waska 2017). The decline of eelgrass in James Bay was first reported by the Cree Nation from their observations while hunting and fishing. Since 1996, there has been less eelgrass habitat overall in James Bay and the eelgrass has been less healthy (Cree trappers, Pers. comm., Lalumiere and Lemieux 2002). The decline of eelgrass and shifts in distribution of geese in east James Bay has affected



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**FIGURE 3.** Eelgrass (*Zostera marina* L.) impacted by a mat of bluegreen algae in Bay of Many Islands, James Bay.

the coastal Cree Nations, their traditional hunting and fishing practices, and their indigenous way of life. Eelgrass in some places is sparse; in other areas it has disappeared altogether. Some eelgrass remains healthy but much of the eelgrass habitat in James Bay now is impacted to some degree by low salinity waters, overgrowth of seaweeds and epiphytes, and by reduced water clarity.

Scientific research, based on Cree traditional knowledge and using up-to-date monitoring techniques, is now under way in James Bay to determine the causes of eelgrass loss. The problem is complex because there have been many environmental changes in Hudson and James Bay during recent decades. Cree Nation trappers are monitoring their trapline coastal areas using GPS, computer tablets and underwater video cameras. Their work is creating an extensive and permanent sampling record of coastal conditions and eelgrass distribution along the coast. Using this information, along with measurements taken by other instruments and ocean, river and eelgrass scientists working with the Cree, will enable further and more complete understanding of the reasons for eelgrass loss in the James Bay ecosystem. The coastal habitat research project is overseen by a Steering Committee established by Niskamoon Corporation and involving Cree Nations and Hydro Québec. It involves university researchers from UNH, Université du Québec à Montréal, Université du Québec à Rimouski, and University of Manitoba.

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## 6. Trends, future scenarios and knowledge gaps

The Hudson Bay system is especially sensitive to climate-related changes due to its subarctic location and the presence of a seasonal ice cover. Numerous studies have highlighted environmental changes that bear on the availability of light and nutrients, including a decrease in sea-ice extent (Parkinson et al. 1999), an increase in average annual air and sea surface temperatures (Galbraith and Larouche 2011), earlier ice breakup and delayed ice formation (Gagnon and Gough 2005a; Hochheim and Barber 2014). The rise of average temperature in surface waters has been faster in recent decades than before (Gagnon and Gough 2005b). Impacts on hydrology have also been reported, including the advance of snowmelt runoff (Westmacott and Burn 1997) and a decline in annual streamflow (Déry et al. 2005). Further analyses revealed that inter-annual fluctuations in river discharge into Hudson Bay were related to precipitation patterns driven by the Arctic Oscillation (Déry and Wood 2004, 2005) against a general decreasing trend that might reverse in the future (Déry et al. 2005, 2011). By contrast, discharge from the wettest, south-eastern portion of the Nelson watershed has increased over the last century (McCullough et al. 2012) and is expected to increase further (Clair et al. 1998). Freshwater supply is also expected to rise in eastern Hudson Bay with the predicted increase of precipitation over northern Quebec in the 21st century (Sottile et al. 2010). Overall, there has been a notable shift towards higher winter discharge into the Bay (Déry et al. 2011).

Freshwater fluxes into Hudson Bay have been and will continue to be impacted by flow regulation for the purpose of hydroelectric power generation, agricultural irrigation and flood control (Déry et al. 2011). The cumulated impacts of these activities on the Nelson and La Grande rivers were documented by Anctil and Couture (1994) and Prinsenber (1980, 1983), who reported a suppression of the strong seasonal cycle that characterized these rivers in their prior unaltered state. This suppression resulted in the temporal flattening of hydrographs (Déry et al. 2011) and, presumably, nutrient deliveries throughout the year. While the discharge of regulated rivers into the Bay is also susceptible to the climate-driven impacts discussed above, spreading out the extra flow over the year versus concentrating a large portion of it within the spring freshet, as is the case in unregulated rivers, is likely to have different impacts on nutrient loading and water transparency. Before these impacts can be assessed, however, a much broader knowledge base of riverine nutrient concentrations and how these concentrations covary with discharge is required. This covariation has been shown to be nutrient-specific, seasonal and often substantial in other areas (e.g.,



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McClelland et al. 2012) and must be understood before a bay-wide estimate of nutrient discharge can be extrapolated from the few rivers in which nutrient data are monitored.

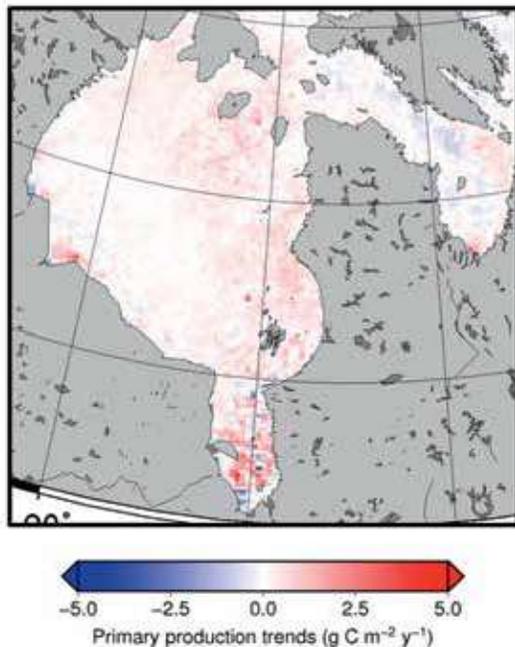
Deliveries of nutrients and organic matter by rivers are also likely to be affected by warming and thawing permafrost, but this export may increase in some regions and decrease in others depending on vegetation, soil composition and microbial activity. Moreover, increased shoreline erosion associated with decreasing ice cover should enhance diffuse inputs of sediment, nutrients, and organic matter around the Bay. The greater light attenuation resulting from enhanced sediment loads (e.g., McClelland et al. 2012) might attenuate or delay the positive impact of nutrient subsidies on nearshore phytoplankton, ice algae (through the production of 'dirty' ice) and eelgrass beds. Dissolved organic nitrogen (DON) loading from major Arctic rivers is a potential source for primary production during post-bloom periods on shelves (Shen et al. 2012; Tank et al. 2012). The labile portion of this DON is usually small, but can be supplemented by photo-ammonification (Le Fouest

et al. 2013). Unfortunately, there is no data on DON availability in Hudson Bay (Kuzyk et al. 2010).

Beyond its immediate positive impact on nutrient availability nearshore, increased river flow leads to increased stratification offshore. This increase can be augmented by reduced ice formation and the ensuing decrease in winter convection (i.e., vertical mixing), resulting in decreased upward nutrient supply and lower overall biological productivity at the bay-wide scale (e.g., Joly et al. 2011). In this scenario, the relative contribution of river nutrient supply to bay-wide productivity is likely to increase while the contribution of oceanic, vertical nutrient supply processes declines. Given the large area covered by central Hudson Bay, these opposing trends would likely lead to an overall decrease in productivity for the system as a whole but possibly favour greater planktonic productivity in coastal EBSAs if water transparency does not decline too strongly. In addition to changes in the magnitude of productivity, the seasonal peak of primary production is likely to shift forward, thereby affecting the coupling between

primary producers and consumers as well as the vertical export of organic matter to the benthos. At the same time, loss of the sea-ice cover and a greater frequency of extreme weather events may enhance episodic wind-driven mixing and upwelling in some areas, notably in Hudson Strait, northern Hudson Bay and the Belcher Islands EBSA. Given the relatively high inventories of nutrients and silicate in particular within the subsurface waters of the Bay's interior (Figure 8), these events could lead to substantial increases in diatom productivity.

Remote sensing studies recently pointed to a small, but not significant increasing trend in bay-wide primary production from 1998 to 2010, with the largest increases occurring close to the Nelson River, in James Bay and in the eastern half of Hudson Bay (Figure 11). These trends are explained mostly by the shortening of the ice-covered period and the extension of the growth season for phytoplankton in these areas. There is no indication that surface Chl *a* biomass (an intermediate variable assessed by remote sensing and used in the primary production algorithm; not shown here) has increased in estuaries, which suggests that river nutrient deliveries have not changed appreciably. However, the inter-annual variability (not shown) is relatively large and the time series is presently too short to examine whether the trends shown in Figure 11 are part of decadal, hemispheric climate patterns (e.g., North Atlantic or



**FIGURE 11.** Trends in satellite-based annual primary production in the Hudson Bay system for the period 1998–2010 (Figure 5B). This figure was produced using data from Bélanger et al. (2013).

Arctic Oscillation), notwithstanding the methodological challenges resulting from the presence of CDOM and the inability of satellites to detect Chl *a* in the SCM and under sea ice.

## 7. Conclusion

While climate change and flow regulation might impact the estuarine and marine ecosystems of Hudson Bay in several ways, our basic understanding of how the biota 1) responds to atmospheric forcing of the upper ocean and sea ice, 2) is affected by the timing and volume of regulated or unregulated river flow, and 3) affects freshwater-marine coupling by processing inorganic and organic nutrients in different sectors of the Bay remains rudimentary. This knowledge gap is largely due to the paucity of synoptic riverine and bay-wide data, especially for the winter-summer transition period when the majority of annual biogeochemical fluxes presumably take place. Most of the fragmentary scientific knowledge of ecological processes in the Bay has been obtained during late summer and fall (Estrada et al. 2012; Lapoussière et al. 2013), whereas modelling efforts based on these data have focused on the central area of the Bay (Sibert et al. 2011). Resolving seasonality and focusing on the critical spring-summer transition are necessary steps toward evaluating the ecological consequences of climate change and flow regulation on the lower food web. This objective will require new observations in the field as well as improvements in our ability to accurately estimate primary production from space and the contribution of under-ice and SCM microalgae to annual productivity.

In parallel to the strictly bottom-up effects of change, warming challenges the uniquely adapted consumers (from bacteria to zooplankton, seals and polar bears) that depend on cold temperatures and sea-ice habitats for nutrition, refuge or reproduction. Reductions in the population size and geographical range of these species, in combination with shifting migratory patterns and northward intrusions by temperate species, will likely alter biodiversity and reshape ecological interactions, with effects rippling down the lower food web. The cumulated impacts of multiple stressors on these species and associated food webs in the short-term (e.g., physiological acclimation, behavioural response) and longer term (e.g., population changes in long-lived mammals, rapid evolutionary adaptation) are poorly known and will need to be addressed with new knowledge and innovative modelling tools. The ongoing BaySys network is expected to close some of these knowledge gaps, notably those pertaining to the influence of the physical environment on the productivity of micro-algae and zooplankton at the base of the food web.

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## II.iii

# Communities of Benthic Invertebrates in the Hudson Bay Marine Region

## AUTHORS

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## Key Messages

- Our knowledge of benthic invertebrates from the Hudson Bay Marine Region is very limited. With an increasing number of research programs, the number of known benthic species keeps increasing (currently 637 taxa). Contrary to what we previously thought, this ecoregion could be a productive marine environment in the Arctic.
- Coastlines in the Hudson Bay Marine Region exhibit a higher biodiversity than offshore, with a large composition of mollusks such as mussels, clams and scallops. The center of the bay shows a low biodiversity with a high composition of sea stars, brittle stars and annelids.
- Modeling studies already show potential changes in salinity along the coast and in the sustainable habitat of benthic species. Changes to the environment may cause changes in some species distribution, and may lead the way for aquatic invasive species.
- It is essential to continue to increase our knowledge about the benthic biodiversity in the Greater Hudson Bay Marine Region in order for communities to identify and manage areas for conservation or areas with a high economic interest.

## 1. Introduction

Organisms which inhabit the seafloor (or bottom of lakes and rivers) are called benthic organisms, or “benthos”. Mainly composed of invertebrates, benthos (animals living on, in, or near the seafloor) are an important component of food webs, providing a source of food for many species of fish, birds and mammals. Benthic organisms that live inside the sediment (infauna, such as clams and worms) and on the surface of the sediment (epifauna such as mussels, crabs and sea stars) are either fixed in one place or have low mobility. Because of their low mobility, benthic organisms are known to be a good indicator of the health of the ecosystems and can be used to assess changes in the marine environment. Recent studies have shown a temporal shift in Arctic benthic communities revealing a change in the composition of benthic assemblages due to variations in ice cover affecting local food supply (Cusson et al. 2007; Renaud et al. 2007; Taylor et al. 2017). Such a result was not highlighted yet in the Greater Hudson Bay Marine Region because datasets on benthic invertebrates

are scarce. However, with climate and hydrological changes to the Hudson Bay Marine Region, programs to develop a better understanding of benthic biodiversity have increased over the past decade thanks to scientific programs like MERICA (2003), ArcticNet (2010 and 2015 specifically in Churchill), CHONe (Snelgrove et al. 2012), BaySys (2016; 2018), CAISN (2011; 2012) (specifically in Churchill, Goldsmit et al. 2014) and BriGhT (Bridging Global Change, Inuit Health and the Transforming Arctic Ocean) (2017).

## 2. Benthic diversity

How many benthic species do live in the Hudson Bay Marine Region? There is no easy answer to that question. Based on historical data, Cusson et al. (2007) reported 167 species in Hudson Bay, a low species richness compared to other Arctic regions focusing only on animal living in the sediment.

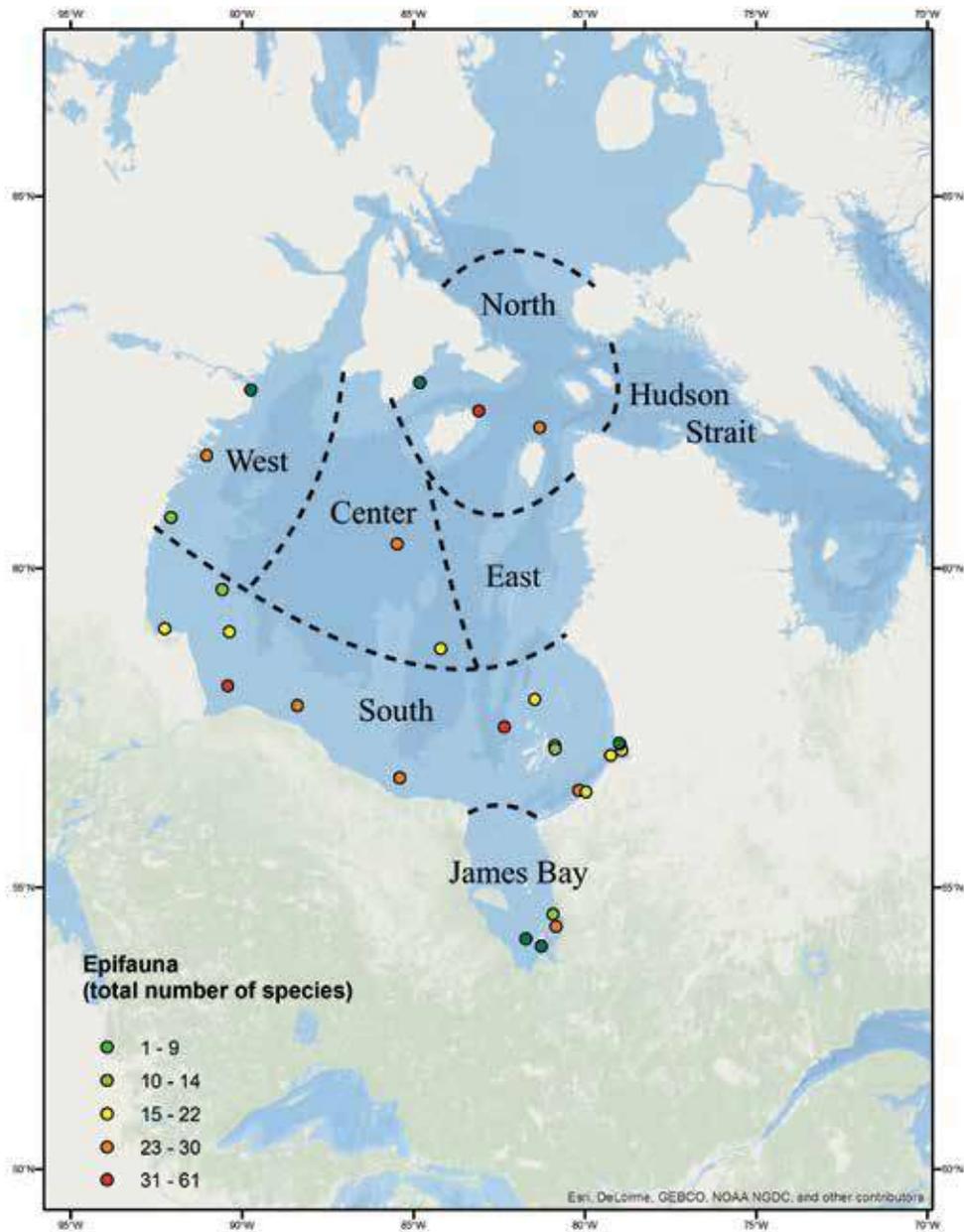
Piepenburg et al. (2010) extended this number to 290 but only 4 major groups of invertebrates were considered (Annelida i.e worms, Echinodermata i.e. sea stars and urchins, Mollusca and Arthropoda). By gathering available historic (Atkinson and Wacasey 1989; Wacasey et al. 1976) and recent data, a total of 643 taxa has recently been recorded in the Marine Region. Goldsmit et al. (2014) identified 84 taxa and 136 taxa for coastal subtidal (< 20 m deep) and intertidal zones in Churchill and Deception Bay (Hudson strait) respectively.

### 2.1. Epifauna

Efforts regarding epifauna sampling were limited in the Hudson Bay Marine Region. However, some trends appear to be relevant. Epifauna composition varied from North to South across the study region (Figure 1). The North of the Bay presents a bottom composed by silt and presented a higher abundance of arthropods such as polar shrimp (*Lebbeus polaris*) or seveline shrimp (*Sabinea septemcarinata*). The Center of the



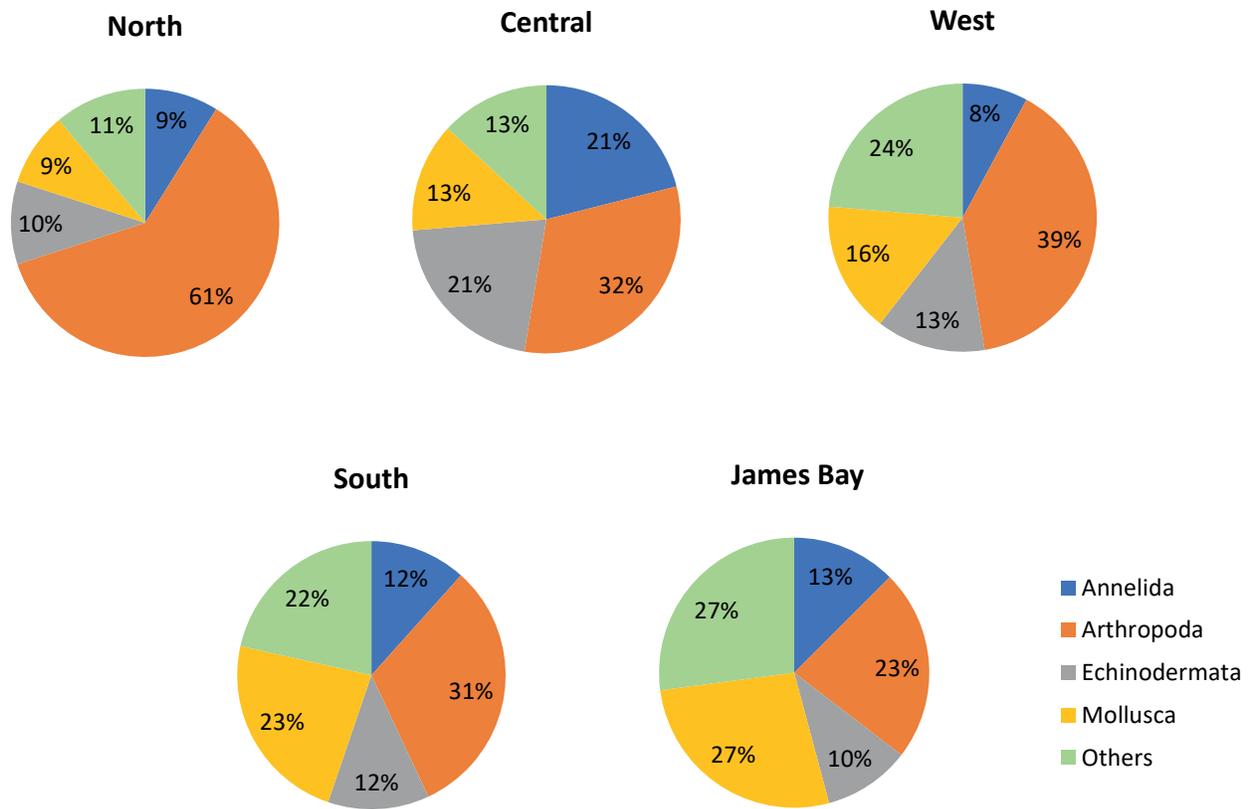
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**FIGURE 1.** Epifauna biodiversity (total number of species) collected in the Hudson Bay Marine Region from 1955 to 2010. Regions of the Hudson Bay are delimited and modified according to Wilkinson et al. (2009).

Bay is characterized by a high quantity of organic carbon and a muddy bottom. Due to these characteristics, this region was mainly composed by deposit feeders, such as annelid worms, sea stars and urchins, which feed on detrital particles (Figure 2). The South and the region of James Bay are located near the margin of the Bay and more specifically close to rivers

where there is greater streamflow (Déry et al. 2016) suggesting a sandy and rocky bottom. These regions exhibited more species tolerant to salinity variations such as arthropods (*Atylus carinatus* and *Eualus* sp.) and filter feeders (organisms which collect food by pumping water through or across their bodies) such as mollusks and other organisms (including sponges)



**FIGURE 2.** Relative composition of benthos living in the sediment (epifauna) for each area of the Hudson Bay Marine Region. ‘Others’ includes sponges, peanut worms and other benthic organisms.



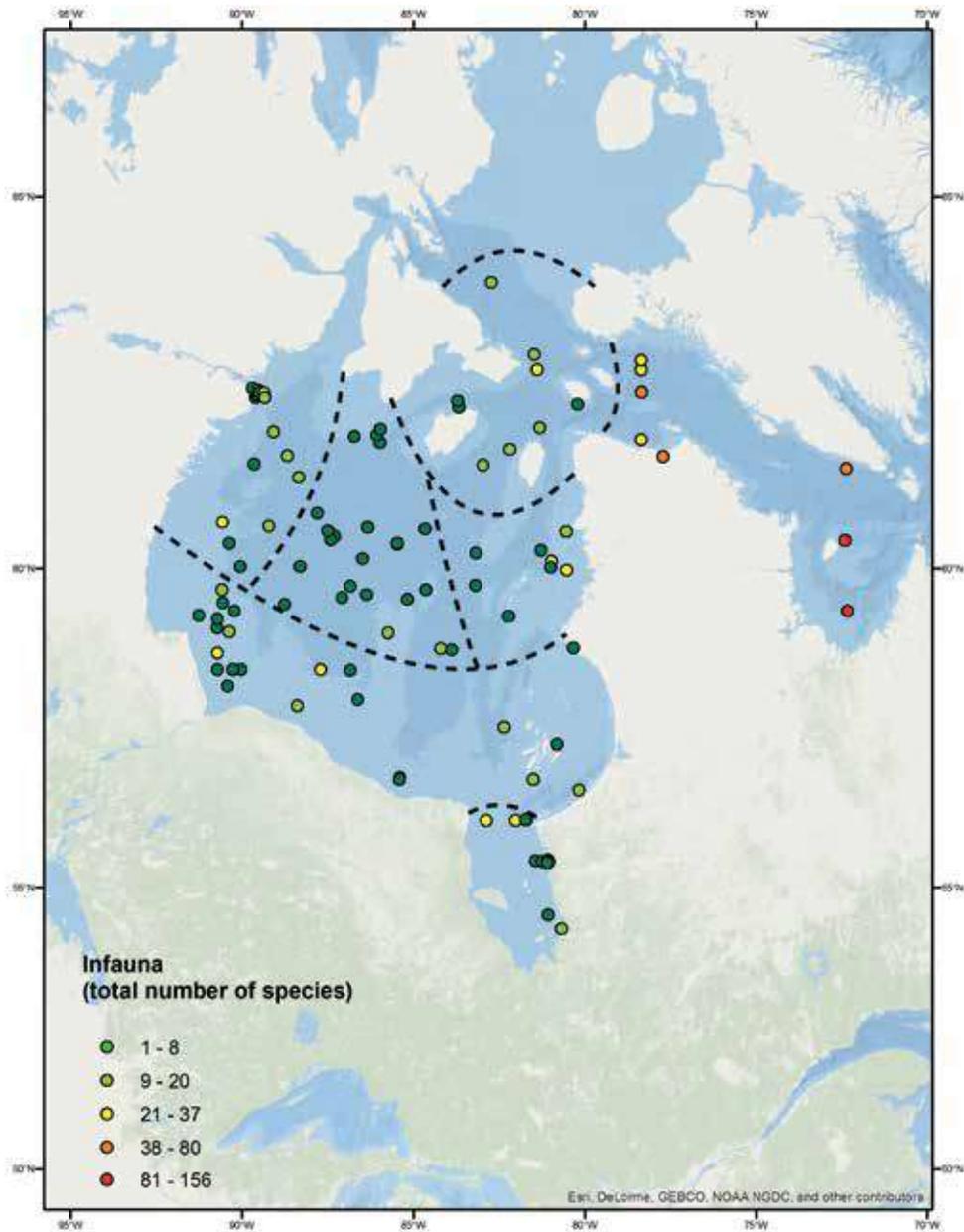
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(Figure 2). Finally, James Bay presented the lowest species richness compared to the South and the Center of the Hudson Bay (Figure 1).

Despite the lack of data, we highlighted differences in epifauna biodiversity mostly explained by differences in sediment composition (muddy, sandy or rocky bottom). However, to better understand the structure of epifauna communities, the freshwater impacts on these communities, and to anticipate the consequences of climate change in the Region, it is necessary to continue the ongoing work.

### 2.2. Infauna

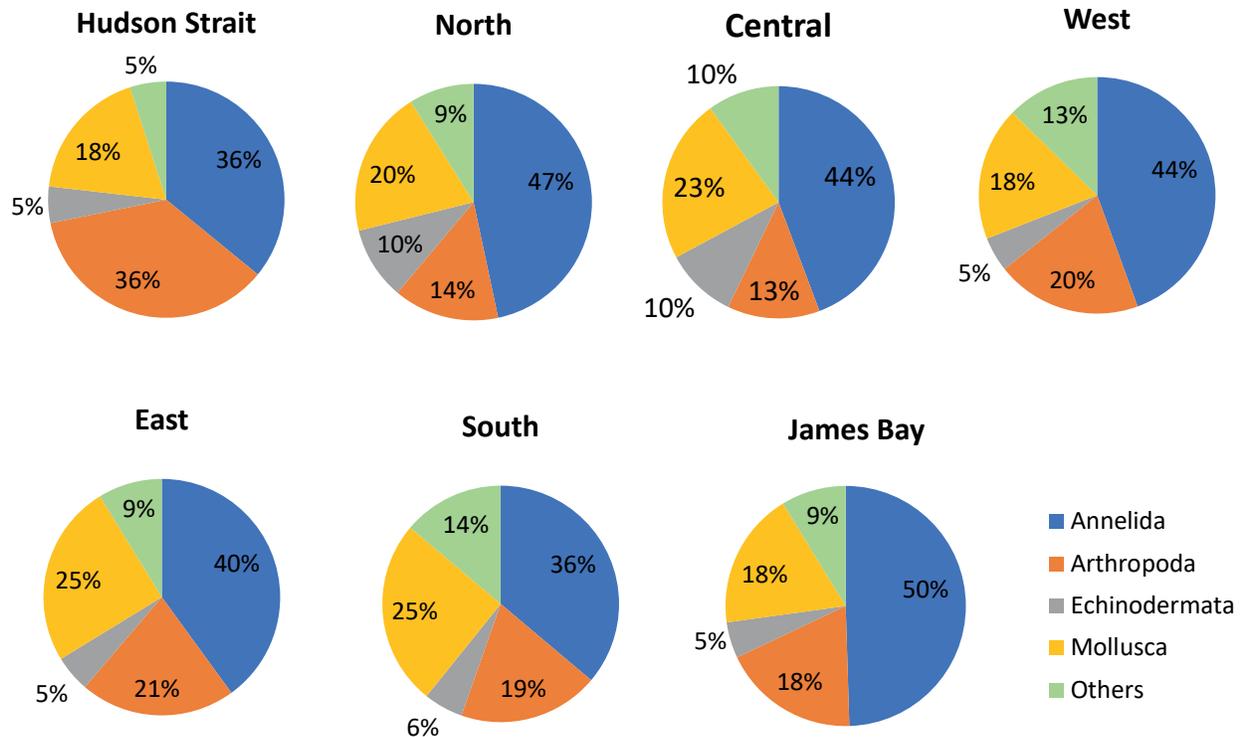
In contrast to the general pattern observed for epifauna communities, infauna communities have shown subtle differences among regions and have more complex patterns. Infauna have shown a lower biodiversity in the Bay, while Hudson Strait exhibited more diverse infauna communities (Figure 3). The center of the Hudson Bay showed a lower biodiversity whereas the West and the East of the Bay showed a higher infauna richness (Figure 3). Interestingly, these areas seem to coincide with the formation of polynyas (areas of persistent open water). Polynyas



**FIGURE 3.** Infauna biodiversity (total number of species) collected in the Hudson Bay Marine Region from 1955 to 2010. Regions of the Hudson Bay are delimited and modified according to Wilkinson et al. (2009).

are generally known to promote greater primary productivity due to increased nutrients and light availability. In these areas, the higher diversity observed could be explained by higher concentrations of potential food sources for benthic animals at the surface of the sediments, which are directly related to high levels of primary production in the surface waters of polynyas

(Kuzyk et al. 2010; Kenchington et al. 2011). In all regions, annelid worms were abundant, representing 35% of all species combined (Figure 4) while mollusks represented about 20% in each region. The same pattern was found for the North and the Center of the Bay with a higher proportion of deposit feeders such as sea stars and urchins compared to the other regions (Figure 4). The same



**FIGURE 4.** Relative composition of benthos living in the seafloor (infauna) for each area of the Hudson Bay Marine Region. ‘Others’ includes sponges, peanut worms and other benthic organisms.

observation can be noted for the South and James Bay areas, while for those regions, suspension-filterers feeders (clams *Mya truncata* and blue mussels *Mytilus edulis*) were dominant.

Compared to epifauna, infauna data cover a larger portion of the Hudson Bay Marine Region. Despite a larger amount of data, infauna community patterns are not perfectly understood and the environmental parameters influencing those communities are not yet identified.

### 3. Projected impacts on benthic ecosystem

Our knowledge about benthos from the Hudson Bay Marine Region is very limited and consequences of climate change on those communities are thus difficult to anticipate (see Goldsmit et al. (2017) for potential invasive species). Changes in the Hudson Bay Marine Region are already ongoing and baseline studies still have to be conducted. Moreover, the ecosystem response to a change in the environment varies depending on the ability of the environment to withstand these disturbances and its level of resilience, i.e. the capacity of the benthic ecosystem of Hudson Bay complex to recover from perturbations (Downes et al. 2002). The resilience of benthic communities in Hudson Bay is unknown and still needs to be established.

Modeling studies already show potential changes in salinity along the coast and in the sustainable habitat of benthic species. Changes in environmental parameters may induce changes in some species distribution. Goldsmit et al. (2017) highlighted the occurrence of potentially suitable habitats for aquatic invasive species such as the commercial clam (*Mya arenaria*) in the south of the Hudson Bay and in



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James Bay and for the red king crab (*Paralithodes camtschaticus*) in the Hudson Bay Marine Region. These species may affect the structure of benthic communities (decline in some epi-infauna organisms such as mollusks) (Oug et al. 2011) and finally benthic ecosystem services. For example, the clam *Mya truncata* represents a main food source for walrus and an important subsistence food resource for Inuit (Wagemann and Stewart 1994; Skoglund et al. 2010). Based on projections of climate change and increased freshwater discharge in south-eastern Hudson Bay, clams could be affected by increased freshwater runoff and their abundance may decline, indirectly affecting walrus.

Kennington et al. (2011) identified Ecologically and Biologically Significant Areas (EBSAs) in the Hudson Bay Marine Region to draw attention to areas of particularly high ecological or biological importance for suitable management. In view of climate change and variation in runoff, the Hudson Bay System Study (BaySys) aims to understand and predict spatial changes (habitat suitability) for benthic communities within the Hudson Bay Marine Region. The prediction and monitoring of



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benthic communities in the Greater Hudson Bay Marine Region becomes necessary to review the EBSAs boundaries and to ensure that management decisions are made based on the best information available.

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## II.iv

# Hudson Bay Fish and Fisheries

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### Summary

Coastal and marine fish species composition varies greatly throughout the region and this variation is reflected in the subsistence fisheries as well as the commercial fisheries in the Kivalliq and Hudson Strait. There has been a shift in the presence and abundance of some fish species and locally there are observations of new species not historically found in those areas. However, not much is known about the biodiversity, distribution and abundance of coastal and offshore fish and invertebrate species, nor about the life histories of the key anadromous species in the region.

This chapter provides an overview of known fish assemblages in the Greater Hudson Bay Marine Region, the subsistence fisheries of Arctic char, and observed changes in fish assemblages and stressors on species related to climate change.

### Key Messages

- **There are 61 recorded fish species in the Hudson Bay marine region but information about their distribution is sparse.**
- **Fish species in the Hudson Bay region consist of species typical of the high Arctic such as Arctic cod and species typical of lower latitudes such as capelin and shannies.**
- **Characteristically Arctic species are more abundant in the central and eastern areas of the Hudson Bay and the Hudson Strait while characteristically sub-arctic species are common in the West and South of the Hudson Bay and James Bay.**
- **Larval fish surveys and studies of predators' diets show that there is a shift in species composition that started between the '90s and early 2000s; capelin has become more abundant while Arctic cod populations have been declining.**

## 1. General diversity and distribution of fish in Hudson Bay

At least 61 fish species representing 31 families are confirmed to inhabit the Hudson Bay marine region (Vladykov 1933; Morin and Dodson 1986; Stewart and Lockhart 2005). Appendix A provides common and scientific names and families of each of these species. Among all species, nine are diadromous, i.e., migrate between fresh and marine waters seasonally or over life. The most important anadromous

species for the economy and subsistence of the Inuit communities (Stewart and Lockhart 2005) is the Arctic char (*Salvelinus alpinus*). In southern Hudson Bay and James Bay, Cree harvest other coastal fish species such as lake whitefish (*Coregonus clupeaformis*), cisco (*Coregonus artedii*) and sea-run brook trout (*Salvelinus fontinalis*). Thirty-five species found in Hudson Bay are marine and the remaining ones are species that live mainly in freshwater but can also occasionally live in brackish water (i.e. slightly salty water). On the whole, an important ecological adaptation by many marine and freshwater species persisting in Hudson Bay is tolerance to important changes in salinity and exploitation of brackish waters which occupy an extensive zone of the bay (Morin and Dodson 1986; Schneider-Vieira, Baker, and Lawrence 1994; Stewart and Lockhart 2005).



C. AUBRY

## 2. Marine fish

The available published literature on marine fish of the Hudson Bay marine region and their abundance is still very limited due to lack of commercial interest from the fishing industry and the remoteness of the area (Morin and Dodson 1986; Stewart and Lockhart 2005).

Some spatial patterns are observed among the marine fish communities of the Hudson Bay system. For example, based on different bottom-trawl surveys in Hudson Strait in the 1970s (MacLaren Marex Inc. 1978; Imaqpiq Fisheries Inc. 1981; Morin and Dodson 1986), the number of Arctic cod (*Boreogadus saida*) and the biomass of Greenland halibut (*Reinhardtius hippoglossoides*) increase toward Eastern Hudson Strait and Davis Strait. In western Hudson Strait, Arctic cod is replaced by lumpfish (*Cyclopterus lumpus*) and snailfish from the family Liparidae (Morin and Dodson, 1986). The full extent of these patterns cannot be understood until more surveys are carried out in the area. However, in general the biomass and the number of marine fish in Hudson Strait decrease toward the west and could be even lower in Hudson Bay proper (Morin and Dodson 1986).

Perhaps unsurprisingly, species that characterise the arctic ecosystem are less common in the south of Hudson Bay whereas they seem to dominate the assemblage in the north (Stewart and Lockhart 2005). Except for this latitudinal change in arctic species abundance, no thorough picture of the distribution or of east-west and north-south gradients of the different fish species in Hudson Bay can be provided due to lack of information.

Hudson Bay seabird and marine mammal diets consist mostly of Arctic cod, capelin (*Mallotus villosus*) and sand lance

(*Ammodytes* spp.) (Gaston and Woo 2008; Provencher et al. 2012; Chambellant, Stirling, and Ferguson 2013; Gaston and Elliott 2014; Yurkowski et al. 2016). This indicates the important role that these fish species have in transferring energy from lower to upper trophic levels within the Hudson Bay marine food web. Hence, thus far, studies of Hudson Bay marine fish have focused on these three species. Although Arctic cod seems to be ubiquitous in Hudson Bay (Vladykov, 1933; Fortier et al., 1995; Coad and Reist 2004), its abundance may have decreased in the last decades. The proportion of Arctic cod in the diets of top predators is diminishing, possibly as a response to environmental changes caused by climate change (Gaston, Woo, and Hipfner 2003, 2012; Provencher et al. 2012; Chambellant, Stirling, and Ferguson 2013; Gaston and Elliott 2014). While the incidence of Arctic cod in their predators' diet has decreased, the incidence of capelin and sand lance has increased (e.g. Gaston et al. 2003) suggesting a shift in the fish community from hyper-specialised arctic species to generalist subarctic ones.

## 3. Coastal fish

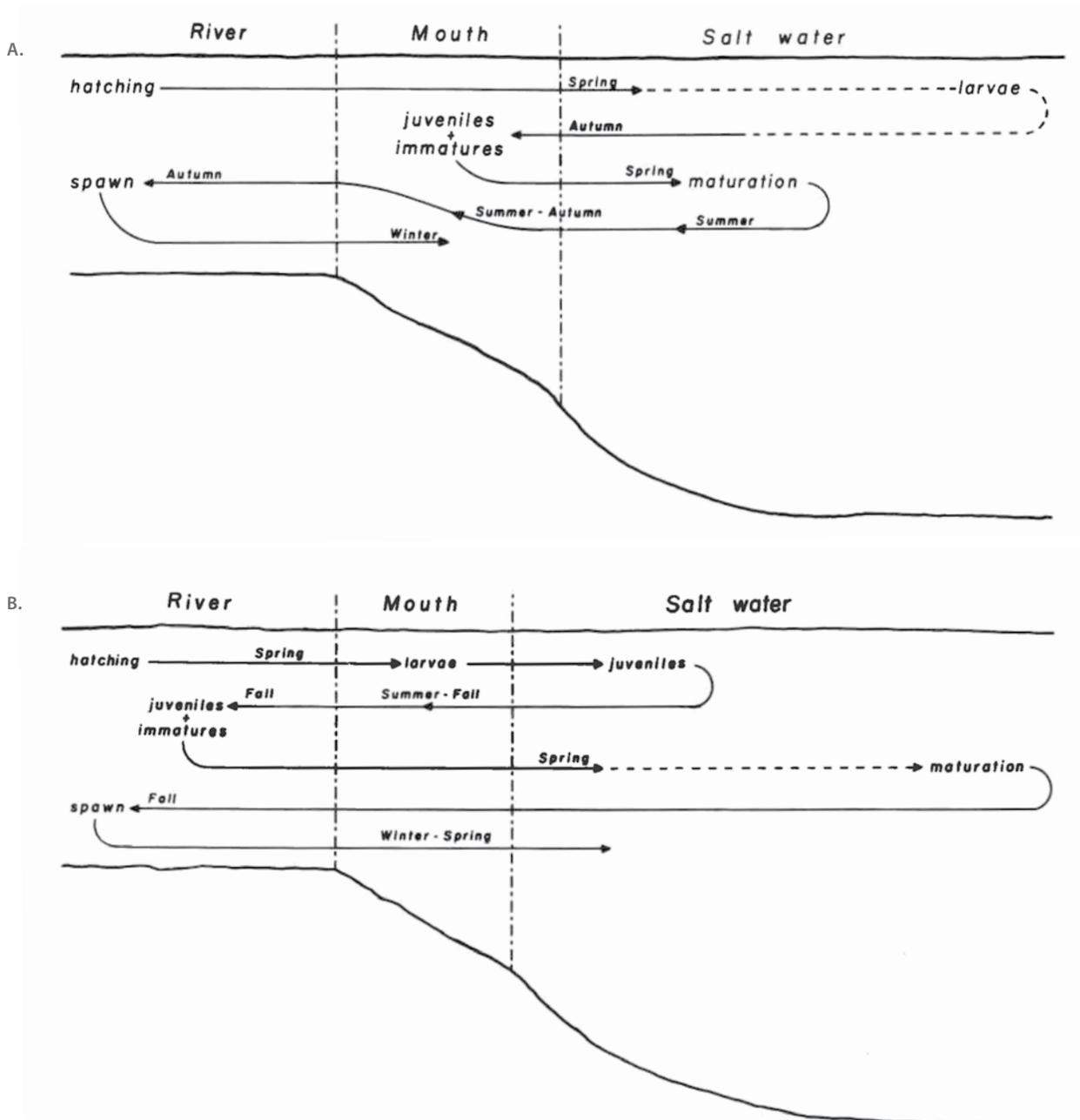
The Hudson and James bays are encircled by a multitude of estuaries where facultative anadromous salmonids, essentially, lake whitefish and cisco predominate (Schneider-Vieira, Baker, and Lawrence 1994). These species are important forage species for marine predators such as beluga whales (*delphinapterus leucas*) and Arctic terns (*sterna paradisaea*) (Watts and Draper 1986; McDonald, Arragutainaq, and Novalinga 1997). Other anadromous salmonids (e.g., round whitefish, Arctic char and brook trout) are also present. Moreover, brackish waters in the estuaries act as refugia for several freshwater, anadromous, diadromous and marine species thanks to the ideal temperature and salinity that provide a highly productive environment. In fact, estuaries often serve as nursery areas for some fish species (Morin, Dodson, and Power 1980; Ochman and Dodson 1982; Gilbert et al. 1992; Stewart and Lockhart 2005), for example; estuaries on the West coast of Hudson Bay are nursery grounds for capelin (Stewart and Lockhart 2005).

Dispersions of fish species in rivers and estuaries of James Bay and southern Hudson Bay largely correspond with physical properties of water such as salinity but it also depends on post-glacial distribution. Obligate freshwater species can be found in estuaries of James Bay – which have low salinities – but not in Hudson Bay, while diadromous and marine species that use brackish water in their life cycle (such as capelin and sand lance) can be found in essentially all coastal areas of the Hudson Bay marine region. Likewise, typically Arctic and sub-arctic species are more prominent in Hudson Bay estuaries than in James Bay estuaries (Morin, Dodson, and Power 1980).

### Coregonids

Facultative anadromous salmonids from the Coregoninae subfamily, such as cisco, lake whitefish and round whitefish, migrate to estuaries to feed and overwinter in freshwater (see

Figure 1 for the general life cycle of cisco and lake whitefish). cisco and lake whitefish presence in Hudson Bay and James Bay rivers and estuaries does not follow a latitudinal trend in distribution. However, different migration and reproductive patterns



**FIGURE 1.** The life cycle of anadromous cisco (a) and lake whitefish (b) in coastal region of James Bay. Horizontal lines indicate the movements through the freshwater, river mouth, and saltwater zone from hatching to post-spawning. Arrows indicate the direction of movements. Dashed lines indicate movements that are speculative. The vertical arrangement of lines bears no relation to the depth distribution. (Figure reproduced from Morin, Dodson and Power 1981)



G. DARNIS/ARCTICNET

have been observed between and within species. These differences may be influenced by differences in the energetic costs of migration between species and populations (Kemp, Bernatchez, and Dodson 1989).

Genetic studies using mitochondrial DNA (DNA inherited exclusively from the mother and thus undergoes less changes through generations), allowed scientist to shed light on past and contemporary events that shaped coregonids' genetic diversity in Hudson Bay. Lake whitefish in northern Hudson Bay are similar to the Atlantic assemblage when examining mitochondrial DNA. This implies that lake whitefish in Atlantic refugia used low salinities of coastal waters to expand their habitat to Hudson Bay during the deglaciation period 11000 – 10000 years ago (Bernatchez and Dodson 1991). Conversely, analyses of mitochondrial DNA revealed that anadromous cisco populations in Hudson Bay and James Bay are quite discrete. This leads to the hypothesis that cisco populations are derived from at least two glacial refugia and they recolonized the area by two major postglacial routes. Furthermore, in Hudson Bay there was a population subdivision between rivers, but this was not the case in James Bay rivers (Bernatchez and Dodson 1990). However, a recent study showed a small-scale genetic subdivision between some populations of adjacent James Bay rivers (Consortium Waska-Genivar 2017). The low salinity, low nutrient waters and the cyclonic current probably contribute in making cisco from James Bay a relatively uniform gene pool (Bernatchez and Dodson 1990).

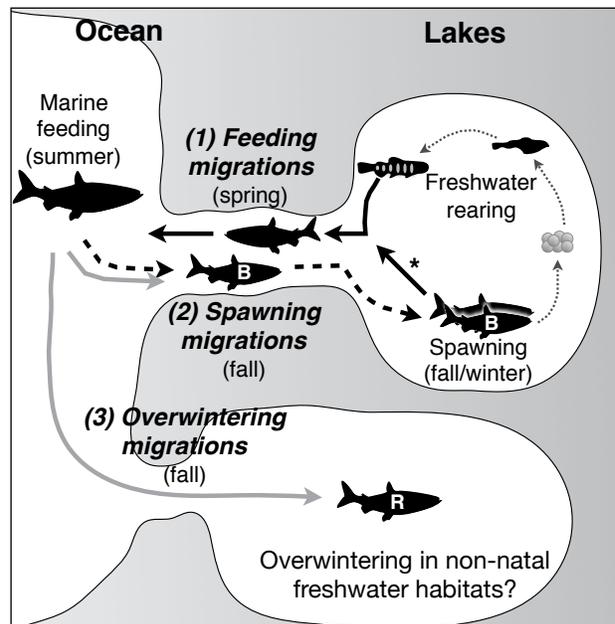
Coregonids, are exploited by subsistence fisheries in coastal regions in James Bay and Eastern Hudson Bay. Anadromous species are very important for subsistence fisheries since these fish make up a significant part of total food

intake of local communities such as Cree on the East coast of James Bay (Dewan 2016). In fact, Cree coastal fisheries do not exploit marine fishes, but mainly rely on the harvesting of few anadromous species in estuaries and coastal regions during the open water season. The most important species for subsistence fisheries are coregonids (especially cisco and lake whitefish) and brook trout, in addition to longnose sucker (*Catostomus catostomus*) and Arctic Char in northeastern Hudson Bay (Berkes 1976, 1977, 1979; R Morin and Dodson 1986; Stewart and Lockhart 2005; Dewan 2016).

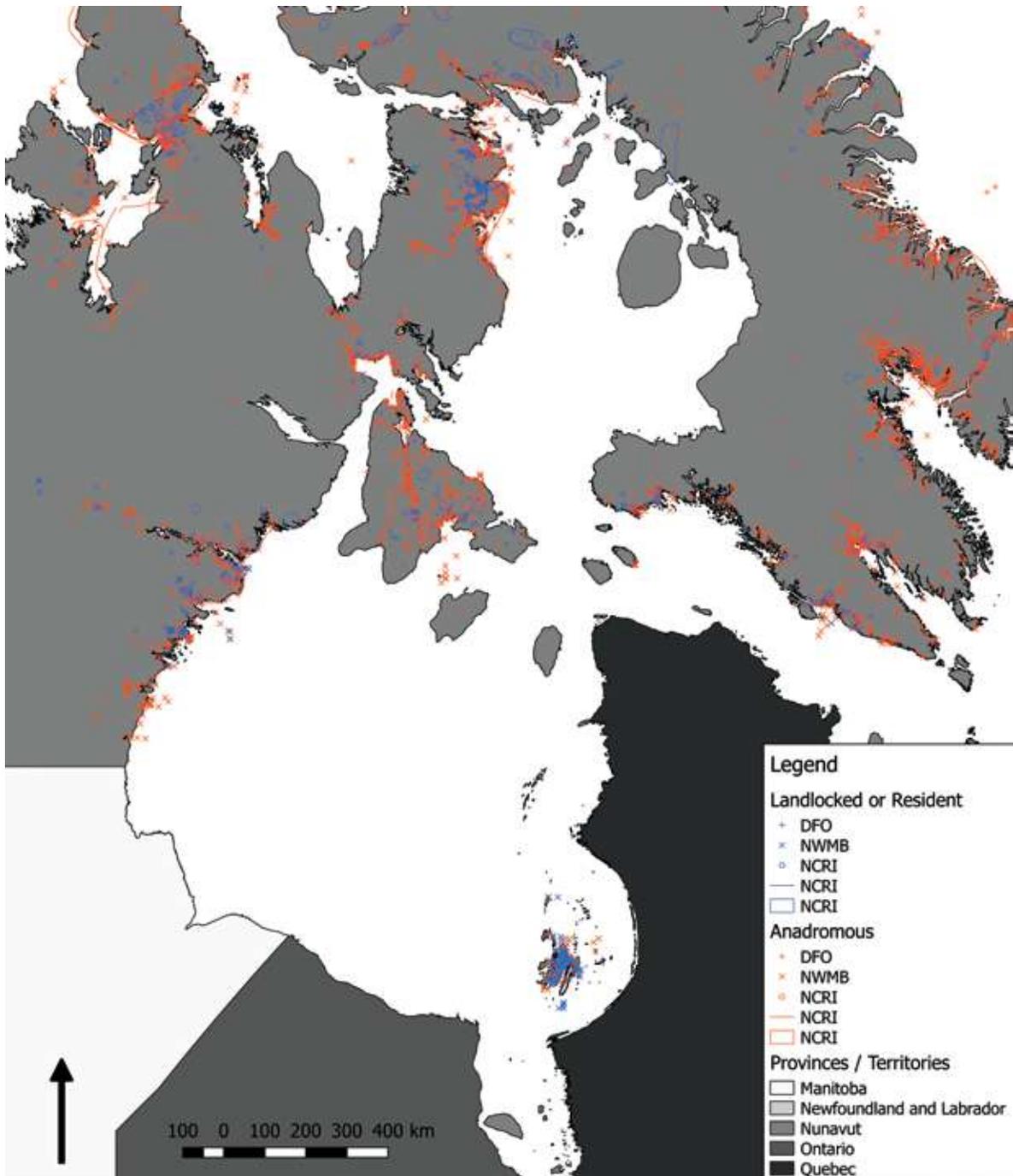
Hydroelectric developments in the Eastern James Bay region had several impacts on estuarine and coastal environmental conditions and raised some concerns about fisheries in Cree coastal communities. Additional research needs to be done in order to document these potential effects and their consequences on Cree traditional life style.

### Arctic char

Arctic char is a circumpolar species that is found along most of the Hudson Bay coast (Johnson 1980; Coad and Reist 2004; Fisheries and Sealing 2008, 2010, 2016a-d). The species exhibit facultative anadromy, whereby only a portion of the population



**FIGURE 2.** The life cycle of anadromous Arctic Char highlighting three distinct migrations: (1) Feeding migrations (black arrows), (2) spawning migrations (dashed black arrows), and (3) overwintering migrations (full grey arrows). Individuals in breeding condition are represented by 'B' and individuals not in breeding condition (resting) by 'R'. (Figure reproduced from Moore et al. 2017)



**FIGURE 3.** Arctic char distribution around Hudson Bay (Nunavut only), by migratory life history (Landlocked or Resident, vs. Anadromous). Data sources: Nunavut Wildlife Harvest Study (Priest and Usher 2004); Nunavut Coastal Resource Inventory (Fisheries and Sealing 2008, 2010, 2016a-d).

migrates while the remainder is resident in freshwater year-round (Figure 2 and 3). Typically, Arctic char home to their natal river to spawn, but can use non-natal rivers to overwinter in the years when they do not spawn (Moore et al. 2013, 2014) (see Figure 2 for the general life cycle of Arctic char). According to a recent genetic study conducted on Arctic char using mitochondrial DNA and microsatellite DNA (tandem repeats of short DNA sequences), in Hudson Bay, the species is derived from a single arctic lineage. Results suggest that Arctic char recolonized the region from a high Arctic refugium located in the Arctic Archipelago or from a refugium within the Beringian refugium following the last glaciation (Moore et al. 2015).



L. CANDLISH

Anadromous Arctic char grow as large as 880 mm (Carder and Peet 1983), which makes them attractive for subsistence and commercial fisheries; although a low reproductive rate and slow growth means careful management is necessary to avoid overharvest. Small Arctic char commercial fisheries have developed along the Kivalliq coast, some of which have been running since the 1930s (Dalrymple 1932, Stewart and Lockhart 2005). Fish are harvested as they move along the coast in the summer, or in lakes in early winter as soon as the ice is thick enough to hold an all-terrain vehicle or snowmachine (Department of Environment 2016). Most commercial catches are sent to the Kivalliq Arctic Foods processing plant in Rankin Inlet (Nunavut Development Corporation 2016).

For communities and fisheries managers, understanding and predicting fish distributions, movements, and response to changes is essential (Knopp 2012). The costs (e.g. energy required to migrate) and benefits (e.g. access to more productive marine feeding areas) of migrating, however, vary across the landscape. Consequently, increasing environmental variability caused by climate change may impact Arctic char migrations. Nunavut communities are already noticing environmental changes in the freshwater and marine environments, such as decreasing water levels, changes in ice formation and breakup, decreased precipitation, new species, erosion, and changes in seasonal timing (Fisheries and Sealing 2008, 2010, 2016a-d, Department of Environment 2005); all of which may affect Arctic char migration patterns. In addition to these direct effects, increasing primary production (Karlsson, Jonsson, and Jansson 2005), water temperatures and changes in flows may affect fish growth, thereby indirectly affecting anadromy (Finstad and Hein 2012, Reist et al. 2006). In addition to affecting subsistence and commercial fisheries, changes in Arctic char migratory patterns could impact freshwater ecology around Hudson Bay (Swanson et al. 2010).

#### 4. Fisheries in Hudson Bay

Inland, inshore and offshore fisheries in Hudson Bay are predominantly recreational and for subsistence use. However, communities are becoming invested and engaged socially, economically and culturally in commercial fishing.

In Nunavut, various institutions are exploring emerging fisheries and exposing communities to economic potential and species never before considered, both at global (e.g. Greenland halibut) and regional scales (e.g. marine plants). As the wage-based economy of Nunavut continues to grow so does the need for partners in fisheries to commit to baseline data collection, training opportunities, knowledge integration, market development (e.g. eco-certified fisheries) and a culturally

relevant sustainability paradigm that addresses important issues, such as food security.

In keeping with the precautionary principle, decision-making is improved by obtaining and sharing the best scientific information available, by being cautious in data-poor situations and greater uncertainties, and by ecosystem-based approaches to management that include the human element. Fisheries management decisions, as per fishery regulations, rely on scientific advice, which may, or may not, be required to be based on complete or exhaustive datasets. It is important that advice strongly encourages incorporation of Indigenous knowledge, despite the lack of a formal framework for doing so. In Nunavut resource managers must also seek the advice of the Nunavut Wildlife Management Board (NWMB) whether inside or outside of the Nunavut Settlement Area.

Where both science and Indigenous knowledge agree is that data should be considered over long, localized time series and that more data and more involvement gets everyone better results. The importance of thorough data collection does not appear to be the source of debate; rather, it is the capacity and necessity for government and/or academic scientists to deliver such intensive programs and the willingness of both groups to negotiate methods and participate in the data collection. In Nunavut, both science and industry face challenges on the methods used to collect data and fish. Many communities are vocal in expressing their concerns regarding certain practices, such as bottom trawling, seismic testing and any research involving acoustics. Essential to any research or development will be the communities' perspective on fisheries; bringing awareness and opportunities to participate in science and fully as shareholders of Hudson Bay's fisheries.

For some commercial species, like Arctic char, a sustainability paradigm that includes secure access to food may need to focus less on exhaustive datasets and more on better science (e.g. being able to develop and refine data-poor resource extraction models), tapping into community-based knowledge, understand basic needs of communities, and subsequently, adequately monitor a fishery long-term and adapt to changes.

Better science and industry accountability will be required to meet the demands of global consumers, and also for local demand on traditionally harvested species (e.g. balancing basic needs with commercial developments). Species migrations, population changes due to warming waters, capacity to fish and infrastructure developments will all be factors for increases in fishing effort. The "take it slow" approach has worked to date because of various limitations to growth; going forward an established vision for Arctic fisheries should ensure that as these limitations are removed there is consensus on what cautious expansion of fisheries will look like. Discussions will need to focus on fishing methods that have detrimental effects



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on vulnerable species and habitats, assessing operational risks, the merits of protecting marine spaces, and ultimately how we will assess the level of impact.

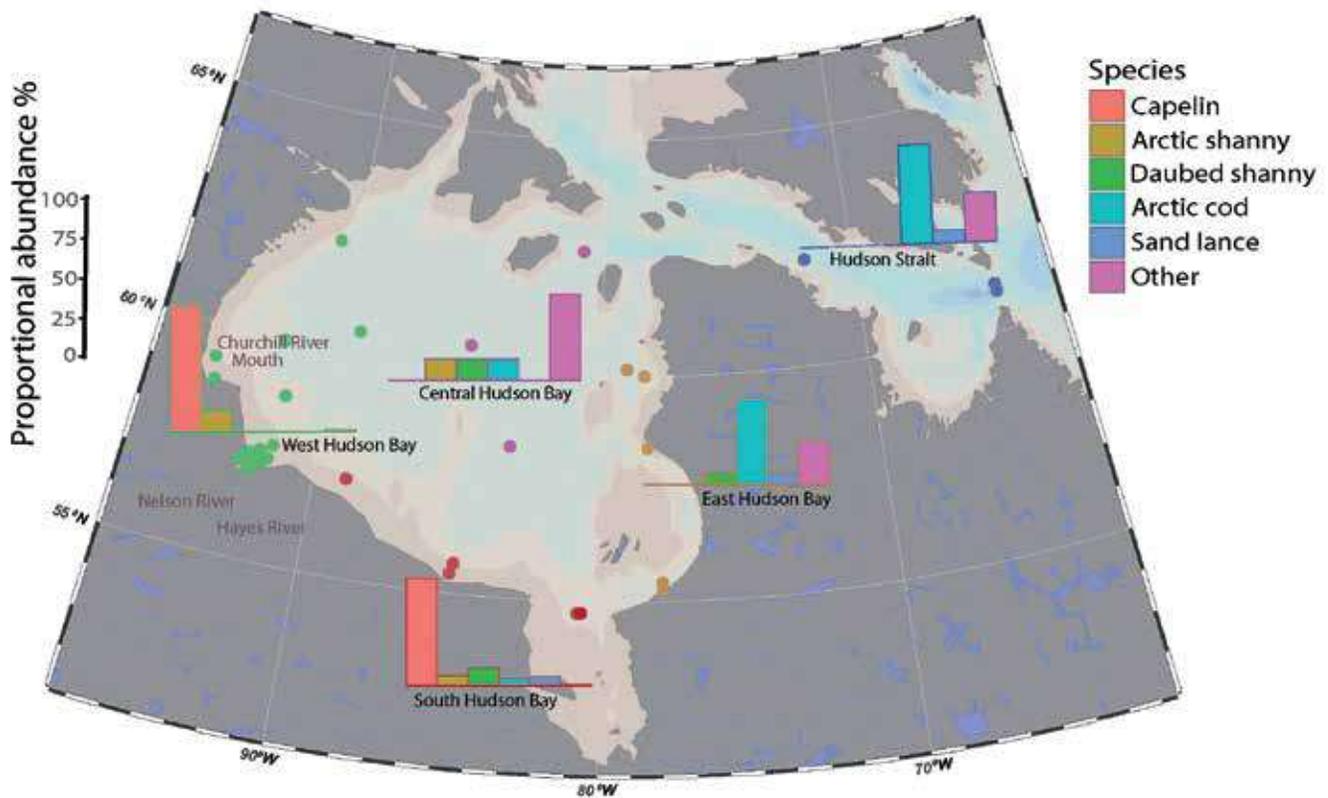
## 5. Recent observations and changes in fish communities

Scientific surveys onboard the CCGS *Amundsen* were carried out in August-September 2005 and June 2010 (Figure 4). Data from nets designed to capture fish larvae and fry and deployed during these surveys show a fish assemblage dominated by a few species (Figure 5). It must be noted that larval fish abundances may not always be representative of the adult fish assemblage because the high larval mortality rate can vary widely between species. Also, the reproduction season, and, hence, the timing of maximum larval abundance, vary among species. Therefore, the larval fish assemblage can vary considerably depending on survey dates (e.g. Ponton, Gagné, and Fortier 1993). However, this larval fish data is still interesting because Arctic cod, a staple in arctic marine ecosystems, was only the fourth most abundant species (Figure 5). On the other

hand, capelin was more abundant than all the other species combined.

Moreover, this type of assemblage is not uniform throughout Hudson Bay. When looking at the proportional abundances of fish in different areas of the bay, distinct regional assemblages emerge (Figure 4). Arctic cod was the most abundant fish in the northeastern side of Hudson Bay and in Hudson Strait. As these regions receive more arctic waters with higher salinity than the regions further south (Harvey, Therriault, and Simard 2001), the fish assemblage is more typically arctic. In contrast, capelin was very abundant in the estuaries at the mouths of large rivers such as the Nelson and Hayes Rivers on the west and south coasts of Hudson Bay. Central and East Hudson Bay were the most diverse regions with fish that were not present in the rest of the bay such as snailfish (*Liparidae spp.*), rainbow smelt (*Osmerus mordax*) and Arctic alligatorfish (*Aspidophoroides olrikii*).

Historically, fish species found in Hudson Bay might have been quite different from what is presented here. There are several indications that fish assemblages in Hudson Bay are changing. Compared to larval fish assemblages reported in 1988 near the Belcher Islands in southeastern Hudson Bay (Drolet et al. 1991), Arctic cod was less abundant and shanny species (family Stichaeidae) more abundant in 2005 and 2010 (Figure 6). The diets of ringed seals (*pusa hispida*) in Western Hudson Bay has also shifted from a dependence on Arctic cod and sand lance in the early 1990s to a heavier reliance on capelin in the 2000s (Chambellant, Stirling, and Ferguson 2013). Furthermore, the diet of thick-billed murre (*Uria lomvia*) in northeastern Hudson Bay between 1980 and 2002 changed from one of predominantly Arctic cod to one with more capelin and sand lance (Gaston, Woo, and Hipfner 2003). This change coincides with the colonization of Coats Island (northeastern Hudson Bay) by razorbills (*Alca torda*), a seabird that preys on capelin (Gaston and Woo 2008).



**FIGURE 4.** Map of sampling locations (dots) in August and September 2005 and June 2010. The stations have been grouped into regions: West Hudson Bay (green), South Hudson Bay (red), East Hudson Bay (orange), Central Hudson Bay (pink) and Hudson Strait (blue). The relative abundances of pelagic larval species in these regions are presented on the map. The category ‘Other’ consists of, in order of abundance: rainbow smelt, shorthorn sculpin, Arctic alligatorfish, variegated snailfish, Arctic staghorn sculpin, atlantic herring, snakeblenny, Newfoundland eelpout and ribbed sculpin. See appendix A for more details.

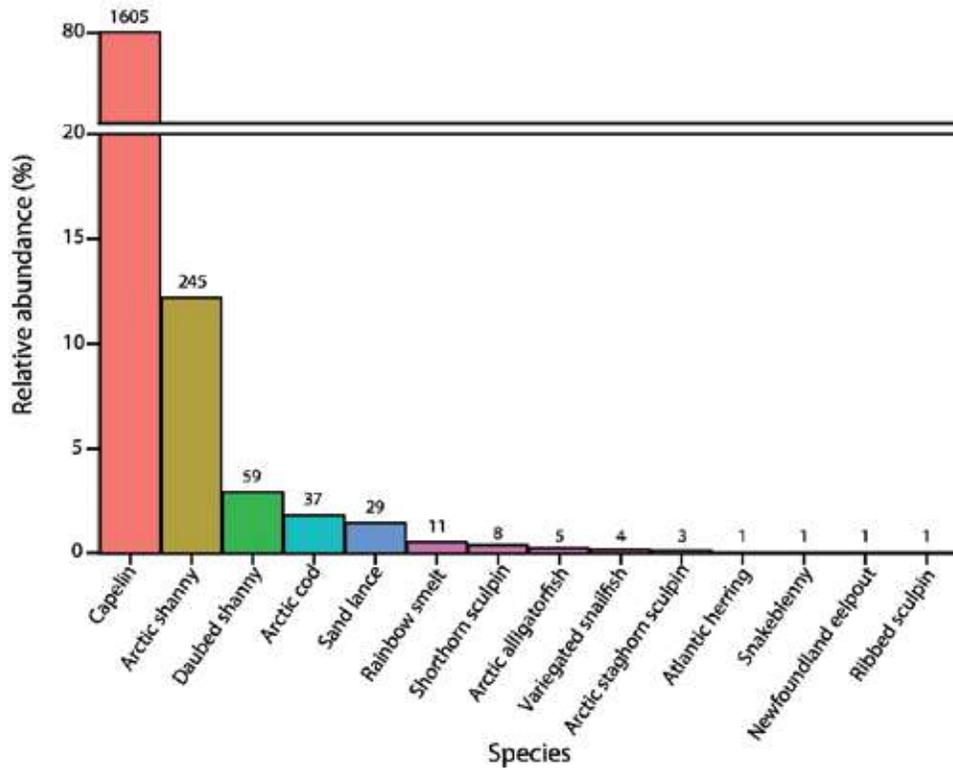


FIGURE 5. Relative abundance of pelagic larval fish species integrated across all stations in Hudson Bay and Hudson Strait from sampling in August and September 2005 and June 2010. The abundance of each species is indicated above bars (n = 2010).

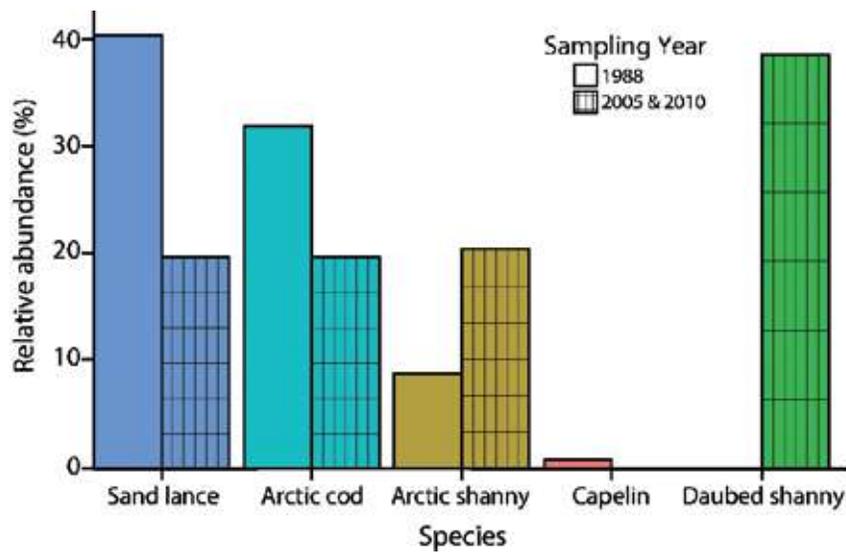


FIGURE 6. Relative abundance of pelagic larval fish species near the Belcher Islands in spring 1988 (from Drolet et al. 1991; n = 2840) and in summer 2005 and 2010 (n = 132).

**Box 1. Zooplankton in the Greater Hudson Bay Marine Region**

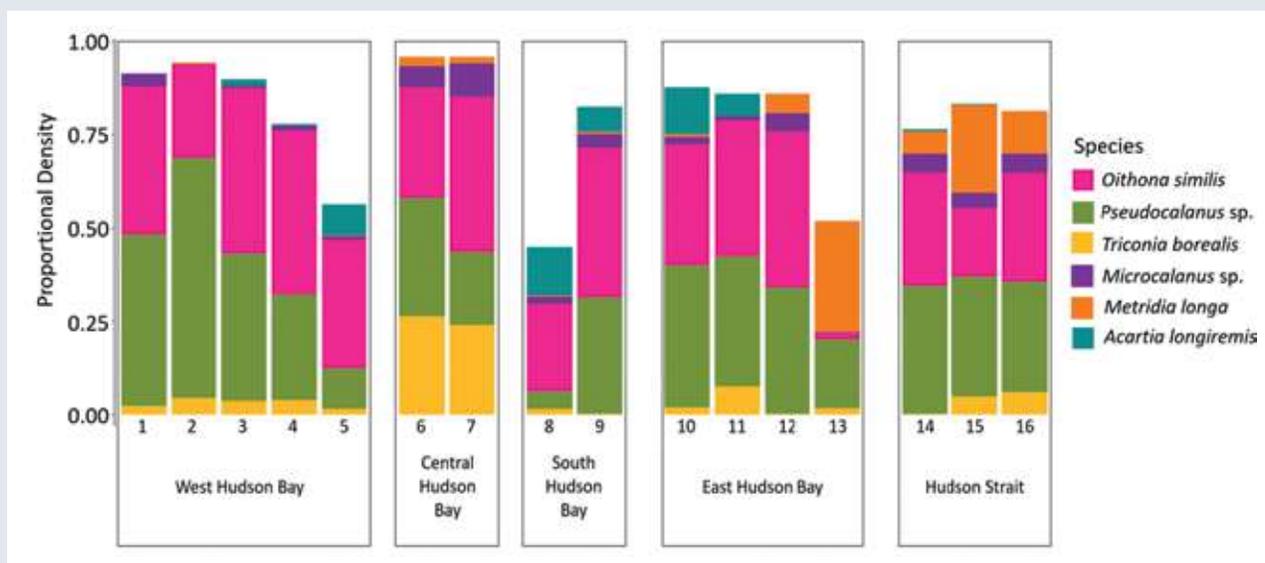
**Zooplankton are the small, floating or weakly swimming organisms** that are critical links between primary producers (microalgae or phytoplankton) and higher trophic levels including benthic and pelagic macroinvertebrates, fish, birds and marine mammals. Zooplankton are diverse, ranging from microscopic heterotrophic plankton to large species, such as jellyfish. The group includes the eggs or larvae of fish and crustaceans, protozoa and copepods, young starfish, clams, worms, and other bottom-dwelling animals.

Despite their importance to the food web, the occurrence, abundance, and ecology of zooplankton in the Greater Hudson Bay Marine Region are not well understood. The majority of zooplankton surveys in the region have been conducted in estuaries ‘downstream’ of existing or proposed hydroelectric developments (cf., Lawrence and Baker 1995; Fortier et al. 1995), which may not be representative of other nearshore or offshore habitats, or during relatively rare oceanographic cruises (Grainger 1959, 1962, 1965; Roff and Legendre 1986). During the last two decades, zooplankton communities have been surveyed in parts of the region on a few occasions as part of the MERICA and ArcticNet cruises (Harvey et al. 2001, 2006; Estrada et al. 2012). According to a review by Fisheries and Oceans Canada (Stewart and Lockhart 2005), sufficient study has been conducted to get a sense of the range of

species that occur in the region but not to properly describe their biogeography.

Zooplankton distributions in relation to environmental variables such as salinity and temperature were investigated by Harvey et al. (2001) and Estrada et al. (2012). Water column structure was shown to be a key driver of zooplankton biomass and diversity in the region (Harvey et al. 2001; Estrada et al. 2012). Water column structure is defined by physical properties such as degree of stratification of the water column which in turn is affected by temperature, salinity and depth. Furthermore, trophic interactions such as competition and predation also influence zooplankton community structures (Estrada et al. 2012). Significant differences in zooplankton community characteristics and total zooplankton biomass were observed among Hudson Strait, Foxe Basin and Hudson Bay, with Hudson Strait having the highest biomass, followed by Foxe Basin, and Hudson Bay having the lowest biomass (Grainger 1959; Harvey et al. 2001; Estrada et al. 2012). Hudson Bay seems to support far fewer zooplankton species than more northern Arctic waters. However, Archambault et al. (2010) point out that under-sampling of some groups (eg. Annelida) in Hudson Bay may bias the comparison. Furthermore, although we do not see a big seasonal change in the type of zooplankton species in the high arctic, the case might be different in the Hudson Bay region.

Copepods are the most abundant group of zooplankton species in the Hudson Bay system, however, in Hudson Bay



**FIGURE 1.** Relative abundance per station of the top six most numerically abundant zooplankton species sampled during the 2005 ArcticNet cruise (September).

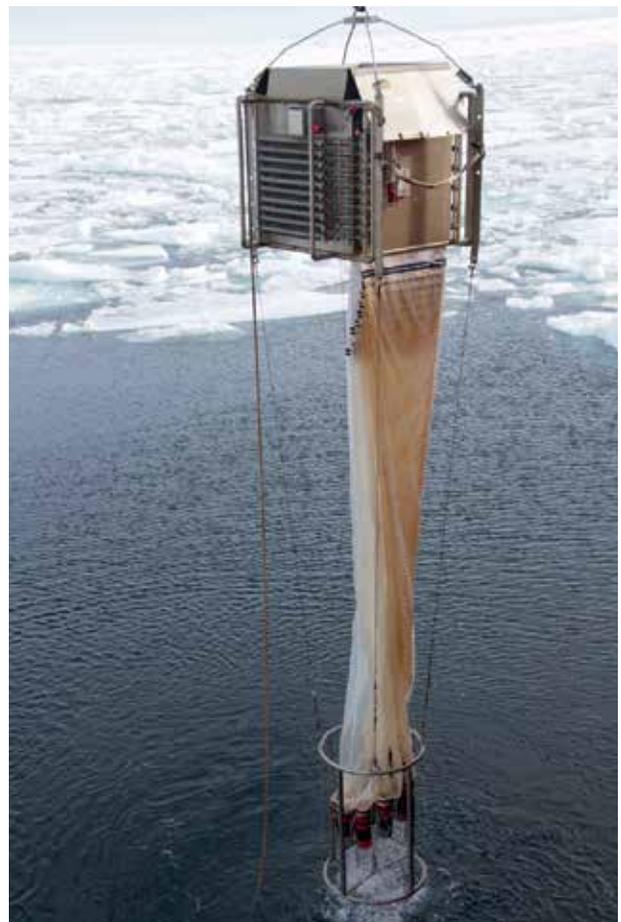
small copepods were recorded in greater numbers than in the Hudson Strait and Foxe Basin (Estrada et al. 2012). Since most of the numerically abundant species are small copepod species, they do not contribute much to total zooplankton biomass, in contrast with other Arctic regions. Large, lipid-rich copepods are most numerous in the middle of the bay and decline in coastal areas where there is a layer of low-salinity surface water (Baker et al. 1993). Cnidarians (jellyfish species) are recorded throughout the bay but they never dominate in terms of biomass (Harvey et al. 2001) with a few exceptions. Diversity of the less common zooplankton phyla (Mollusca, Ctenophora, Chaetognatha, and Chordata) in Hudson Bay was similar to that in other Arctic regions. Zooplankton species typical in Arctic areas such as *Calanus glacialis*, *C. hyperboreus*, and *Pseudocalanus minutus* are most abundant in the north and central regions of Foxe Basin and much less common in Hudson Strait and Hudson Bay (Grainger 1962). Species indicative of sub-Arctic influence (e.g., *Calanus finmarchicus*) are more common in southern Foxe Basin than in the north and abundant in Hudson Strait (Harvey et al. 2001). In the Hudson Strait and to a lesser extent in central Hudson Bay, we also find more *Metridia longa*, a relatively large copepod associated with arctic ecosystems (see Figure 1). In the southern coastal areas of the Hudson Bay, *Acartia longiremis* – a species with a pan-arctic, boreal and estuarine distribution – is abundant (Figure 1).

Two zooplankton compartments, microzooplankton (20–200 µm) and mesozooplankton (200–2000 µm), were included in the pelagic ecosystem model developed for the region (Sibert et al. 2011). The simulated zooplankton biomass results compare well with the observations of Harvey et al. (2001) including the maximum biomass in Hudson Strait, slightly lower biomass in Foxe Basin, and lowest biomass in Hudson Bay. The model simulates a west-east gradient in zooplankton biomass across Hudson Bay with lower biomass in the east. The model also simulated weak zooplankton biomass in James Bay with microzooplankton comprising 80–100% of the biomass. In general, the ratio of mesozooplankton to total zooplankton biomass was found to be lower in the coastal zone of Hudson Bay implying a greater prominence of microzooplankton. Sibert et al. (2011) attribute this trend to the small phytoplankton distribution and regenerated production regime of coastal (especially southeast) Hudson Bay. Mesozooplankton were estimated to make up two-thirds of the secondary production in the region, on average (Sibert et al. 2011).

*Continued on following page*

## 6. Human pressures on Hudson Bay fish communities and future predictions

Since no commercial exploitation of any marine species (excluding anadromous species such as char) takes place presently in Hudson Bay, the two major sources of human-caused stresses on fish population are ongoing climate change and hydroelectric power plants along major rivers such as Nelson, Churchill and La Grande rivers in Hudson Bay and Moose River in James Bay. Hydroelectric dams result in smaller seasonal fluctuations of freshwater input into the bay, leading to a more constant freshwater supply year-round (Wang et al. 2012). Ongoing climate change might amplify this trend since higher temperatures and increased precipitation are predicted in winter in Eastern Hudson Bay (Huard et al. 2014), both resulting in higher freshwater flow in winter. Lower salinity along the Hudson Bay coast could increase dispersal of species including ones that are not native to the Hudson Bay system. Such a phenomenon has already been observed with rainbow smelt passing down Nelson River and migrating to Churchill River



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The southeast Hudson Bay coast also has been noted for high abundance (7% of total zooplankton abundance) of chaetognaths (*Sagitta elegans*) (Harvey et al. 2001, 2006; Lapoussière et al. 2009), which are a carnivorous species, grazing on mesozooplankton (mainly copepods). Furthermore, large quantities of the holoplanktonic jellyfish *Aglantha digitale* were collected in sediment traps deployed at 100 m water depth in that area during fall 2006 and summer 2007 (Lalande and Fortier 2011). There are insufficient data to assess whether the trap recorded an increased frequency of jellyfish blooms in southeastern Hudson Bay during those years. The timing of the large occurrence of *Aglantha digitale* (June to August 2007) was also unusual in that it lay outside the usual seasonal descent to depths expected of this species. It was speculated that a warming of the upper layers could have induced the descent of jellyfish during summer 2007 but additional data are required to assess whether the observed patterns were representative of a trend or relate to environmental change.

Considerably more research is required in both coastal and offshore areas. In addition, studies that span more than one season or year are urgently needed to establish present zooplankton community characteristics within the region. Only when additional research and studies have been completed can a zooplankton database be developed from which we can hope to assess the impacts of environmental change in the Greater Hudson Bay Marine Region.

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- via coastal waters (Stewart and Lockhart 2005). Fish that use estuarine and brackish water habitats such as sand lance, Arctic shanny (*Stichaeus punctatus*) and capelin (Ponton, Gagné, and Fortier 1993; Stewart and Lockhart 2005) would be expected to find the new conditions favourable.
- Recent climate change is heavily impacting sea-ice formation; in the past 40 years, annual sea-ice cover in the Arctic has been shrinking by 11% per decade (Tivy et al. 2011). Sea-ice enables the growth of under-ice microalgae on which a number of copepods species are dependent for reproduction and growth (Tourangeau and Runge 1991). Copepods are small crustaceans that often represent the main food of fish (See Box 1). Their nauplii (i.e. first larval stages) are the main prey of Arctic cod larvae at first feeding (Bouchard et al. 2016). The Arctic cod thus being a cryopelagic species (i.e. associated with under-ice ecosystem), less ice cover, and consequently higher sea temperatures, could contribute to its decline in the long term (Tynan and DeMaster 1997; Moline et al. 2008; Bouchard et al. 2017). However, in the short term, warmer conditions could lead to higher biomass of Arctic cod by increasing larval



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survival and recruitment (Bouchard et al. 2017). A long term decreasing number of Arctic cod might have several implications. Arctic cod inhabits the whole water column throughout its lifetime (Geoffroy et al. 2016) and holds a key role in the ecosystem (Welch et al. 1992). Hence, several species linked to Arctic cod might be affected by its replacement by subarctic and boreal forage fish. The high lipid content of adult Arctic Cod makes it relatively energy-rich compared to other pelagic and near-shore demersal species such as capelin, sand lance and daubed shanny (*Leptoclinus maculatus*) (Van Pelt et al. 1997; Robards et al. 1999; Anthony, Roby, and Turco 2000). By making energy available to higher trophic levels, Arctic cod is able to support top predators in numbers that other fish with smaller fat stores might not be able to (Welch et al. 1992; Hop, Tonn, and Welch 1997).

As less ice covers Hudson Bay in spring and fall, it will become more accessible to maritime activities that may impact fish populations by harming their health, damaging

their habitat or introducing alien species (Halpern et al. 2008). Activities such as increased shipping might have these consequences in Hudson Bay (Andrews et al. 2016). Additionally, several attempts to establish a large-scale fishing industry in Hudson Bay have been made but have been unsuccessful due to the remoteness and low yield of the catches (Hunter 1968; Dunbar 1970). The viability of this industry might change as Hudson Bay becomes more accessible and fish stocks are depleted in other areas.

Overall, increasing temperatures and declining ice-cover might provide ideal conditions for the settlement of sub-arctic species. However, their passage to Hudson Bay may be halted at Hudson Strait which could stay colder for longer (Stewart and Lockhart 2005).

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## APPENDIX A

### Fish species in the Hudson Bay system (including James Bay and Hudson Strait)

This species list has been extracted from Stewart and Lockhart (2005). Recordings of species in published literature and from listings in the National Museum of Natural Sciences, Ottawa, or Royal Ontario Museum, Toronto, collections were combined

to create the following list. The species recorded, their locations and the number of individual caught during the 2005 and 2010 CCGS Amundsen research cruises are also shown. Habitat where the species has been recorded is indicated in the 'Habitat' column;

M – Marine  
B – Brackish  
F – Fresh

Family	Scientific Name	Common Name	Habitat	West Hudson Bay	South Hudson Bay	East Hudson Bay	Central Hudson Bay	Hudson Strait
Somniosidae	<i>Somniosus microcephalus</i>	Greenland shark	MB					
Rajidae	<i>Amblyraja jenseni</i>	Shorttail skate	M					
	<i>Amblyraja radiata</i>	Thorny skate	MB					
	<i>Bathyraja spinicauda</i>	Spinytail skate	M					
Acipenseridae	<i>Acipenser fulvescens</i>	Lake sturgeon	F					
Clupeidae (n=1)	<i>Clupea harengus</i> (n=1)	Atlantic herring	MB		√			
Cyprinidae	<i>Couesius plumbeus</i>	Lake chub	F					
	<i>Notropis atherinoides</i>	Emerald shiner	F					
Catostomidae	<i>Catostomous catostomous</i>	Longnose sucker	BF					
	<i>Catostomus commersonii</i>	White sucker	MBF					
	<i>Moxostoma macrolepidotum</i>	Shorthead redhorse	F					
Esocidae	<i>Esox lucius</i>	Northern pike	BF					
Osmeridae (n=278)	<i>Mallotus villosus</i> (n=267)	Capelin	MBF	√	√			
	<i>Osmerus mordax</i> mordax (n=11)	Rainbow smelt	MBF	√			√	
Salmonidae	<i>Coregonus artedi</i>	Cisco (lake cisco)	MBF					
	<i>Coregonus clupeaformis</i>	Lake whitefish	MBF					
	<i>Prosopium cylindraceum</i>	Round whitefish	BF					
	<i>Salmo salar</i>	Atlantic salmon	MBF					
	<i>Salvelinus alpinus alpinus</i>	Arctic charr	MBF					
	<i>Salvelinus fontinalis</i>	Brook trout	MBF					
	<i>Salvelinus namaycush</i>	Lake trout	F					
	<i>Thymallus arcticus</i>	Arctic grayling	F					
Paralepididae	<i>Arctozenus risso</i>	White barracudina	M					
Bathylagidae	<i>Bathylagus euryops</i>	Goitre blacksmelt	M					
Myctophidae	<i>Benthoosema glaciale</i>	Glacier lanternfish	M					
	<i>Lampanyctus crocodilus</i>	Jewel lanternfish	M					
	<i>Lampanyctus macdonaldi</i>	Rakery lanternfish (Rakery beaconlamp)	M					
	<i>Notoscopelus kroyeri</i>	Krøyer's lanternfish	M					
	<i>Symbolophorus veranyi</i>	Largescale lanternfish	M					
Percopsidae	<i>Percopsis omiscomaycus</i>	Trout-perch	F					
Macrouridae	<i>Macrourus berglax</i>	Roughhead grenadier	M					
Moridae	<i>Antimora rostrata</i>	Blue antimora (Blue hake)	M					

Family	Scientific Name	Common Name	Habitat	West Hudson Bay	South Hudson Bay	East Hudson Bay	Central Hudson Bay	Hudson Strait
Phycidae	<i>Gaidropsarus ensis</i>	Threadfin rockling	M					
	<i>Phycis chesteri</i>	Longfin hake	M					
Gadidae (n=37)	<i>Arctogadus glacialis</i>	Polar cod	M					
	<i>Boreogadus saida</i> (n=37)	Arctic cod	M		√	√	√	√
	<i>Gadus morhua</i>	Atlantic cod	MB					
	<i>Gadus macrocephalus</i>	Greenland cod	MB					
	<i>Lota lota</i>	Burbot	BF					
Gasterosteidae	<i>Culaea inconstans</i>	Brook stickleback	F					
	<i>Gasterosteus aculeatus</i>	Threespine stickleback	MBF					
	<i>Pungitius pungitius</i>	Nine-spined stickleback	MBF					
Scorpaenidae	<i>Sebastes mentella</i>	Deepwater redfish	M					
	<i>Sebastes norvegicus</i>	Golden redfish	M					
Cottidae (n=12)	<i>Artediellus scaber</i>	Rough hookear (Hamecon)	MB					
	<i>Artediellus uncinatus</i>	Arctic hookear sculpin	M					
	<i>Cottus cognatus</i>	Slimy sculpin	BF					
	<i>Cottus ricei</i>	Spoonhead sculpin	F					
	<i>Gymnocephalus tricuspis</i> (n=3)	Arctic staghorn sculpin	M	√		√		
	<i>Icelus bicornis</i>	Twohorn sculpin	M					
	<i>Icelus spatula</i>	Spatulate sculpin	M					
	<i>Myoxocephalus aeneus</i>	Grubby	MB					
	<i>Myoxocephalus octodecemspinosus</i>	Longhorn sculpin	MB					
	<i>Myoxocephalus quadricornis</i>	Fourhorn sculpin	MBF					
	<i>Myoxocephalus scorpioides</i>	Arctic sculpin	MB					
	<i>Myoxocephalus scorpius</i> (n=8)	Shorthorn sculpin	MB	√		√		
	<i>Triglops murrayi</i>	Moustache sculpin	M					
	<i>Triglops nybelini</i>	Bigeye sculpin	M					
<i>Triglops pingelii</i> (n=1)	Ribbed sculpin	M		√				
Agonidae (n=5)	<i>Aspidophoroides monopterygius</i>	Alligatorfish	M					
	<i>Leptagonus decagonus</i>	Alligator poacher	M					
	<i>Aspidophoroides olrikii</i> * (n=5)	Atlantic alligatorfish	MB	√		√	√	√
Psychrolutidae	<i>Cottunculus microps</i>	Polar sculpin	M					
Cyclopteridae	<i>Cyclopteropsis jordani</i>	Smooth lumpfish	M					
	<i>Cyclopterus lumpus</i>	Lumpfish	M					
	<i>Eumicrotremus derjugini</i>	Leatherfin lumpsucker	M					
	<i>Eumicrotremus spinosus</i>	Atlantic spiny lumpsucker	M					
Liparidae (n=4)	<i>Careproctus longipinnis</i>	Longfin snailfish	M					
	<i>Careproctus reinhardti</i>	Sea tadpole	M					
	<i>Liparis atlanticus</i>	Atlantic snailfish	M					
	<i>Liparis fabricii</i>	Gelatinous snailfish	M					
	<i>Liparis gibbus</i> (n=4)	Dusky snailfish	M				√	√
<i>Liparis tunicatus</i>	Kelp snailfish	MB						
Percidae	<i>Sander vitreus</i>	Walleye	BF					

Family	Scientific Name	Common Name	Habitat	West Hudson Bay	South Hudson Bay	East Hudson Bay	Central Hudson Bay	Hudson Strait
Zoarcidae (n=1)	<i>Gymnelus viridis</i>	Barsukov's pout (Fish doctor)	M					
	<i>Lycenchelys kolthoffi</i>	Wolf eel	M					
	<i>Lycenchelys paxillus</i>	Common wolf eel	M					
	<i>Lycenchelys verrillii</i>	Wolf eelpout	M					
	<i>Lycodes esmarkii</i>	Greater eelpout	M					
	<i>Lycodes lavalei</i> (n=1)	Newfoundland eelpout	M	√				
	<i>Lycodes mucosus</i>	Saddled eelpout	M					
	<i>Lycodes pallidus</i>	Pale eelpout	M					
	<i>Lycodes polaris</i>	Polar eelpout	M					
	<i>Lycodes reticulatus</i>	Arctic eelpout	M					
	<i>Lycodes vahlii</i>	Checker eelpout	M					
Stichaeidae (n=305)	<i>Anisarchus medius</i>	Stout eelblenny	M					
	<i>Eumesogrammus praecisus</i>	Fourline snakeblenny	M					
	<i>Leptoclinus maculatus</i> (n=59)	Daubed shanny	M	√	√	√	√	
	<i>Lumpenus fabricii</i>	Slender eelblenny	M					
	<i>Lumpenus lampretaeformis</i> (n=1)	Snake blenny	M	√				
	<i>Stichaeus punctatus punctatus</i> (n=245)	Arctic shanny	M	√	√		√	
Pholidae	<i>Pholis fasciata</i>	Banded gunnel	M					
Anarhichadidae	<i>Anarhichas lupus</i>	Atlantic wolffish	M					
	<i>Anarhichas minor</i>	Spotted wolffish	M					
Ammodytidae (n=29)	<i>Ammodytes dubius</i>	Northern sand lance	M	√**	√**	√**		
	<i>Ammodytes hexapterus</i>	Pacific sand lance	MB					√**
Pleuronectidae	<i>Hippoglossoides platessoides</i>	Canadian plaice	M					
	<i>Reinhardtius hippoglossoides</i>	Turbot (Greenland halibut)	M					
<b>Totals</b>	<b>672</b>			<b>433</b>	<b>205</b>	<b>14</b>	<b>7</b>	<b>13</b>

\* Previously known as *Ulcina olriki*

\*\* *Ammodytes* sp. were identified to genus level





## II.v

# Seabirds, Geese, Ducks and Waterfowl found in the Hudson Bay Marine Region

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### Summary

**B**irds are well-recognized components of marine ecosystems and the Greater Hudson Bay Marine Region is no exception. The Region supports many species of birds, including nationally and globally significant populations. Regionally, many bird species including goose and eider duck species have a central role in Cree and Inuit culture and are harvested for food and clothing. Some bird species remain in the Bay year round like the common eider, while for several species, such as snow, Ross's and Canada geese, the Greater Hudson Bay Region provides important staging habitat during migration. A number of large bird colonies are found along the shorelines of the Greater Hudson Bay Marine Region. To the south, vast wetlands (Hudson Bay lowlands) and eelgrass habitat (James Bay) supports large populations of Geese during their migration. In the north, Coats and Digges Island support enormous seabird colonies, some of which have been monitored since the 1970's. Through these ongoing monitoring stations, impacts from multiple stressors related to climate change on the seabird populations themselves as well as other aspects of the marine ecosystem through changes in bird diet, have been documented. This chapter reviews the numerous bird species and their populations, as well as discusses impacts from climate change and other industrial activities on bird populations in the Greater Hudson Bay Marine Region.

### Key Messages

- **Hudson and James Bay are used by a variety of bird species, including many species that breed along its coast line, use a variety of habitats for moulting and migration stopovers, or winter in or near polynyas.**
- **The ice-free summer period has increased by 1-2 months in Hudson Bay over recent decades, and the Bay in summer is now more equivalent to a north temperate than Arctic ecosystem. Due to the longer ice-free period, birds are spending longer in the Bay during moult, migration and winter.**
- **Due to the above climatic change, Arctic birds in Hudson Bay are impacted negatively by top-down effects (increased predation and parasitism), invasive species and bottom-up effects (altered prey structure).**

- **Geese populations are increasing rapidly due to subsidies on their wintering grounds, leading to large goose barrens where other bird species cannot breed.**
- **Changes in eelgrass ecosystems and the impacts on migratory birds needs further study.**

## 1. Introduction

The Greater Hudson Bay Marine Region is home to many species of birds, including nationally and globally significant populations of several species (Mallory and Lafontaine 2004; Ferguson et al. 2010; Gaston et al. 2012). Most of the central, pelagic region of Hudson Bay is out of reach for most seabirds during the breeding season and covered in ice in the winter. However, the region provides important staging areas for

several seabird species during migration. More important, perhaps, are the coastal wetlands that host large populations of declining or threatened shorebirds, such as Hudsonian godwits (*Limosa haemastica*), red knots (*Calidris canutus*) and semipalmated sandpipers (*Calidris pusilla*). Alongside shorebirds, snow and Canada geese nest in large areas in the coastal lowlands, with rapidly increasing goose numbers degrading shorebird habitat in areas such as near Churchill and Southampton Island (Jehl 2007). The areas with suitable breeding habitat can also provide breeding habitat for auks, such as the Digges Sound region where one million thick-billed murres (*Uria lomvia*) nest alongside several other seabird species (Gaston 1985). As is typical of the Arctic, the majority of seabirds breed in a small number of very large colonies (>10 000 birds), but there are also substantial numbers of non-colonial or small-colony breeding populations (Gaston et al. 2012).



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Seabird and goose colonies were some of the first natural features described by European explorers, and feature heavily in the names given to locations by Inuit (Gaston et al. 2012). Indeed, the first site to be recognizably described by a European explorer in the Canadian Arctic was the enormous Digges Island seabird colony, and friction between Inuit and sailors over that resource led to one of the first disputes between the two groups (Gaston et al. 2012). Some of the bird colonies have existed for at least several thousand years (Gaston and Donaldson 1996), and Inuit and Cree peoples regularly harvested adults and eggs, a tradition that has continued into the present (Gaston et al. 2012). Despite the importance of seabird populations in the Bay historically, there is little recent information about the population abundance and trends of many seabird species (Gaston et al. 2012).

As is the case for the marine mammals, seabirds are responding to the rapid changes occurring in Hudson Bay. Earlier snow melt and longer ice-free periods extend breeding periods for bird populations (Gaston et al. 2009; Senner 2016). However, because cold-blooded prey respond more quickly to such changes than warm-blooded predators, such as birds, rapid warming can lead to a mismatch in prey availability and predator needs (Gaston et al. 2009; Senner 2016). That mismatch is thought to cause reduced reproductive success in some species (Gaston et al. 2009; Senner 2016). At the same time, the longer ice-free period has meant that some predators, typically polar bears, overlap with seabirds (Smith et al. 2010; Gaston and Elliott 2014). For some bird colonies, polar bears are now eating all eggs produced (Smith et al. 2010; Gaston and Elliott 2014; Dey et al. 2017). Apart from bottom-up and top-down effects of climate change, seabirds are also being impacted by invasive species (Gaston and Woo 2008). As Hudson Bay switches to becoming a temperate rather than Arctic ecosystem in the summer, southern species have moved into the Bay (Gaston and Woo 2008). The net effect of climate change on Hudson Bay seabirds is likely to be an avian community that is more similar to southern, temperate latitudes (Ferguson et al. 2010). Alongside the direct impact of climate change, seabirds are likely to be impacted by increased shipping and ecotourism as the Bay becomes more accessible.

Any assessment of impacts on Hudson Bay is hampered by a lack of information about bird distribution and abundance in the Bay. The Protocol for Regional and International Shorebird Monitoring (PRISM) has surveyed many of the habitats around Hudson Bay while long-term monitoring stations at East Bay (Southampton Island) and Churchill have provided detailed monitoring information (Johnston et al. 2012). Thus, shorebird breeding abundance, distribution and trends are known fairly well. Similarly, thick-billed murre populations are well-monitored via long-term monitoring at Coats and Digges

Island colonies (Gaston et al. 2016). Although goose productivity and populations are well-monitored at key colonies, many new colonies are poorly monitored. Abundance of many other waterfowl, loon, tern and gull species are largely unknown. Trends for some species are known from the wintering grounds, but for many species no trend information is available. Perhaps the greatest missing piece for Hudson Bay is a lack of at-sea surveys so that the abundance and distribution of birds using the marine portions of Hudson Bay is largely unknown, especially during migration. The use of year-round tracking data for some species has made up for the absence of at-sea data, and shown that the western Bay can be an important area in autumn. Regardless, more information on bird distribution, abundance and trends in Hudson Bay, especially at-sea, is sorely needed. Given the detailed local knowledge of bird populations by Inuit and Cree, platforms that empower individuals or groups to share that knowledge may eventually lead to more general knowledge of species distributions and trends.

## 2. Long-term monitoring

There are several annual long-term monitoring sites in Hudson Bay that provided important information on trends. Since 1979 (Digges) and 1981 (Coats), thick-billed murres' and *Larus* gulls' population status, reproductive success, and survival have been monitored at those two sites, with annual monitoring at Coats (Gaston et al. 2012; Smith and Gaston 2012). Since 1997, common eiders' (*Somateria mollissima*) reproductive success, timing of breeding and survival have been monitored at East Bay (Descamps et al. 2009). Finally, shorebird populations, especially semipalmated plovers (*Charadrius semipalmatus*), have been monitored since the 1980s at Churchill, Manitoba. In addition, the Ontario, Quebec and Manitoba Breeding Bird Atlases have provided some information on the distribution, abundance and trends of birds on the provincial coastlines, and the Nunavut Checklist Program (now integrated with eBird.org) has provided some information for Nunavut. Those long-term monitoring projects provide key information on the health of seabird populations in and around Hudson Bay, which often act as indicators for the overall health of marine ecosystems.

Breeding waterfowl populations have also been monitored in northern Quebec, the core breeding range of the Atlantic population of the Canada goose, since 1993. Initially, reconnaissance surveys were conducted between 1955 and 1966 to document the distribution and breeding range of this population (Kaczynski and Chamberlain 1968). Additional surveys were carried out in 1988 to verify the status of the population (Malecki and Trost 1990). In the early 1990s, after a decrease in numbers in all Canada goose populations, the

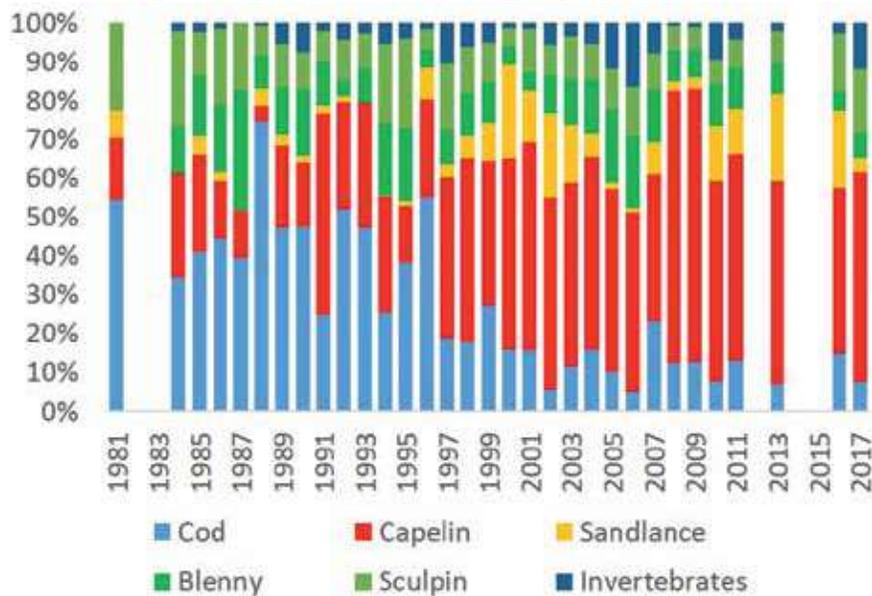
Atlantic Flyway Council, US Fish and Wildlife Service (USFWS) and Canadian Wildlife Service (CWS) decided to establish the Waterfowl Survey of Northern Quebec (WNOR). The first survey, which took place in 1993, covered all of northern Quebec. Those surveys have shown a substantial increase in Canada goose populations since 1955.

### 3. Auks

Thick-billed murres and black guillemots (*Cephus grylle*) are the two species of auks that commonly occur in Hudson Bay. Both species are closely associated with ice in the Arctic, as they prey heavily on Arctic cod, an ice-associated fish. Apart from murres and guillemots, a few pairs of Atlantic puffins (*Fratercula*

*arctica*) and razorbills (*Alca torda*) live in the Digges Sound region (Gaston 1985). In recent years, razorbills have apparently followed increased sand lance concentrations deeper into the Bay, and have likely bred in the Coats Island region (Gaston and Woo 2008), see Figure 1.

The thick-billed murre is a circumpolar species that spends its entire year below the 8° Celsius isotherm in cold, typically icy water (Gaston and Nettleship 1981). They weigh about 1 kg and are black above and white below. They have a slightly wider bill than the congeneric common murre because thick-billed murres feed primarily on plankton. In Hudson Bay, thick-billed murres breed at Coats Island (~30 000 pairs) and Digges Sound (~400 000 pairs), as well as at several sites along Hudson Strait (Gaston and Nettleship 1981). They breed on high cliffs that drop directly into the ocean, and the absence of such habitat



**FIGURE 1.** Thick-billed murre (akpa) diet in northern Hudson Bay 1981-2017 has switched from Arctic cod (left) to capelin (right). Arctic cod is an ice-associated fish typical of Arctic food webs while capelin is more typical of temperate, North Atlantic food webs. Murre chicks grow faster when they are fed Arctic cod than when they are fed capelin, as cod is typically larger than capelin.

along most of the Hudson Bay coast presumably limits their distribution in the Bay. They lay their single egg typically in mid-June, with chicks hatching 30 days later (Gaston and Nettleship 1981). After about 20 days at the nest during which time the chick is fed by both parents, the chick fledges with the father, which cares for the chick for about 40 days at sea (Elliott et al. 2017). Maximum longevity for thick-billed murres is 37 years, with a Coats Island bird being the oldest known individual, and they first breed at about 5 years of age (Elliott et al. 2013).

At most colonies in Canada, Arctic cod (*Boreogadus saida*) is the key prey of thick-billed murres, and that was the case at the Hudson Bay colonies until the mid-1990s. Since 1997, the diet of murres has been typically <10% Arctic cod and >50% capelin (*Mallotus villosus*), a reversal of the pre-1990s diet (Gaston et al. 2003; Gaston and Elliott 2014). Presumably, reduced ice cover in recent years has meant that capelin has replaced Arctic cod in the surrounding waters of northern Hudson Bay (Gaston et al. 2003). In 1998, 2003, 2011, 2016 and 2018, one or more polar bears consumed up to 30% of the Coats Island colony (Gaston and Elliott 2013), see figure 2. As observations of polar bears near the colony have increased dramatically in recent years, this appears to be a consequence of longer ice-free periods where bears are on land searching for terrestrial food. Similarly, recent years have seen

an increase in windless days, and the consequent increase in mortality and reproductive failure due to mosquito parasitism (Gaston et al. 2002; Gaston and Elliott 2013). Recent surveys of Coats and Digges Island have suggested that the colony numbers may have declined by 10% in recent years, likely due to the combined bottom-up effect of reduced Arctic cod and top-down effect of increased polar bear predation and mosquito parasitism.

The Coats Island thick-billed murre population is used by the Northern Contaminants Program as a key indicator for contaminants level in marine wildlife, with eggs archived since 1993 (Braune et al. 2014). Those analyses have clearly shown a decline in organochlorine pesticides and brominated flame retardants following global restrictions (Braune et al. 2015). However, levels of some perfluorinated compounds continue to increase, and mercury levels are also continuing to increase after adjustment for trophic level (Braune et al. 2015).

Recent tracking studies have illuminated the activities of thick-billed murres when they are not at the colony. During the breeding season, murres from Coats and Digges Islands span out to cover much of northern Hudson Bay (Gaston et al. 2013). Whereas the Coats Island birds forage exclusively within 100 km of the colony in Evans Strait and adjacent waters, the Digges Island birds forage up to 300 km from the colony in



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**FIGURE 2.** A polar bear eating a seabird (*akpa* or thick-billed murre). In recent years, polar bears have arrived on land earlier, and have switched to eating significant numbers of seabirds and their eggs.

virtually all directions (Gaston et al. 2013). Given that murrens have the highest energy costs for their size of any animal, those commutes are made directly (Elliott et al. 2013). The floe edge is important, with birds commuting to and from the floe edge when it is within range. Following the breeding season, birds from both colonies spread out across northern and western Hudson Bay, where they spend two months moulting (Gaston et al. 2008; Tranquilla et al. 2013). They are flightless during that period. In late November or early December, they typically migrate to wintering areas in the North Atlantic (first year birds typically winter near Newfoundland with adults farther out to sea; Gaston et al. 2008; Tranquilla et al. 2013; Elliott et al. 2017). However, in years of low ice, some individuals remain within the Bay at polynyas year-round, possibly becoming trapped by ice should weather deteriorate.

Black guillemots weigh roughly 400 g, are all black with white wings and red feet. Black guillemots are poorly monitored in Hudson Bay, although there was some early research in the Digges Sound region in the early 1980s (Cairns 1980, 1987). Guillemots lay two eggs in rock crevices in late June shortly after snow melt (Divoky et al. 2015). The eggs are incubated by both parents for about 30 days. Both chicks are then fed at the colony for ~40 days they are able to fly, known as fledging. After fledging, the young are independent of the parents. Some, perhaps most, individuals winter in leads and polynyas within Hudson Bay. Guillemots occur at much lower densities than murrens, with large colonies (few hundred pairs) occurring only in the Digges Sound region. Most 'colonies' are only of a handful of pairs (Gaston et al. 2012). Little is known about the trends in guillemots, although there are some reports of declining trends in eastern James Bay.

#### 4. Gulls and terns

Several species of gulls and terns use the Hudson Bay region. The region is particularly important for Sabine's gull (*Xema sabini*), with a significant proportion of the North American population living in the area (Stenhouse et al. 2006). Sabine's gulls weigh about 180 g, and are white with a grey head and yellow tip to the bill, and a distinctive white triangle on the wing. The only member of its genus, Sabine's gull typically returns to breed when it is two years old. During the breeding season, they lay two eggs that are incubated for about 25 days. The chicks fledge at about 30 days of age. Sabine's gulls winter off the coast of Africa. During the breeding season, they forage on aquatic insects in freshwater wetlands near the coast, switching to marine fish and invertebrates for the rest of the year spent at sea.

Arctic terns (*Sterna paradisaea*) are also common in the Hudson Bay region. Switching from a marine diet for most



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of the year to a partially freshwater diet during the breeding season, Arctic tern colonies are found both inland and along the coast. Famous for migrating to the Antarctic each year, conducting the longest migrations in the animal kingdom, Arctic terns are pale grey with a black cap, forked tail and orange bill. Arctic terns typically lay two eggs and can live over 30 years in the wild. The eggs are incubated for about 25 days and the chicks fledge at about 22 days. As is the case for Sabine's gull, population trends and distribution are poorly known in Hudson Bay for this circumpolar species. However, although not formally monitored, populations are believed to have decreased along western Hudson Bay, eastern James Bay and in Churchill, two of the very few places where the species has been monitored (E. Nol and M. Humphries, pers. comm.). Increased common raven populations associated with towns and goose population increases may be having an impact on reproductive success (E. Nol, pers. comm.).

Three species of *Larus* gulls occur within the Hudson Bay region: glaucous gull (*Larus hyperboreus*), Iceland gull (*Larus glaucooides*) and herring gull (*Larus argentatus*). All three have circumpolar distributions, weigh 1-3 kg, are white with a grey back, lay typically three eggs that are incubated about 30 days. The young fledge after about 45 days, and are cared by the parents for up to an additional six months. It typically takes four years to reach sexual maturity, and longevity for *Larus* gulls can be upwards of 40 years. Iceland gulls are primarily marine, nesting on cliffs along ocean coasts, with several colonies along the northern rim of Hudson Bay. Populations appear stable (Gaston et al. 2012). Herring gulls are colonial in some regions, but also occur in loose colonies or nest alone around much of the coastal region of Hudson Bay, and populations also seem stable (Allard et al. 2009). Glaucous gulls also occur in colonies, often being predators of other seabirds, especially murrens. However, they also occur solitarily or in loose colonies. Glaucous gulls in eastern Hudson Bay have declined substantially in recent years (Gilchrist and Robertson 2009), a trend supported by counts on the wintering grounds (Gaston et al.



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2012), although increases may have occurred at some communities (Gaston et al. 2012).

Apart from those species already listed, Ross's gull, an endangered species, is known from several breeding records near Churchill, although it seems to have disappeared from that site recently. Similarly, little gulls breed in the lowlands at the southern edge of the bay, and Bonaparte's gull similarly breeds in nearby wetlands. All three jaeger species also occur, with Pomarine jaegers moving nomadically to take advantage of pulses in lemming availability. Long-tailed and parasitic jaegers tend to remain in a particular area, and regularly occur along the coastline of Hudson Bay. Parasitic jaegers may prey on the nests (or goslings) of Canada geese, as well as on several shorebird species. They will also steal food from other species, such as black guillemots and terns. Little is known about the distribution and trends of any of these species.

## 5. Seaducks and loons

Several species of seaducks occur in the Greater Hudson Bay region: common eider, king eider (*Somateria spectabilis*) and long-tailed duck (*Clangula hyemalis*). Common eiders (*Somateria mollissima sedentaria*) are likely the most important culturally, as they nest in large colonies that are harvested for down and eggs. Moreover, a large colony at East Bay Migratory Bird Sanctuary has been monitored for many years, providing excellent trend information. The common eider is a large seaduck. The male is largely white and the female, which does all the incubation, is mottled brown. The female incubates the eggs for approximately 24 days during which period she does not feed, but only leaves the nest once per day to drink. At colonies, the chicks leave the nest to form creches where females take turns protecting ducklings (Mackinnon et al. 2006). Common



G. GILCHRIST AND J. HEATH/THE ARCTIC EIDER SOCIETY

eiders from Hudson Bay winter either in the polynyas near the Belcher Islands, or in coastal areas of Greenland (Mosbech et al. 2006). Eider populations may be declining, with a 75% decline reported for the Belcher Islands between 1985 and 1997 (Robertson and Gilchrist 1998).

The *sedentaria* subspecies of the Common Eider occurs typically in Hudson Bay and James Bay on a year-round basis. *Sedentaria* eiders nest in colonies on the coastal islands in Hudson Bay and James Bay. This subspecies is particularly abundant on the Belcher Islands, Sleeper Islands and Ottawa Islands,

all offshore archipelagos located off the east coast of Hudson Bay (Snyder 1941). Individuals may also breed in the northern end of Hudson Bay, on Southampton, Coats and Mansel Islands (Robertson and Gilchrist 1998). Most *sedentaria* drakes leave the nesting islands around the middle of the incubation period (Guild 1974; Manning 1976) to head to their moulting areas. Flocks of males congregate in the Belcher, King George and Sleeper Islands after breeding, but leave these sites in early August (Manning 1976). All the moulting areas in Hudson Bay have not yet been identified. Males lose their ability to fly in late June and regain it in late August or early September; females probably moult a few weeks later.

Climate change is expected to bring new parasites and diseases into the Arctic, and the first records of avian cholera in northern Hudson Bay eiders occurred in Digges Sound in 2004 (Descamps et al. 2011). A major outbreak followed, reducing the East Bay colony in half (Descamps et al. 2011). During the outbreak, those hens with a large clutch size had low survival illustrating the strong cost of reproduction during the outbreak (Descamps et al. 2009). Furthermore, duckling survival declined by 90%, leading to almost no recruitment into subsequent generations (Descamps et al. 2011).

Predation associated with climate change has also played a strong role within the East Bay system (Iverson et al. 2014; Dey et al. 2017). As the ice-free period has lengthened, polar bears have come on shore earlier, encountering incubating common eiders. Since the polar bear invasion became annual in the late 2000s, there has been essentially no recruitment to the population as the bears eat all eggs or chicks prior to their departure (Dey et al. 2017). The effect of polar bears on colony dynamics is pronounced, with bears having a disproportionate effect on large colonies. It is expected that eider colony size will decline in Hudson Bay as eiders choose smaller colonies to avoid polar bear predation (Dey et al. 2017).

King eiders tend to nest in smaller groups or solitarily compared with common eiders. They are also somewhat smaller (~1.5 kg), but with similar plumage differences between males and females. As with common eiders, they have a large clutch size of four to seven eggs that is incubated by the hen alone for ~22 days before the hen alone cares for the ducklings. King eiders winter in the North Atlantic. Long-tailed ducks are a smaller species of white-and-brown seaduck (~750 g) with the hen similarly doing all incubation and chick-rearing. Long-tailed ducks nest near inland lakes where they forage on aquatic invertebrates. They winter in the coastal North Atlantic and Great Lakes, feeding on mussels and other invertebrates. Widespread in coastal Hudson Bay, the population trends for king eiders and long-tailed ducks in the region are poorly known. King Eider nests on the edge of freshwater ponds in the tundra, no more than 50 km from the coast (Lamothe

and Choinière 1996). In addition, the long-tailed duck breeds along the coast of Hudson Bay and James Bay (Lamothe and Choinière 1996).

There are three species of scoter in Hudson Bay. The surf scoter breeds in Ontario's Hudson Bay lowlands as well as in Quebec. The Atlantic (or eastern) population Black Scoter (*Melanitta nigra*) breeds in the northern half of Quebec, and the Hudson Bay lowlands of Ontario (Bordage and Savard 1995; Perry et al. 2004). The white winged scoter breeds mainly along the northeast coast of James Bay. The coastal regions are mainly used for moulting, with tens of thousands of scoters from all three species using the Hudson and James Bay coasts in late summer (Benoit et al. 1994, 1995).

Two merganser species can be found in James and Hudson Bay coasts. The common merganser is common along rivers leading into the Bay, such as the vast Great Whale and Little Whale river regions. Once trees and shrubs make way to tundra the habitat is less suitable for breeding for the species. The Red-breasted Merganser is the most northerly of the species of mergansers, and also the one that spends the most time in marine habitats. The species breeds on islands and in coastal habitats in the boreal forest and tundra. Preferred nest sites may include the wooded banks of a river, marsh or lake, the shoreline of a sheltered bay, lagoon or estuary, or a rocky islet or coastal island; the nest is most often close to saltwater, but brackish or freshwater environments may also be used (Alvo and Bourget 1996; Titman 1999). Although the northern limit of the Common Merganser's range does not extend much beyond the taiga, that of the Red-breasted Merganser extends much further north, into the shrub tundra and beyond. The Red-breasted Merganser, like the Common Merganser, moults in large numbers along the northeast coast of James Bay (Benoit et al. 1994; Reed et al. 1996).

Pacific loon (*Gavia pacifica*) and red-throated loon (*Gavia stellata*) are common in the Hudson Bay region. Red-throated

loons tend to breed on smaller waterbodies than Pacific loons, because they will commute to the ocean to feed, while Pacific loons require a waterbody large enough to sustain a loon family, including one or two young, as they do not commute to the ocean. Both species migrate to coastal areas (Pacific Ocean for Pacific loons, Great Lakes and Atlantic Ocean for red-throated loon) for the winter. They both typically lay two eggs per clutch that are incubated for 25 days. The parents feed the offspring fish and small invertebrates for roughly 45 days post-hatch, and adults can live over 20 years. Common loons (*Gavia immer*) and yellow-billed loons (*Gavia adamsii*) also occur in small numbers in the region. Population trends and distribution in the Hudson Bay region are poorly known for all loon species, although trends on the wintering grounds are stable.

## 6. Shorebirds

Shorebirds are among the most diverse group in Hudson Bay, and include both sandpipers and plovers (Johnston et al. 2012). All species typically lay four eggs that are incubated for two to three weeks. Many species of shorebirds migrate long distances, with black-bellied plover (*Pluvialis squatarola*) and dunlin (*Calidris alpina*) 'only' migrating to the southern United States, and Hudsonian godwits, white-rumped sandpipers (*Calidris fuscicollis*) and American golden-plovers (*Pluvialis dominica*) migrating to Patagonia (South America), with many species wintering in between. The distribution and abundance of shorebirds in many regions around Hudson Bay, have been well-described by the Protocol for Regional and International Shorebird Monitoring and the provincial Breeding Bird Atlases. Furthermore, detailed studies at Churchill and at East Bay Migratory Bird Sanctuary have provided an excellent context for understanding population trends (Jehl and Lin 2001; Smith et al. 2012; Bart et al. 2012).

The impacts of climate change will vary among shorebird species, depending on a number of factors, including the particular habitats in which they nest and forage, the potential increase in nest predators with vegetation encroachment and a warming climate (particularly common ravens *Corvus corax*), the perception and potential avoidance by nesting birds of areas with shrub and tree encroachment, and their dependence on marine or freshwater invertebrates for prey for developing eggs (females) or for their young (Ballantyne and Nol 2011, 2015). There is some evidence that encroachment of trees and shrubs in one area in the Churchill region is associated with a disappearance of nesting whimbrel (*Numenius phaeopus*; Ballantyne and Nol 2011, 2015). For dunlin, there is no association between the density of trees in the environment and the probability of hatching and, in general, nest sites for dunlin continue to



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have relatively low numbers of trees and shrubs (Holmes 2014). Drying of areas around nests reduces the amount of prey for precocial chicks, and this could be a factor in reducing fledgling success (Holmes 2014). Other species, like the semipalmated plover, which forages on mudflat environments and in the supratidal region, can be impacted by greater deposition of algal mats over potential foraging areas due to earlier ice out and more frequent onshore storms (E. Nol., pers. comm.). There is little evidence so far that a mismatch between the emergence of the invertebrate prey and the timing of breeding for either dunlin (McKinnon et al. 2013) or semipalmated

plovers (Corkery 2013), results in either lower growth rates or lower survival success. However, there is some evidence from Hudsonian godwits that mismatch may play a role in poor hatching success (Senner 2016). Hudsonian godwits select sites with more grasses and shrubs, and as this habitat will increase rather than decrease in Churchill, there may be an increase in suitable habitat of Hudsonian godwits (Swift et al. 2017).

The rapid increase in populations of geese using the coastal wetlands around Hudson Bay may also be impacting shorebird nesting habitat and nest predation rates (Flemming et al. 2016). Intensive and repeated grazing of grass-like plants by



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Canada goose hunted in James Bay.

### Box 1. Goose Break

*(Printed with permission from CBC News – original can be found at <https://www.cbc.ca/news/canada/north/goose-break-cree-youth-1.3568144>)*

**Every spring, several communities in Northern Quebec all but close down for a few weeks** while people head out on the land to hunt returning geese and spend time with family and friends. The tradition is a centuries old practice that connects Cree youth with culture. Goose Break is a way to teach traditional ways and strengthen community ties in James Bay. Elders go out on the land with youth and teach skills like hunting safety tips, how to make a goose call, spending time in a goose blind and how to clean their own kill.

“This is a good experience for the youth,” said Anna Bosum, one of the volunteers. “Once you expose them to the things they will learn, they will remember it for a long time. Even the storytelling at camp, they will also learn from.”

In the community of Chisasibi, at the end of the James Bay Highway about 1,000 kilometres north of Oujé-Bougoumou, the local youth council has come up with a different way to encourage more young people to get out for Goose Break.

It has launched “Adopt a Youth for Goose Break,” a program where families can sign up to bring an extra young person or two — aged 13 to 35 — out on the land with them.

Young people who want to take part are invited to sign up or are referred by Chisasibi’s social services department.

In the past, it was commonplace for a family to bring an extra person or two out with them for Goose Break.

“That is part of Cree culture, back in the day people would always tag along with other people to their traplines,” said Paula Napash, Chisasibi’s youth chief. We want people to live together in harmony and to hang out (together).”

For Napash, the project is a chance to teach youth about Cree language, culture, skills and values, as well as a chance for youth to learn to respect the land and animals.

“I would always stay with my grandparents and would learn so much at my aunt’s,” she said.



CBC

A Whapmagoostui youth holding his first goose in May of 2014.

geese has reduced the suitability of large areas of the Hudson Bay lowlands for many nesting shorebirds and around Churchill, it may in part be responsible for the local declines. The disappearance of semipalmated sandpipers in the Churchill area appears to be associated with snow goose herbivory (Jehl 2007). Endangered *rufa* red knots (*Calidris canutus rufa*) also use some goose-affected areas as stopover sites during migration and therefore may be affected (McKellar et al. 2015). Similarly, many of the goose barrens—goose colonies where overgrazing limits the availability of nests for shorebirds and other species—on Baffin Island and Southampton Island occur in coastal regions where shorebirds are common. Shorebirds as a guild are rapidly declining on migration counts, especially semipalmated sandpipers (*Calidris pusilla*), and increasing geese populations throughout the Arctic may play a role. Increased winter survival of common ravens near towns, such as Churchill, may also play a role as there is high predation pressure from ravens on species such as semipalmated plover prior to goose hatch. In general, at Churchill, dunlin populations have been stable since 2008, semipalmated plover populations are slightly declining, red-necked phalarope populations have declined steeply since the 1980s, semipalmated sandpipers have disappeared, and whimbrels and godwits are stable (Ballantyne and Nol 2011, 2014; Senner 2016).

## 7. Geese and other waterfowl

Snow geese (*Anser caerulescens*) and much smaller numbers of Ross's geese (*Anser rossii*) are important food sources for Inuit and Cree living along the Hudson and James Bay shorelines. They also play an important role in the overall avian communities as goose barrens are regions where few other bird species occur. Furthermore, goose colonies can provide food for predators, such as foxes, jaegers and ravens, leading to elevated

populations that impact other species, either beneficially because predators have easier prey or negatively because predator abundance is higher.

Goose populations at La Perouse Bay, Southampton and Coats Island, and elsewhere in western Hudson Bay, have increased due to grain subsidies and reduced hunting on the wintering grounds in the South. Once a conservation concern due to overharvest, goose populations have rapidly increased since the 1970s, and due to subsidies on wintering sites, may be larger than historic populations. Indeed, new goose populations have been found in some regions, such as Coats Island. In some areas, polar bears appear to be increasingly consuming goose eggs during the lengthy ice-free period (Rockwell et al. 2010; Smith et al. 2010), which may have a population-level impact. Nonetheless, white goose populations appear to be increasing substantially in the Hudson Bay region.

Two other goose species breed in the Hudson Bay region, Canada goose (*Branta canadensis*) and its smaller congener, cackling goose (*Branta hutchinsii*). The Canada goose increased rapidly following restrictions on quotas in the 1970s, and is now common throughout much of the Hudson Bay coastal regions, while cackling geese are largely found near cliffs at the northern edge of the Bay. Both species winter in southern Canada and the United States.

The main core nesting area of the Atlantic population of Canada geese is on the Hudson Bay coast (Harvey et al. 2017). For example, in the best breeding habitat, densities were much higher in the coastal lowlands of Hudson Bay (85.1 nests/km<sup>2</sup>) than those of Ungava Bay (31.7 nests/km<sup>2</sup>) (Harvey and Rodrigue 2002). The number of breeding pairs of the Atlantic population of Canada geese was about 160 000 in 2017. In 1995 hunting was closed in Québec, part of Ontario and 18 US states. Following the recovery of the population the season was opened in 2001 (Harvey et al. 2017). The most influential factor in the productivity of



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Atlantic Canada Geese is the weather, particularly temperature and snow cover during the critical egg-laying and incubation periods (late May to early June).

Brant (*Branta bernicla*) migrate through eastern James Bay where eelgrass beds play an important role as staging habitat prior to their migration to the east coast of North America. There are anecdotal reports of declines in the region following disruption of eelgrass by hydroelectric projects, a subject that warrants more investigation. For further information on eelgrass see Box 1 in Theme II, Chapter ii, Nutrient Dynamics. Many species of dabbling duck also occur in the region, and are an important part of local harvests. Little is known about trends and distributions north of annual aerial surveys. The core breeding range of the Atlantic population of Brant is concentrated around Foxe Basin.

The spring migration takes the birds from eastern United States overland to James Bay (New Jersey Division of Fish and Wildlife 2003; Ward et al. 2005). Some birds stop in Montreal or Lake Champlain on their way north, while other birds make an almost direct flight between their wintering grounds and James Bay. Some birds then spend as many as four or five weeks in James Bay feeding on eel grass to build up fat reserves (New Jersey Division of Fish and Wildlife 2003), with confirmed concentrations of over 50,000 Brant in Rupert Bay in late May (Tecsult Environnement Inc. 2004).

A number of other bird species occasionally use the Bay. For example, tundra swans and greater and lesser scaup breed in the coastal wetlands of Nunavik, and likely use the Bay during migration.

## 8. Summary and recommendations

The Greater Hudson Bay Marine Region is used by a variety of bird species, including many species that breed along its coast line, use a variety of habitats for moulting and migration stopovers, or winter in or near polynyas. The ice-free summer period has increased by 1-2 months in Hudson Bay over recent decades, and the Bay in summer is now more equivalent to a north temperate than Arctic ecosystem. Due to the longer ice-free period, birds are spending longer in the Bay during moult, migration and winter. Arctic birds in Hudson Bay are impacted negatively by top-down effects (increased predation and parasitism), invasive species and bottom-up effects (altered prey structure). With the above concerns the following recommendations should be put into place to conserve and protect seabirds:

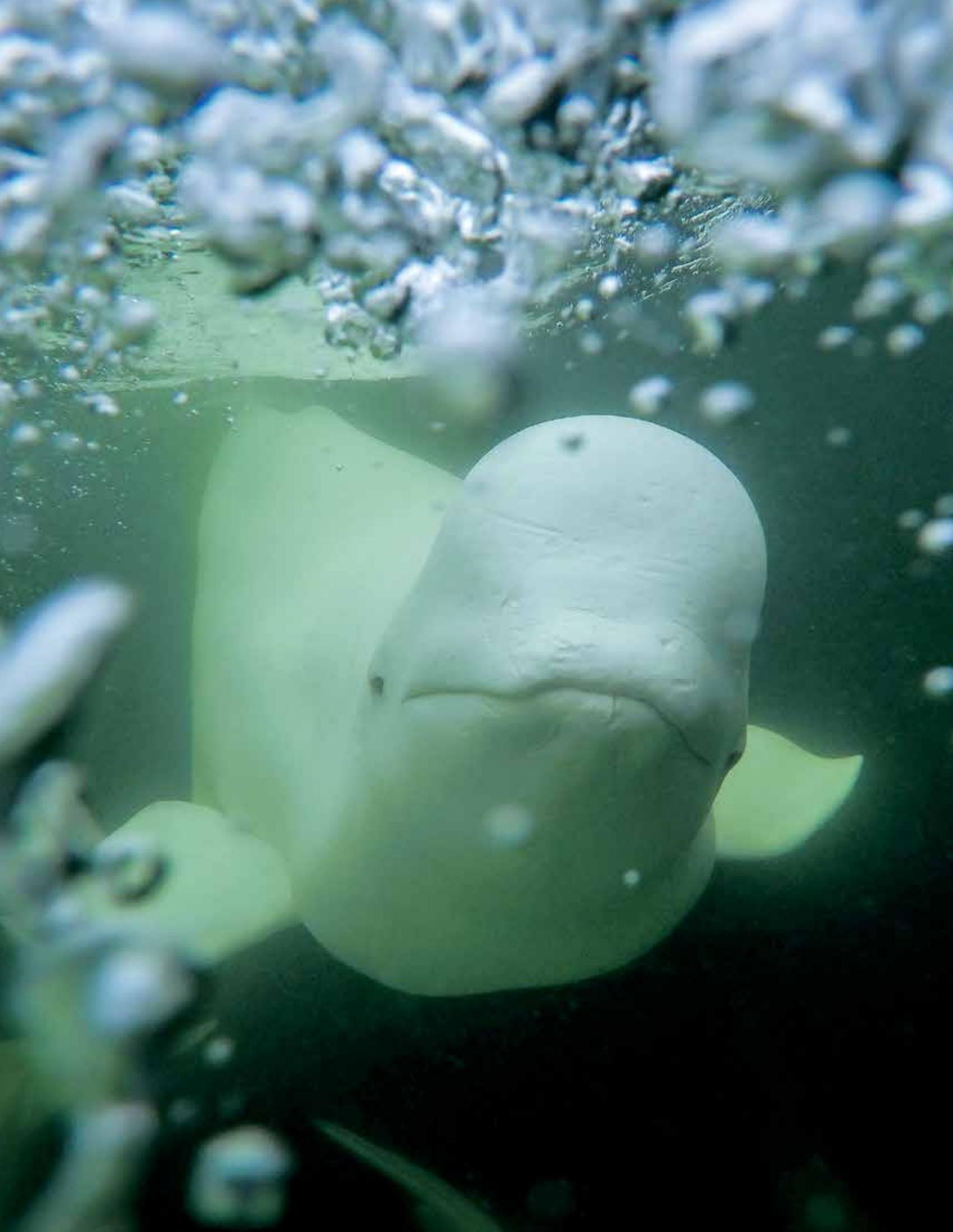
- Continue long-term monitoring stations that provide important data in a time of shifting baselines.

- Conduct at-sea surveys in Hudson Bay to combine with year-round tracking data to delineate critical at-sea habitat in Hudson Bay.
- Given that birds are obvious and well-recognized components of ecosystems, find ways to connect scientific and traditional Indigenous knowledge about birds.

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## II.vi

# Whales, Seals, and Walrus of the Greater Hudson Bay Marine Region

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## Summary

**M**arine mammals, such as beluga whales and ringed seals, are an integral part of the lives of the people who live around the Greater Hudson Bay Marine Region. This is particularly true for Inuit who depend on the harvesting of marine mammals for subsistence food, a pillar of their culture and wellbeing. In the Greater Hudson Bay Marine Region, year-round resident whale species include beluga, narwhal, and bowhead, while seasonal sightings of killer, humpback, and minke whales have increased in recent years. In addition, a number of seal species make Hudson Bay their year-long residence including ringed seals, bearded seals, harbor seals, and walrus. This chapter provides an overview of the marine mammal species, their distribution and stressors, and management in the Greater Hudson Bay Marine Region.

## Key Messages

- **Loss of ice habitat, changing food availability, increases in diseases, and the invasion of southern species are taking their toll on Hudson Bay marine mammals and suggesting an ecosystem on the verge of a shift.**
- **Some Inuit communities have noted a change in seal stomach contents, with more open water fishes, indicating that the distribution and availability of food resource species are changing.**
- **Belugas in Hudson Bay varied timing of migration in response to variations in temperatures. These migrations may affect the ability of people to find and use these resources.**
- **Early spring sea ice retreat reduces suitable breeding and pup rearing habitat for ringed seals.**
- **The more temperate killer whale that eats marine mammals is expanding into Hudson Bay waters which may affect beluga, narwhal, and bowhead populations.**



S. BLONDEAU

## 1. Introduction

Changes in climate, causing decreases in sea ice cover and duration, have resulted in changes in seasonal movement and population dynamics of marine mammals in Hudson Bay (Laidre et al. 2008; Ferguson et al. 2010a; Hammill 2013). Within the Greater Hudson Bay ecosystem, it is expected that some species may become locally extinct or isolated (e.g., southern Hudson Bay polar bears; Derocher et al. 2004), while others may expand their ranges as a result of warmer temperatures and reduced ice cover (e.g., killer whales; Higdon and Ferguson 2009). Due to the presence of seasonal sea ice at this southerly extent and estuarine characteristics of the Hudson Bay marine ecosystem, a number of Arctic cetaceans (placental marine mammals such as beluga whales) repeatedly return to coastal areas during the summer season. The waters of Hudson Bay are seasonally frequented by beluga, narwhal and bowhead, which migrate to the region as ice conditions permit (Stewart and Lockhart 2005). In addition, a number of seal species make Hudson Bay their year-long residence, including ringed seals, bearded seals, harbor seals, and walrus (Young et al. 2010). The abundance and distribution of these populations are influenced by a variety of factors, such as sea ice characteristics, resource availability, and factors related to mortality and reproduction (Stewart and Lockhart 2005; Ferguson et al. 2010a). In addition, seasonal migrants to the area in summer include

harp seals, hooded seals, minke whales, and humpback whales (Mansfield 1967; Higdon and Ferguson 2009).

As the ice-free season lengthens in western Hudson Bay, the port of Churchill, Manitoba may become a region of increased activity and development (See Theme III. Chapter ii. for more details related to shipping). Marine vessel disturbance (strikes and noise), land and freshwater use and development, and climate change affecting ice presence and water temperature, can cause marine mammals to temporarily or permanently abandon summer feeding grounds and calving areas, and could reduce their ability to reproduce or survive through the winter months (Mallory et al. 2010; Richardson et al. 2013; Gavrilchuk and Lesage 2014). The Hudson Bay ecosystem has been strongly influenced by commercial hunting in the past (Reeves and Mitchell 1987), and traditional subsistence lifestyles continue to be closely linked to the health and abundance of whale, walrus, and seal populations. Narwhals and belugas provide a high economic value to Hudson Bay communities such as Nauyas largely due to their food value. However, the beluga hunt overall provides greater revenue because more belugas are harvested (Hoover et al. 2013). Predicting how changes in climate will impact the Hudson Bay marine ecosystem will be difficult but requires relevant science and maintaining long-term monitoring programs that can provide adaptive strategies (Petersen et al. 2010; Laidre et al. 2015).

## 2. Marine mammals

### 2.1. Beluga whales

Belugas live in Arctic and sub-Arctic waters throughout Canada and are most numerous in Hudson Bay. They are sociable animals often seen in groups and are born grey at birth at about

1.5 m in length (Dodge 1990). Adult belugas range in total length from 2.6 to 4.5 metres and can weigh up to 1,900 kg with females averaging about 2/3 the length/weight of adult males (Brodie 1982). Sometime around when they reach sexual maturity they become white (Sergeant and Brodie 1969). Females and males become sexually mature at 8-14 and 12-14 years of

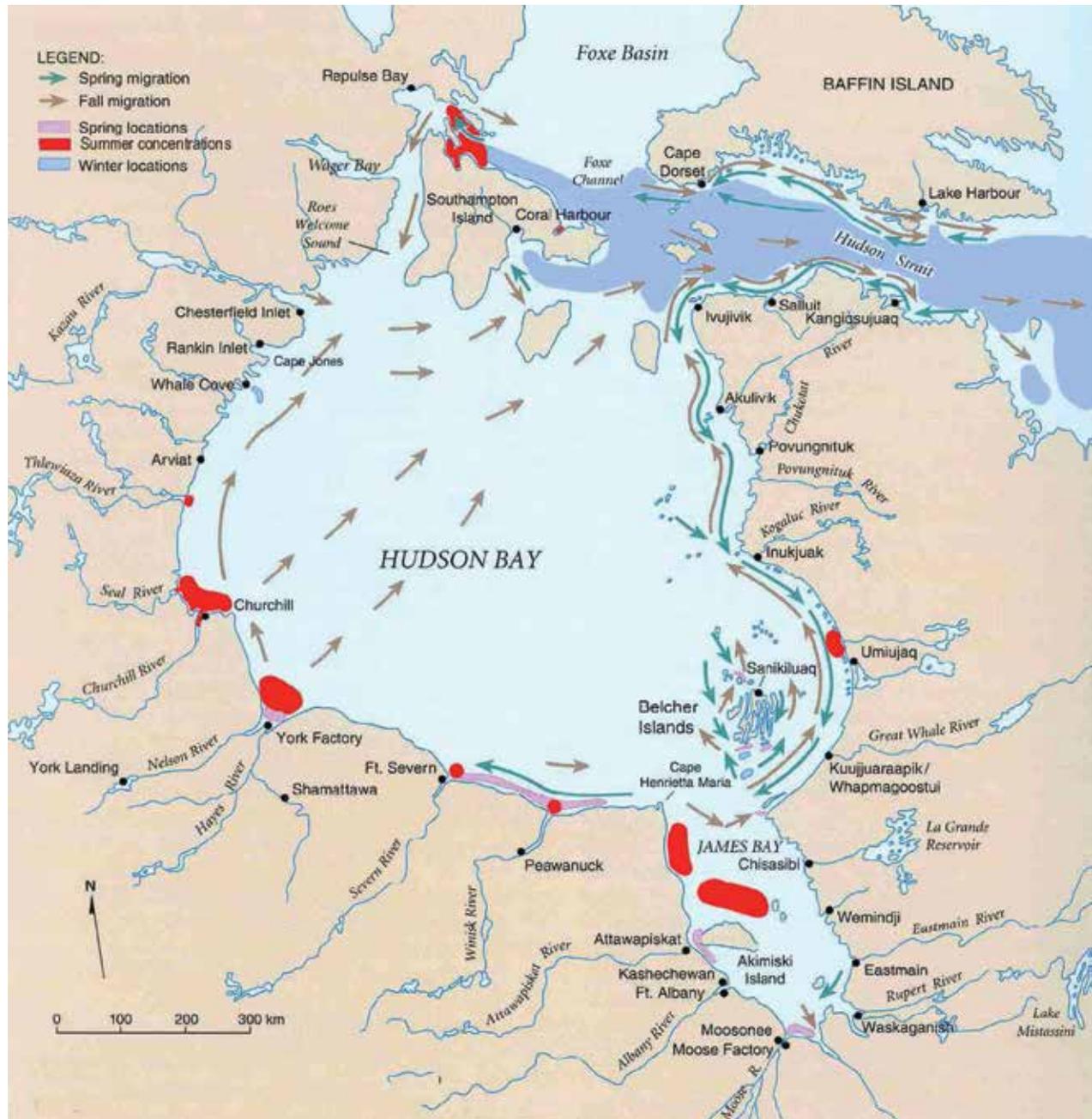


FIGURE 1. The spring and fall movements of Hudson Bay belugas and areas where they migrate in spring, concentrate in summer, and migrate to spend the winter. Compiled from traditional and scientific sources. From Stewart and Lockhart (2005).

age, respectively (Heide-Jørgensen and Teilmann 1994). Mating is thought to occur during late winter to early spring (Burns and Seaman 1985; Doidge 1990), and calves are born between June and September (Sergeant 1973). Gestation lasts 12.8 to 14.5 months (Doidge 1990) and lactation from 20 to 32 months, resulting in a three-year interbirth cycle (Sergeant 1973; Doidge 1990; Burns and Seaman 1985; Matthews and Ferguson 2015).

Belugas have a seasonal cycle of feeding with most studies reporting intensive summer feeding often in deep areas that can be far from their summer estuary distribution (Smith and Martin 1994; Kelley et al. 2010). However, Inuit knowledge indicates that in Hudson Bay belugas are fattest in winter and early spring and thin in the fall, suggesting fall and winter intensive feeding (Breton-Honeyman et al. 2016). Belugas feed mainly on fishes, primarily Arctic cod (*Boreogadus saida*), but secondarily shrimp and cephalopods. Other forage fish food includes Greenland halibut (*Reinhardtius hippoglossoides*) and other flatfish, capelin (*Mallotus villosus*), saffron cod (*Eleginus novaga*), rainbow smelt (*Osmerus mordax*), Pacific herring (*Clupea pallasii*), sandlance (*Ammodytes* sp.), and cisco (*Coregonus sardinella*) (Kilabuk 1998; Quakenbush et al. 2015; Breton-Honeyman et al. 2016; Loseto et al. 2017). Various species of invertebrates are also consumed (McLeod et al. 2008).

Belugas vary their habitat use seasonally with greater deep offshore areas used during fall and winter and shallow coastal waters used in summer. Most populations migrate between summer and winter ranges during early spring and late fall, although some smaller populations are more sedentary. Hudson Bay belugas spend winter in partially ice-covered areas away from the coast (Jonkel 1969; Lewis et al. 2009) and some wintering areas are shared by more than one stock. Related individuals tend to follow the same routes (Colbeck et al. 2013). During summer, belugas are often associated with coastal bays and estuaries (Sergeant 1973), and they show strong fidelity to these areas from one year to the next (Caron and Smith 1990; Smith et al. 1994). Belugas use these summer estuary areas for a number of activities and estuary use likely varies geographically and includes moulting (St. Aubin et al. 1990), feeding, or calving (Stewart and Stewart 1989), and protection from killer whale (*Orcinus orca*) predation (Kilabuk 1998; Cardinal 2013; Smith et al. 2017).

### 2.1.1. Western Hudson Bay belugas

The Western Hudson Bay population is the largest in the world with more than 50,000 animals (Richard 2005; Mathews et al. 2017) spending summer primarily in the Seal, Churchill and Nelson River estuaries of western Hudson Bay and migrating to Hudson Strait during the winter (Smith 1987). Estuary-specific maternal lineages from the Seal, Churchill, and Nelson Rivers may occur (de March and Postma 2003). Most Inuit communities along the Hudson Bay coastline harvest belugas at different

times of the year. Historical commercial harvests occurred in Churchill by the Hudson Bay Company from 1688 to about 1930 (Reeves and Mitchell 1989) and then by a Manitoba company from 1949 to 1968 (Sergeant 1981). In summer, belugas from the Western Hudson Bay population are also found in smaller numbers from the Winisk River to the east all along the coastline north to the Naujaat (formally Repulse Bay) area (Sergeant 1973).

Belugas tagged with satellite transmitters in the Nelson River estuary, 2003-05, were mostly in eastern Hudson Strait in winter (November to March), with some individuals located off the coast of northern Labrador (Smith 2007). The whales tagged at the Seal River estuary in 2012 overwintered in western Hudson Strait (DFO unpublished data). Belugas tagged in Churchill in 2015 were located south of Southampton Island in December when tags stopped transmitting (DFO unpublished data).

### 2.1.2. Eastern Hudson Bay belugas

The Eastern Hudson Bay beluga population numbers about 3500 and summers in the arc of eastern Hudson Bay and winters in Hudson Strait (Gosselin et al. 2013). This population was severely reduced by intensive commercial hunting, and has not recovered due in part to continued subsistence hunting (Reeves and Mitchell 1987; Hammill et al. 2004). In the spring, Eastern Hudson Bay belugas migrate westward along the southern shore of Hudson Strait into eastern Hudson Bay to summer at the Nastapoka and Little Whale rivers. During summer they occur near the coast from Inukjuak to Kuujuarapik with some whales moving offshore to the Belcher Islands (Kingsley 2000). Satellite-tagged belugas between 1993 and 2004 (Lewis et al. 2009) began the fall migration north along the eastern Hudson Bay coastline, spending time northeast of the Belcher Islands, and then moved east through Hudson Strait, overwintering in the Ungava Bay region and along the coast to the Labrador Sea (Bailleul et al. 2012).

### 2.1.3. James Bay belugas

Satellite tagging, genetics, and local knowledge suggest that the James Bay beluga population is mostly restricted in movements to James Bay (Postma et al. 2012; Bailleul et al. 2012). The population numbers about 15000 whales (Gosselin et al. 2013) and appears to be largely non-migratory. Beluga feeding areas have been identified in southern James Bay, near Moose Factory and in Hannah Bay (McDonald et al. 1997).

## 2.2. Northern Hudson Bay narwhal

The narwhal is an Arctic cetacean known to travel in summer to bays and fjords and then migrate in winter to deep offshore areas of heavy pack ice (Laidre et al. 2002). The northern Hudson Bay narwhal population numbers about 12500 whales (Asselin et al. 2011) and spends summer in the area of Naujaat



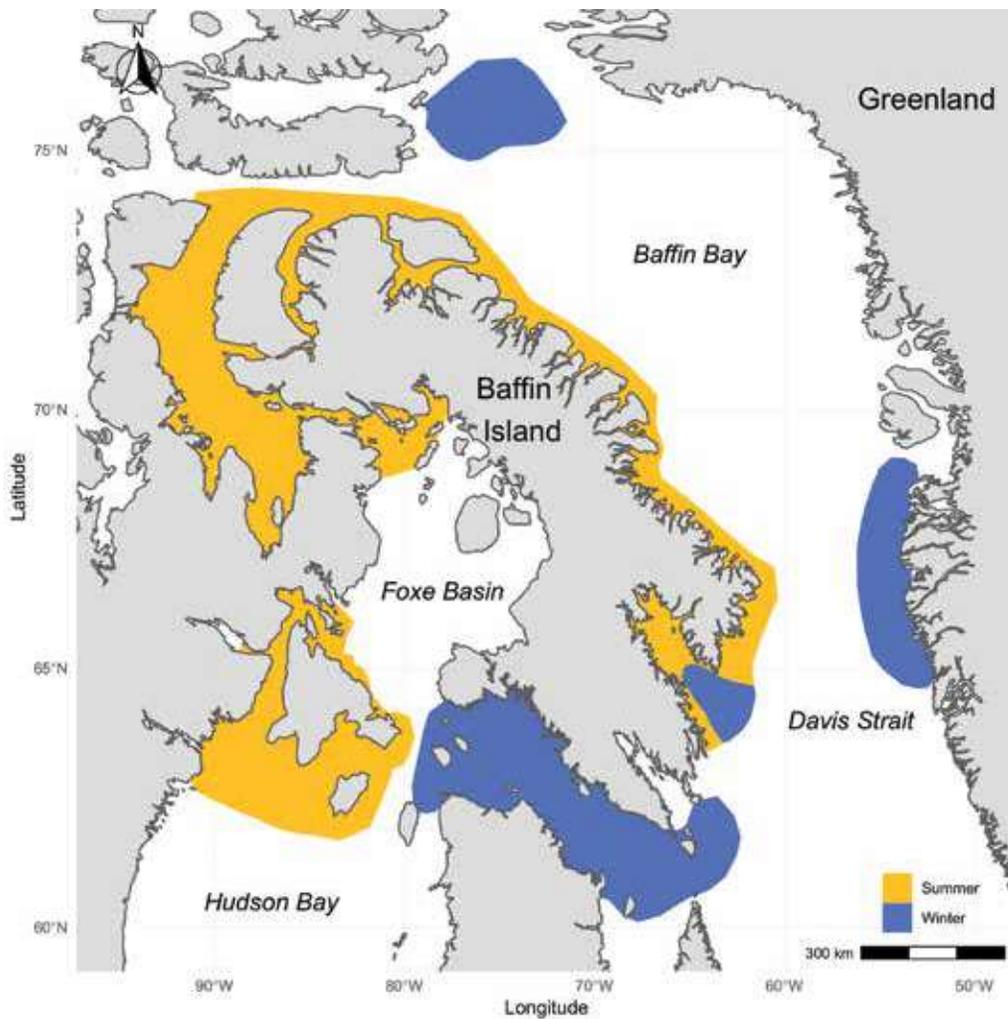
M. MARCOUX

(previously Repulse Bay), Nunavut (Bourassa 2002) and travels east into Hudson Strait in the winter (Westdal et al. 2010). This population is hunted by local Inuit primarily from Nauyasat (Repulse Bay), and occasionally from five other communities in Nunavut: Chesterfield Inlet (Igluligaarjuk), Coral Harbour (Salliq),

Rankin Inlet (Kangiqliniq), Whale Cove (Tikrarjuaq), and Cape Dorset (Kingait). The harvest of this population is currently co-managed by the local Hunters and Trappers Organizations, the Nunavut Wildlife Management Board and Fisheries and Oceans Canada (DFO).

### 2.3. Bowhead whale in Hudson Bay

The bowhead whale is the largest Arctic cetacean and the only baleen whale to remain at high latitudes year-round, with a circumpolar distribution, and occur in open water to thick sea ice (Moore and Reeves 1993). Adults can be more than 18 m long with a very large head comprising about 30% of the total length, including baleen plates up to 4 m long in each side of the upper jaw (Haldiman and Tarpley 1993). Typical length of sexually mature females, which tend to be larger than males, is



**FIGURE 2.** Eastern Canada-West Greenland bowhead whale distributions. Winter distributions (blue) and areas of summer aggregations (yellow) were reproduced from COSEWIC (2005), with modifications after Matthews and Ferguson (2015a).

approximately 13.5 m (Koski et al. 1993), whereas male estimated age of sexual maturity is 25 years at more than 12.5 m (George et al. 1999).

Bowheads of the Eastern Canada – West Greenland population declined to very low numbers after centuries of commercial whaling, but their numbers have grown to a recent estimate of approximately 10000 from an original population size of approximately 18500 (Higdon and Ferguson 2016). Hudson Strait is the most important wintering area for this population (Koski et al. 2006). In April and May, some whales move west through Hudson Strait to spring aggregation areas in northwest Hudson Bay and northern Foxe Basin (Reeves and Mitchell 1990). Northwest Hudson Bay was also a focal area for commercial whalers in the late 1800s and early 1900s (Higdon 2010). The floe edge in northern Foxe Basin is considered a critical area of use for cow-calf pairs as a nursery area (Cosens and Blouw 2003).

Bowhead whales are specialized filter feeders that primarily eat pelagic crustacean zooplankton, particularly copepods (primarily *Calanus* spp.) and euphausiids, in addition to epibenthic organisms (Lowry et al. 2004). Lowry (1993) suggested that bowheads rely on abundant food in late summer and fall to acquire the lipid reserves necessary to sustain them during the winter. This would suggest that northwest Hudson Bay is an important fall foraging area for a segment of the Eastern Canada–West Greenland population (Higdon and Ferguson 2010).

Foxe Basin is currently the primary nursery ground for cow/calf pairs occupying the Hudson Bay region (Cosens and Blouw 2003) and therefore significantly fewer adult whales and more juvenile and subadult whales occur here. Higdon and Ferguson (2010) hypothesize that bowhead whales use Foxe Basin as a nursery area because it historically was not occupied by killer whales (Reeves and Mitchell 1988). Juvenile whales are more susceptible to predation and therefore in need of protection (Ford and Reeves 2008). As sea ice declines, the Foxe Basin region may become less useful for bowhead whales as a predation refuge habitat.

Besides losing sea ice for protection against killer whale predation, bowhead whales in this region have additional concerns. The increased length of the open water season will likely increase shipping traffic (Lawson and Lesage 2013). Bowhead whales are sensitive to noise (Richardson et al. 2013) and ship strikes (Reeves et al. 2012). If fishing activity were to increase then bowheads would be susceptible to net entanglement (Citta et al. 2014).

#### 2.4. Hudson Bay killer whales

The killer whale exists in all oceans of the world but frequents productive temperate waters at relatively high densities (Baird 1999). With climate change causing the loss of sea



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ice, killer whales have taken up seasonal residence in Arctic waters, including Hudson Bay (Higdon et al. 2012). Higdon and Ferguson (2009) summarized killer whale sighting records in Hudson Strait, Hudson Bay, James Bay and Foxe Basin from 1900 to 2006 and indicated an exponential increase in sightings per decade. The first killer whale sighting within Hudson Bay occurred in the 1940s, with most sightings occurring since the 1960s and the majority along the western coast. More recently, killer whales have been observed in southwestern Hudson Bay with predation events on beluga whales being recorded (Westdal et al. 2016). Recently (January 2013 and again in 2016), killer whales were entrapped in ice in eastern Hudson Bay, an event that likely resulted in their deaths (Westdal et al. 2017; Matthews et al. (2019).

Killer whales likely arrive from the northwest Atlantic and are first seen in Hudson Strait in July before peaking in Hudson Bay in August. In September, there is a significant decline in the number of reports throughout the region. These reports indicate that killer whales generally travel west through Hudson Strait in July occurring most often in Hudson Bay and Foxe Basin in August, and typically depart in September (Ferguson et al. 2010b). Inuit observers have noted several concentration areas in the Hudson Bay region, including near Naujaat - Lyon Inlet area and the area north of Igloolik. The former area is an important summer concentration for narwhal, and the latter area in northern Foxe Basin contains large numbers of bowhead whales (Higdon and Ferguson 2010).

Killer whales in Hudson Bay preferentially, if not exclusively, prey on marine mammals (versus fish; Ferguson et al. 2012a). Typical food includes narwhal and beluga followed by bowhead and seals. Foxe Basin is an important nursery area for bowhead cow-calves and killer whales select bowhead calves (Ferguson et al. 2010b). Inuit interviews suggest that 3-4 bowhead whales are killed every summer in the Foxe Basin area by killer whales (Ferguson et al. 2010b). When a large whale is killed, killer whales typically consume only a small amount, leading to observations of scavenging by polar bears (Galicia et al. 2016).

A photo-identification study indicated at least 21 distinct killer whales within the western portion of Hudson Bay (Young et al. 2011) with no evidence of movement of killer whales between Hudson Bay and Baffin Bay. Killer whales likely feed more during the summer season and a model of feeding in the Hudson Bay area was used to predict the impact of killer whales on marine mammal prey populations (Ferguson et al. 2012b). Results suggest that each year about 20 killer whales can kill 28-72 bowhead, 77-234 narwhal, 89-271 beluga, and 83-322 seals.

### 2.5. Other whales

A recent summary reported sightings of humpback whales and minke whales in the Hudson Bay region despite bowhead whales being the only baleen whale historically known from Hudson Bay (Higdon and Ferguson 2011). Minke whales have previously been reported in southern Hudson Bay and James Bay, and recently Inuit hunters have indicated possible sightings in Foxe Basin and western Hudson Bay. Minke whales are commonly observed by Inuit in eastern Hudson Strait and recent sightings may be related to reduced ice cover and increased open water.

### 2.6. Ringed seals

Ringed seals are one of the smallest seal species and have a circumpolar distribution (Mansfield 1967). Sexually mature animals use primarily stable land-fast ice with sufficient snow cover to build sub-nivean birth lairs that are critical for pup survival (McLaren 1958a). The species is adapted to exploit sea-ice habitat for reproduction and survive polar bear predation (Smith and Stirling 1975). Predicted shifts in species distribution associated with climate change will result in new predators (e.g., killer whales; Higdon and Ferguson 2009) and possibly new competitors such as harbour seals (Florko et al. 2018). Information on density and distribution of ringed seals in Hudson Bay has been limited to estimates obtained by aerial surveys conducted in 1974 in James Bay and southwestern Hudson Bay (Smith 1975); 1978 southeastern Hudson Bay (Breton-Provencher 1979); and 1994–2013 over western Hudson Bay (Lunn et al. 1997; Chambellant et al. 2013; Young and Ferguson 2014). Recent evidence suggests that major climatic shifts have resulted in episodic declines in ringed seals of Hudson Bay possibly due to disease (Ferguson et al. 2017).

Hunter harvests in Hudson Bay indicate 50:50 sex ratio with a mean age of females higher than that of males (maximum ages for females and males were 35 and 27 years,



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respectively) (Chambellant 2010). Compared with other locations in the Arctic, ringed seals in Hudson Bay were smaller both in length and mass supporting the hypothesis of latitudinal size differences (Cleator 2001; Chambellant 2010).

In Hudson Bay, females reach sexual maturity 3–6 years of age and male ringed seals reach sexual maturity around five years of age. The reproductive cycle of ringed seals in Hudson Bay includes pups born on land-fast or stable pack ice in sub-nivean lairs that require a snow depth on the ground of 20 cm or more (Ferguson et al. 2005). In Hudson Bay, the pupping period starts in February and peaks around mid-March (Chambellant 2010). This supports the hypothesis of a latitudinal gradient in timing of pupping with earlier births in southern areas (Smith et al. 1991). Pups are weaned before break-up, after nursing for 5–7 weeks (Hammill et al. 1991).

Mating is thought to take place underwater around the time of weaning with a peak of male sexual activity from February to April (Breton-Provencher 1979). Ringed seal gestation lasts around 10.5 months, including a 2–3 month period of arrested development (McLaren 1958a). In June, ringed seals undertake their annual moult and require an ice platform to haul-out (Young and Ferguson 2014).

As in other regions of the Arctic, ringed seals in Hudson Bay are thought to feed year-round, but with intensive feeding in late summer and fall, as shown by the increase in fat depth measurements in the fall (Young and Ferguson 2013). Body condition of ringed seals is poorest in early summer after fasting during the breeding and moulting periods. During the open water period all age-classes feed intensively (Smith 1987). When the ice starts to form in late fall, adults establish territories close to shore with juveniles excluded from these habitats (Krafft et al. 2007). Adult ringed seals show signs of site fidelity during the winter months (Smith and Hammill 1981), and may have a weakly polygynous mating system (Yurkowski et al. 2011).

Diet composition varies greatly with geographical location, season and life-stage, but Arctic cod (*Boreogadus saida*) and invertebrates such as mysids (Mysida), amphipods (Amphipoda) and euphasiids (Euphausiacea) are common prey (Chambellant 2010). In southeastern Hudson Bay, a hyperiid amphipod and the pelagic fish sandlance were major prey of ringed seals, but Arctic cod were absent from the 218 stomach contents analyzed (Breton-Provencher 1979; DFO data on file). In western Hudson Bay, 93% of the otoliths found in the stomach contents of ringed seals collected from 1998 to 2000 were from sandlance and 6% from Arctic cod (Stirling 2005). In southeastern Hudson Bay, stomach contents of ringed seals collected during the Inuit fall and early winter (October–January) subsistence harvest from 2003 to 2005, confirmed the importance of amphipods and sandlance in the diet of

ringed seals around the Belcher Islands (Chambellant et al. 2012a). However, capelin and mysids represented important prey as well, and Arctic cod were present in more than 20% of the stomachs, which contrasts with results from the late 1970s (Breton-Provencher 1979). Most (95%) of the energy acquired came from fish, including 54% from capelin (Chambellant et al. 2012b; Young and Ferguson 2013).

### 2.7. Bearded seal

The bearded seal is a large pinniped compared to the ringed seal and grows to an average length of 2.0–2.5 m and about 300 kg. They are distinguished by square-shaped fore flippers, a disproportionately small head, and long noticeable vibrissae; all likely morphological adaptations to benthic feeding. Their distribution is circumpolar and in Canada extends south to Hudson Bay, Hudson Strait, and James Bay where they exist at relatively low densities, typically living in areas of broken ice and open water with depths of less than 200 m (Fay 1974). Bearded seals sometimes haul out on land and they also enter freshwater systems and are frequently observed up to 50 km inland from Hudson Bay in the Nelson River (COSEWIC 2007).

Bearded seals breed between mid-April and late May and males reach sexual maturity at 5 to 7 years of age, and females mature at 3 to 4 years of age. Most (80%) adult females pup each year with pups born on the ice at the edges of leads or on small ice pans, and weaned in about 24 days (Burns 1967, 1981). Maximum longevity in the wild is between 23 and 31 years. The mating system is considered somewhat polygynous with males defending territories (Stirling and Thomas 2003).

Although bearded seals consume a wide variety of food items, including pelagic fishes, they are primarily benthic feeders consuming mostly fishes, crustaceans, and molluscs (Burns and Frost 1979; Lowry et al. 1980; Young et al. 2010).



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The estimated number of bearded seals in the Foxe Basin, Hudson Bay, and Hudson Strait areas is 186,000 (McLaren 1958b) with estimated densities in western Hudson Bay of 0.02 – 0.12 per km<sup>2</sup> (Lunn et al. 1997). Hunting near communities is common in Nunavut and Nunavik; however, the importance of this species to Inuit has diminished in many communities in recent years (Cleator 1996). Polar bear predation remains a significant mortality factor (Stirling and Archibald 1977).

### 2.8. Harbour seals

The harbour seal is arguably the most ubiquitous of the true seals with the widest geographical distribution. The preferred habitats are coastal waters and bays, typically about 10 miles from the shoreline (Banfield 1974). Within Hudson Bay, harbor seals are most commonly found throughout the river systems of the Maguse, Thlewaiza, and Copperneedle river systems, as well as in Ranger Seal Lake (Riewe 1992; Florko et al. 2018). Satellite-tagged harbor seals from Churchill estuary moved seasonally offshore in winter and inshore in summer (Bajzak et al. 2013). Food is typically fish and mollusks (Bowen et al. 2002). Mating occurs from late July to early September, and pups are born between mid-May and Mid-June of the following year. The Nunavut communities that were reported to have harvested harbour seals include: Arviat, Baker Lake, Chesterfield Inlet, Coral Harbour, Rankin Inlet, Kugaaruk, Cape Dorset, Iqaluit, and Kimmirut (Priest and Usher 2004).

### 2.9. Walrus

Walrus are a large pinniped species that have a discontinuous circumpolar distribution throughout the Arctic and subarctic. Walruses of both sexes are most easily recognized by their prominent tusks, long upper canines that can exceed 1 meter in length (although the tusks are longer and thicker in males, which use them for dominance displays and fighting). The Atlantic walrus (*Odobenus rosmarus rosmarus*), one of two living subspecies of walrus, occupy a large range throughout the eastern and central Canadian Arctic. The vast majority of these walruses are distributed primarily in northern and southeastern Hudson Bay, Foxe Basin and Hudson Strait. Walrus in the Hudson Bay ecoregion are genetically distinct from walrus in the Canadian High Arctic (Shafer et al. 2014). Further substructure is indicated by differences in distribution, growth patterns, contaminant profiles, and stable lead isotope ratios (Stewart 2008), although walrus in these areas cannot be differentiated genetically (Shafer et al. 2014).

Recent abundance estimates indicate upwards of 17,500 walruses are throughout the Hudson Bay ecoregion. They are most abundant in Foxe Basin (10,380), followed by northern Hudson Bay and Hudson Strait (7,100), and southeastern Hudson Bay, where an estimated 200 animals occur (Stewart et al. 2013; Hammill et al. 2016). Seasonal movements and



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habitat use of walrus in the Hudson Bay ecoregion remain poorly understood. Walruses occur year-round in polynyas and moving pack ice in northern Hudson Bay, Foxe Basin, and western Hudson Strait, while others migrate seasonally in response to changing ice conditions, perhaps as far east as Davis Strait. Walrus in southeastern Hudson Bay are not thought to undertake large seasonal movements into or out of the area, instead displaying only localized movements.

For much of the year, walrus associate with moving pack ice, hauling out in herds of several to thousands of animals at terrestrial sites during summer when sea ice is sparse or not available. Walrus feed primarily on bivalve molluscs, but are also known to eat other benthic invertebrates, seabirds, and ringed and bearded seals. Their selection of haul-out site is restricted by their need to have access to shallow waters overlying rich bivalve beds, and walrus therefore show strong site fidelity to established haul-out sites. Most terrestrial haul-out sites in the Hudson Bay ecoregion occur in north and southwestern Foxe Basin, around Southhampton Island, and western Hudson Strait. Studies have shown that seafloor disturbance by foraging walrus, which extract their prey using powerful suction, creates patchy benthic habitat and influences nutrient flux and productivity. The relatively high numbers of walrus in the Hudson Bay ecoregion may be an important keystone species that help shape benthic community structure.

Atlantic walrus populations throughout the eastern Canadian Arctic suffered large declines due to commercial hunts in the 1800s, and their abundance remains low relative to historic levels. Today, walrus are hunted by Inuit for food and other products such as ivory, and remain an important economic and cultural resource for many of the communities

in the Greater Hudson Bay Region. Although hunting is the greatest known cause of mortality, recent assessments indicate that total annual harvests from these communities are sustainable (Stewart et al. 2013; Hammill et al. 2016; Matthews et al. 2018). Impacts of climate change-induced sea ice loss on Atlantic walrus are uncertain. Arctic marine ecosystems may switch from an ice algae dominated system that is strongly coupled to benthic community productivity, to a more open-water system in which nutrients are cycled within the water column. On the other hand, declines in sea ice extent and duration could open up foraging areas near terrestrial haul-out sites currently made inaccessible by landfast ice during winter (COSEWIC 2017).

Walrus are particularly sensitive to mechanical noise caused by vessel and aircraft-based traffic (DFO 2019), which can cause stampedes that have been associated with mortality due to trampling, abortion of fetuses, and separation of cow-calf pairs (COSEWIC 2017). Studies in Hudson Bay show walrus can abandon haul-out sites for up to three or four days after being disturbed by boats and aircraft (Mansfield and St. Aubin 1991), while prolonged or repeated disturbances can cause long-term abandonment of haul-out sites and preferred feeding areas (Johnson et al. 1989; Born et al. 1995). Forecasted growth in shipping, aircraft traffic, tourism, and port development with declining sea ice therefore have the potential to negatively impact walrus throughout the Greater Hudson Bay Marine Region. Impacts could be greatest in Foxe Basin and Hudson Strait, where planned shipping routes associated with mine development run right through areas of highest walrus densities in winter (Elliott 2013).

### 3. Management practices

Wildlife and hunting are culturally entrenched in the *values, language, social organization, knowledge, life skills, and perceptions of Inuit* and associated with Inuit Qaujimagatuqangit (IQ). Wildlife species are important to Inuit as they form the basis of the traditional and current food system in contemporary Inuit diets.

In Nunavut, the responsibility for management of wildlife is shared (i.e., co-managed) among the Government of Nunavut, the Government of Canada, the Nunavut Wildlife Management Board (NWMB) and the Designated Inuit Organizations (Nunavut Tunngavik Incorporated, Regional Wildlife Organizations, and Hunters and Trappers Organizations). The Nunavut Land Claims Act (NLCA) defines a decision-making process that requires the NWMB to submit their decisions to the appropriate responsible Minister (e.g., Fisheries and Oceans) for approval. Established in 1994 as part of the Nunavut Land Claims Agreement (NLCA), the NWMB

is the main wildlife regulator in the Nunavut Settlement Area (NSA). The role of the NWMB predominantly involves setting total allowable harvest (TAH) and non-quota limitations (NQL). The agency is also responsible for approving management plans and status designation for rare and threatened species.

In northern Quebec, the responsibility for management of terrestrial resources falls under the James Bay and Quebec Agreement (JBNQA) signed in 1975. The JBNQA established a consultative committee, consisting of representatives from the Inuit and Cree communities as well as representatives from the federal and provincial governments to provide advice to the appropriate minister with respect to management decisions. The JBNQA did not address management in marine areas. The Nunavik Inuit Landclaim Agreement (NILCA), which received Royal assent in 2008, addressed issues related to marine resources and some additional issues related to land use in Quebec lying to the north of 55°N. The NILCA is very similar to the Nunavut agreement in that the responsibility for management of wildlife is shared (i.e., co-managed) between the Nunavik Marine Region Wildlife Board, and the Government of Canada. The Board membership includes three members appointed by Makivik corporation, one member appointed by the Government of Nunavut, and two members appointed by the Government of Canada representing the ministries responsible for fish and marine mammals, and for the Canadian Wildlife Service. The three government bodies also select a chair, based on a list of names submitted by the Board appointees. The NILCA defines a decision-making process that requires the NMRWB to submit their decisions to the appropriate responsible Minister (e.g., Fisheries and Oceans) for approval. The role of the NMRWB predominantly involves setting total allowable takes (TAT) and non-quota limitations (NQL). The agency is also responsible for approving management plans and status designation for rare and threatened species.

Fisheries and Oceans (DFO) is a federal government agency that is “responsible for developing and implementing policies and programs in support of Canada’s economic, ecological and scientific interests in oceans and inland waters” (including marine mammals other than the polar bear). DFO delivers this mandate under the authority of the Fisheries Act that considers both conservation and sustainable use of Canada’s fisheries resources. In Nunavut, Environment Canada is responsible for protection of migratory birds through implementation of the Migratory Birds Convention Act, the Migratory Birds Regulations and the Migratory Birds Sanctuary Regulations.

The Regional Wildlife Organizations (RWO) in Nunavut and the Regional Nunavimmi Umajulivijit Katujiqatigininga” or “RNUK” in Nunavik role is to govern hunting, fishing and trapping in both areas. The RWO and RNUK role includes regulating the activities of the local Hunters and Trappers Organizations

(HTO) in Nunavut and the Local Nunavimmi Umajulivijit Katujiqatigininga” or “LNUK” in Nunavik; including allocation of the TAH (Nunavut) or TAT (Nunavik) among communities, distributing accumulated harvest credits as required to cover accidental, defence, or illegal kills.

The role of the HTOs and LNUKs includes regulating the harvesting activities of their members (all beneficiaries within the community), including allocation of tags for species with a TAH or TAT, and setting of harvest seasons.

Inuit have exchanged Aboriginal title of traditional land in the Nunavut Settlement Area for the rights and benefits established under the Nunavut Land Claims Agreement (NLCA) signed in 1993 and in the Nunavik region with the signing of NILCA. The Nunavut Tunngavik Incorporated (NTI) safeguards and promotes the agreement on behalf of Inuit beneficiaries in Nunavut. This role is assumed by Makivik corporation in Nunavik. Within the context of wildlife management, NTI/ Makivik coordinates and manages Inuit responsibilities for wildlife and works with federal and territorial governments to ensure that their obligations are met.

Compared to terrestrial mammals, marine mammals are more at risk of population declines partly due to difficulties in gathering adequate stock assessment information. Arctic marine mammals are of particular concern since they are adapted to living in and on sea ice that has declined with warming (Laidre et al. 2008; 2014). Loss of sea ice will affect all of the marine mammal populations in Hudson Bay including the ice whales, beluga, narwhal, and bowhead whales, the ice seals (ringed and bearded seals), and the walrus. All three whale species seasonally migrate from Hudson Bay areas in winter to Hudson Strait during the ice-free season. The ice seals and walrus remain year-round within the Greater Hudson Bay Marine Region, although seasonal migration occurs to various degrees. All seven of the ice-adapted marine mammals living in Hudson Bay depend on sea ice for survival and reproduction and are important to Inuit that generally depend on harvesting for subsistence food, economic benefits, and cultural wellbeing. For example, based on harvests from 2007, Naujaat hunters gained \$266,504 for beluga and \$321,500 for narwhal hunting as an economic use value (Hoover et al. 2013). In Nunavut, 74% and 45% of participants in the Inuit Health Survey (2007-2008) reported eating ringed seal meat and beluga mattaaq, respectively (Egeland et al. 2010).

The wildlife management board is responsible for managing wildlife harvests. The appropriate co-management board (NWMB in Nunavut; NMRWB in Nunavik), seeks advice from scientists and hunters on population abundance and acceptable levels of harvest that respect the management objectives for the stock to be harvested (Anonymous 1993, 2006). The Boards can set limits to harvesting via setting quotas

or by using non-quota limitations such as zone or seasonal closures. The Board decides on the appropriate management regime for the stock, and forwards its recommendations to the appropriate Minister. Under the land claim, the Minister can only restrict or limit Inuit harvesting to effect a conservation purpose, for purposes of allocation, or to provide for public health and safety. Upon receiving the recommendations from the Board, the Minister has 60 days to accept or reject the recommendations from the Board and inform the Board of his decision in writing. If the Minister rejects the Board’s decision, reasons for this decision must be provided in writing. If the Minister has rejected the Board’s decision, the Board shall reconsider the decision taking into account the reasons for the rejection, make a final decision and forward this decision to the Minister. Upon receiving the second decision from the Board, the Minister shall accept, reject or vary the final decision and provide reasons for doing so to the Board.

#### 4. Concluding remarks

The consequences of warming include widespread melting of sea ice resulting in a longer open water season. These environmental alterations associated with climate warming will have a direct impact on the Hudson Bay marine ecosystem as well as indirect effects through increased human development. The high trophic level marine mammals have already experienced a cascade of environmental changes including a shifting prey base, new temperate predators and competitors, and continued subsistence hunting pressure. The variability and magnitude of effects on these top predators need to be adequately assessed to begin mitigating and adapting to predicted changes.



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# A Brief Note on Polar Bears

From the IRIS Steering Committee and Editorial Team

Polar bear management is a significant issue in the Greater Hudson Bay Marine Region. There are more than 4500 polar bears distributed among three subpopulations - Foxe Basin, Southern Hudson Bay and Western Hudson Bay. Inuit, whose deep knowledge and relationship with polar bears is evident in Inuit Qaujimagatugangit (IQ) and Traditional Knowledge (TK), know that polar bears in the region are at healthy population levels (NMRWB 2018; Simon 2009; CWS 2009). Scientific assessments also show that the subpopulations are stable (CAFF 2017) with the exception of the southern Hudson Bay subpopulation that has declined in the most recent surveys (Obbard et al., 2018). However, information on polar bear population status and trends from different sources are sometimes difficult to reconcile, perhaps due to variability in scope and methods. Distributional changes within polar bear populations can lead to differing perceptions or assessments of subpopulation trends (CAFF 2017). There is also the expectation that climate change will negatively affect polar bears, as it will affect all ice-associated wildlife (Harvey et al. 2018). As climate change intensifies, it is important that wildlife management boards and community members can access accurate and trustworthy information about the status of the subpopulations. Key questions also need to be answered, such as when the ice loss in the region will affect the health and abundance of polar bears; and what subpopulations will be affected. This information is critical in order for boards to decide what, if anything, should be done to alter management plans in the near term, when the effects are not clear.

Unfortunately, it seems challenging if not impossible at the present time to separate the *knowledge* about polar bears and the threats facing them and the *emotions* and *politics* that surround this issue. There is no chapter on polar bears in this IRIS because we found it impossible to confirm the facts and present them without bias, nor could we present all 'sides' of the issue in this volume. This note is included to make readers aware that this is a complex issue that needs resolution because polar bears are a culturally and economically important resource that must be sustainably managed by the Inuit and Cree in the region. We hope that readers will take pause and question the way polar bears are portrayed in the media and in internet blogs. It is important to remember that

sensationalized messaging of any type can impact policy, in some cases bringing about policy changes that affect human culture, mental health, safety, food security, and economy. The political 'spin' that can be put upon scientific findings underlines the need for scientific rigour, innovation in questions and approaches, honest assessments of the limits and the level of certainty of knowledge. At the same time, we need to improve our understanding of different knowledge systems and how to combine them to improve the reliability of the information upon which management decisions are based. Going forward, it seems clear that wildlife boards and other agencies mandated with polar bear management in the region need access to the best available scientific information and also a means to use IQ and TK effectively in their decision making.

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# THEME III MODERNIZATION AND DEVELOPMENT

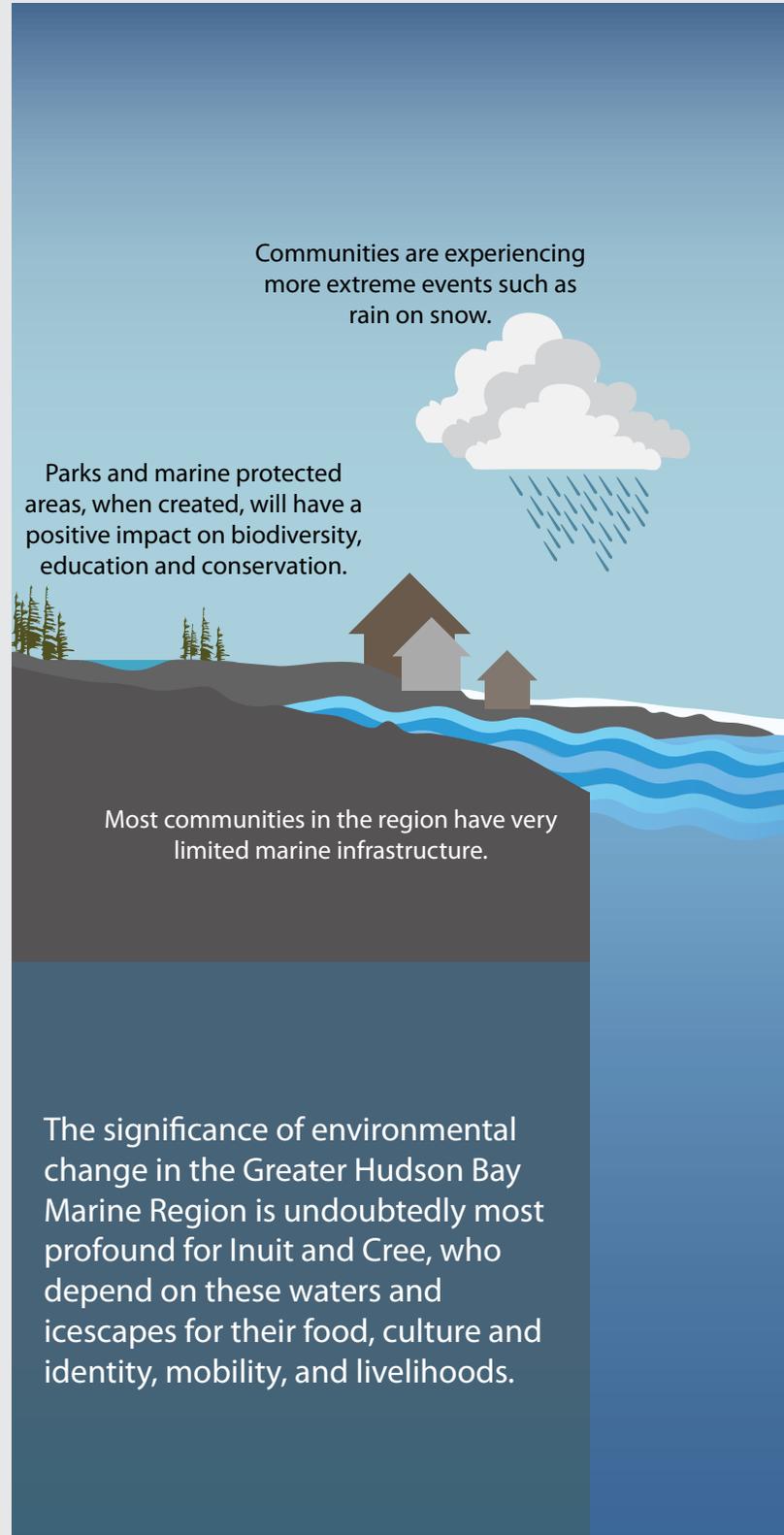
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**M**ost, if not all, aspects of modernization and development come with both positives and negatives. There is a longer season during which large ships are entering the region and increased activity by ships with no ice classifications. While community resupply by sea-lift may benefit from the reduced sea ice, future potential changes in fish and wildlife raise concerns about the security of country foods. With increased shipping there is also an increased likelihood of a spill and risk of introducing contaminants into the marine environment. Contaminants are present in the Greater Hudson Bay Marine Region as they are throughout the North. Regulations are helping to reduce sources of mercury and the concentrations in some wildlife tissues have begun to decrease. However, there are new and emerging contaminants that have been found. Tourism is important economically within most communities in the Greater Hudson Bay Region and the ecotourism industry is growing and diversifying. However, an increase in tourism in the region may have adverse impacts on small communities and wildlife.

The following chapters provide some background and insight into key issues with modernization and development in the Greater Hudson Bay Marine Region.



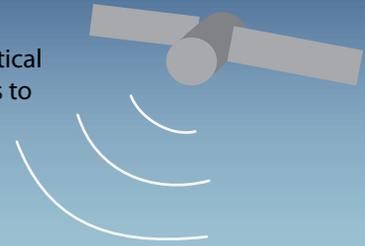
Communities are experiencing more extreme events such as rain on snow.

Parks and marine protected areas, when created, will have a positive impact on biodiversity, education and conservation.

Most communities in the region have very limited marine infrastructure.

The significance of environmental change in the Greater Hudson Bay Marine Region is undoubtedly most profound for Inuit and Cree, who depend on these waters and icescapes for their food, culture and identity, mobility, and livelihoods.

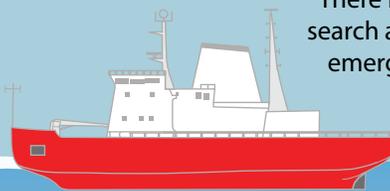
Access to technology is critical for northern communities to adapt.



Ice is critical travel infrastructure for communities. The changes in sea ice are affecting travel and causing concerns for safety.



There is an increasing need for search and rescue capability and emergency response capacity in the region.



Communities are seeing changes to the amount and timing of freshwater entering the bay.



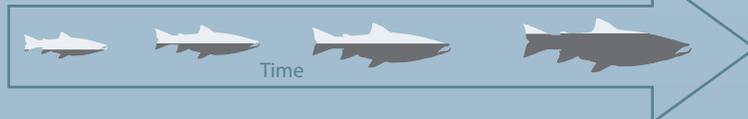
Increased ship traffic poses risks to whales and walrus.



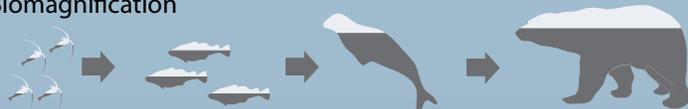
Increased shipping and development leads to higher risk of contamination from spills.

Communities are concerned about the bioaccumulation and biomagnification of contaminants affecting the quality of country foods.

### Bioaccumulation



### Biomagnification



■ Contaminant Levels

FIGURE MODIFIED BY L. CANDLISH FROM SKETCHES CREATED BY H. HINAM





### III.i

# Contaminant Cycling, Ecosystem Pathways, and Wildlife Trends in a Changing Climate

## AUTHORS

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## Summary

Contaminants are defined as substances that are present in the environment at concentrations that either exceed their natural background levels or, in the case of manufactured substances, are detectable even in the absence of direct pollution. Many contaminants in Hudson Bay are produced externally and arrive in the North by long-range transport through the atmosphere, oceans and rivers. Many contaminants take a long time to break down naturally in the environment, and this is especially applicable in colder climates as in the Arctic. Furthermore, some contaminants are resistant to metabolism and elimination. Resistant contaminants can accumulate in organisms over a period of time (“bioaccumulation”), and can also accumulate up the food chain (“biomagnification”). At elevated concentrations, contaminants can begin to compromise the health or condition of biological systems. It is for these reasons that contaminants impact the *quality* of country foods, one of the issues surrounding food security in the North (the others being accessibility and availability). Environmental monitoring programs serve the dual purpose of providing information to evaluate the safety of country food consumption as well as the effectiveness of global pollution emissions regulations.

## Key Messages

- Atmospheric concentrations of mercury appear to be decreasing in the sub-arctic.
- With an anticipated rise in marine shipping traffic to service natural resource industries in and around the Bay, the risk of point source pollution (e.g., oil spills) will increase. Current understanding of sea-ice processes and their interactions with oil is poorly understood.
- There have been significant declines in mercury for ringed seals and, in western Hudson Bay, female beluga up to the mid-2000s.
- Increases in mercury have been reported from Arctic char in western Hudson Bay up to 2007-2008, as well as for thick-billed murre eggs from Coats Island (up to 2009).
- Mercury levels have remained stable for polar bear subpopulations.

- **Hudson Bay ringed seals have the lowest measured legacy persistent organic pollutants (POPs) concentrations across the Arctic. Furthermore POPs levels have significantly decreased in thick-billed murre eggs, ringed seals and polar bear subpopulations in Hudson Bay. However, increasing trends of ΣPFCA, one of the newer, emerging contaminants, have been observed for polar bears in the region.**
- **Concentrations of POPs tend to be relatively high in benthic invertebrates and fish, or species dependent on a benthic diet.**

## 1. What are contaminants and why do we care?

“Contaminants” are defined as substances that are present in the environment at concentrations that either exceed their natural background levels (e.g., mercury) or, in the case of manufactured substances (e.g., industrial chemicals), are detectable even in the absence of direct pollution (e.g. point sources such as wastewater discharge) (ICES 1989). Contaminants matter in the Arctic for several reasons:

- **Resistance/persistence:** Many contaminants take a long time to break down naturally in the environment, and this is especially applicable in colder climates as in the Arctic. Furthermore, some contaminants are resistant to metabolism and elimination. Resistant contaminants can accumulate in organisms over a period of time (“bioaccumulation”), and can also accumulate up the food chain (“biomagnification”).
- **Bioavailability:** This term describes the extent to which contaminants are available for uptake by an organism. Species such as invertebrates and fish are exposed to water-soluble contaminants via respiration, while marine mammals and birds are primarily exposed to particulate-bound contaminants via their diet.
- **Toxicity:** At elevated concentrations, contaminants can begin to compromise the health or condition of biological systems. High mercury concentrations, for example, have been correlated with neurological and developmental delays in children exposed in the womb (Grandjean et al. 1997, 2003). Other examples pertaining to organic contaminants include hindered immune, reproductive or endocrine (hormone) functions in animals (e.g., Letcher et al. 2010).

It is for these reasons that contaminants impact the *quality* of country foods, one of the issues surrounding food security in the North (the others being accessibility and availability).

Country foods are plants and animals harvested from the land and sea for traditional consumption by Indigenous peoples. For example, from the sea, Arctic char, ringed seal and beluga are among the most commonly consumed country foods in Nunavik (Blanchet and Rochette 2008) and Nunavut (IHS 2011). Not only are there positive social and physical aspects of hunting, fishing, gathering and sharing these meals, but these foods also provide essential nutrients that protect against chronic diseases (e.g., type 2 diabetes, cardiovascular disease) (IHS 2011) and some contaminants (INAC 2017). Today, traditional diets of country foods have been supplemented with market foods which are less nutritious (e.g., contain processed fats, high levels of carbohydrates) and ultimately reduce diet quality among northern residents. Country foods are also generally less expensive than store-bought foods, which are typically two times the price in Nunavut compared with prices in the rest of Canada (Nunavut Bureau of Statistics 2015). Finally, Indigenous peoples across Canada share a deep cultural connection to the harvesting, sharing and use of country foods and their parts (e.g., skins for clothing). Indigenous livelihoods are defined by their relationship to harvestable plants and animals.

In general, Indigenous peoples tend to have higher levels of many chemical contaminants than southern Canadians due to their diet of (relatively contaminated) marine mammals (INAC 2017). Of particular concern is the link between the dietary contaminant exposure of pregnant women and the long-term health effects in their children. For example, the Nunavik Child Development Study (Nasivvik Centre for Inuit Health and Changing Environments) found that 11-year old children with previous exposure to relatively high pre-natal mercury levels were at increased risk of attention deficit hyperactivity disorder (ADHD) (INAC 2017). Therefore, the measurement of contaminant levels in country foods is important in revealing what parts of animals are safe for consumption by way of comparison to national health guidelines, e.g., the Health Canada guideline for mercury in fish is 0.5 micrograms per gram (Health Canada 2004). When animal tissues exceed such guidelines, territorial and national health authorities step in to develop risk management strategies to reduce negative health effects to country food consumers. Because of the benefits offered by country foods, only in rare cases of unacceptable risk should consumption advisories be placed on specific animal tissues in certain species’ populations. Examples of consumption advisories include ringed seal liver (Nunavut) and beluga muscle (Nunavik) for women of child-bearing age (e.g., NTI 2012).

This chapter focuses on mercury and persistent organic pollutants (POPs), both of which persist and accumulate over time in marine wildlife and pose a toxicological risk to the health of Indigenous peoples. Information specific to

contaminants in the diet and impacts to human health is documented in the other ArcticNet IRIS reports (IRIS 4, chapter 3; IRIS 2, chapters 12 & 13; IRIS 1, chapter 5) and other sources (e.g. Donaldson et al. 2010; Lemire et al. 2015). This chapter will describe the mechanisms by which contaminants are transported to Hudson Bay and how they enter the food web, and it will also review spatial and temporal contaminant trends in selected wildlife. A discussion of how climate change and variability impact contaminants, along with recommendations for decision makers, concludes the chapter.

## 2. Who studies contaminants in the Arctic?

Many groups have an interest in studying and monitoring contaminant concentrations in Arctic marine ecosystems. By far the most important stakeholders in this context are Indigenous communities, whose residents depend upon healthy country foods for subsistence. Regulators also need contaminants information to fine-tune guidelines for global pollutants and pollution-emitting activities (e.g., Stockholm Convention on Persistent Organic Pollutants). Monitoring studies can indicate if emissions regulations are effective at reducing contaminant concentrations in air, seawater, sediments, ice and wildlife, and can indicate if further action is needed.

Agencies researching contaminants in Hudson Bay include the Northern Contaminant Program (NCP) of Indigenous and Northern Affairs Canada (INAC) (since 1991), Environment and Climate Change Canada, ArcticNet, Nunavut General Monitoring Plan, Nunavik Research Centre, Arctic Eider Society, and the Arctic Monitoring Assessment Program (AMAP), a working group of the Arctic Council. Foundation-funded Arctic monitoring (e.g., by Pew Foundation), through single-mission advocacy groups (e.g., World Wildlife Fund), also builds the knowledge base about contaminant distributions in various matrices.

Local harvesters and data monitors in the Arctic and sub-Arctic are an essential link enabling the contaminants-knowledge pool to keep growing. Community-based monitoring projects promote partnerships with Indigenous communities, with the potential to enhance all project stages (e.g., planning to knowledge mobilisation) with the contribution of Indigenous Knowledge (See the Introductory Chapter for a discussion on Indigenous Knowledge). These types of studies are excellent models for engaging collaborators and ultimately provide deliverables which are relevant and meaningful for communities. There have been many examples of community-based monitoring projects within the Hudson Bay marine ecosystem facilitating harvest-based programs carried

out by Hunters and Trappers Organizations for contaminants.. Some, but certainly not all, have included collection programs for beluga (Arviat 1984-2012; Sanikiluaq 1984-2017), walrus (Hall Beach 1988-2008; Igloodik 1982-2009), narwhal (Repulse Bay 1993-2001), ringed seal (e.g., Arviat 2004-2012), Western Hudson Bay polar bears (2002-2018) and Northern Hudson Bay sea bird eggs (1975-2017) in collaboration with the Northern Contaminants Program, federal agencies and other groups, at the time of writing.



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In the last few years there have been several community-driven projects in the Hudson Bay region exploring contaminants issues in country foods. One is a study conducted in partnership by Environment and Climate Change Canada, the Northern Contaminants Program and the Arctic Eider Society in Eastern Hudson Bay/James Bay (Box 1). This study leverages the Arctic Eider Society's Community-Driven Research Network with the communities of Sanikiluaq, Inukjuak, Umiujaq, Kuujuaapik and Chisasibi (Arctic Eider Society 2016) to look at the spatiotemporal trends in contaminants throughout the marine food web, including plankton, benthic invertebrates, fish, birds and marine mammals. The project has placed an emphasis on building connections among parallel programs in each community to piece together the bigger picture of contaminants distribution in the region, and has been providing innovative online and mobile tools to facilitate community engagement as well as to incorporate Inuit and Cree observations of environmental conditions and food web dynamics that may affect contaminants accumulation in the marine ecosystem.

**Box 1. Case study: A community-driven research network approach to studying northern contaminants**

**Communities in East Hudson Bay and James Bay are concerned** about ecosystem changes observed in recent decades, particularly related to sea-ice conditions, effects on wildlife, and also about potential impacts of contaminants from long-range atmospheric transport and regional human activities including hydroelectric development. In response to community priorities to address large-scale cumulative environmental impacts in the region, the Arctic Eider Society worked with community partners in Sanikiluaq, Inukjuak, Umiujaq, Kuujjuaraapik and Chisasibi to form a Community-Driven Research Network engaging partners in academia, government, regional and non-profit organizations with funding from the Nunavut General Monitoring Plan, Nunavik Marine Region Wildlife Board, Cree Nation of Chisasibi, ArcticNet and the University of Manitoba. Programs initially focused on sea ice and oceanographic monitoring, and following priorities identified by the communities, expanded on this capacity in 2015 to collect new information on contaminants (particularly mercury) through support from the Northern Contaminants Program (Crown-Indigenous Relations and Northern Affairs Canada) in partnership with Environment Canada, to provide a regional perspective on metal exposure in the marine food web (Chételat et al. 2016).

Each of the five communities are participated in this three year study (2015 to 2018) of metal bioaccumulation in the marine food web of East Hudson Bay and James Bay. Inuit hunters from Sanikiluaq, Kuujjuaraapik, Inukjuak and Umiujaq, and Cree hunters from Chisasibi collected coastal bioindicator species (blue mussels, sea urchins, common eider), which provided information on spatial patterns of metal bioaccumulation within the study region. In addition, offshore animal species (ringed seal, plankton, and marine fish) were collected from Kuujjuaraapik, Inukjuak and Sanikiluaq. Sampling kits were provided to local coordinators in each of the communities for the collection of animal tissues, which were then shipped frozen to the National Wildlife Research Centre (Environment and Climate Change Canada, Ottawa) for chemical analysis. These locally-important animal species are being used as bio-indicators of geographic and habitat-specific (benthic and pelagic) patterns of metal accumulation. The measurements will also inform on the ecological processes controlling metal levels in the marine food web in East Hudson Bay and James Bay. Community-driven execution of biological collections as well as parallel ecosystem measurements on sea ice and water conducted by the Community-Driven Research Network will



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**Vincent Tooktoo checks oceanographic conditions at a sampling site near Kuujjuaraapik as a part of ongoing programs with the Arctic Eider Society’s Community-Driven Research Network.**

allow for more integrated research in the context of environmental change.

The Arctic Eider Society is developing novel ways to share progress of environmental research and to document Inuit and Cree observations of ecosystem trends and processes in the study region. A pilot web-based “Interactive Knowledge Mapping Platform” provided a means to document and wildlife sampling among communities and research partners in a social media-style framework that allows tagging each hunting story (i.e., collection) with profiles for the wildlife

species and individuals involved in collections displaying these on timelines and interactive maps (Heath et al. 2015). This has allowed community members to view results of their own contributions as well those of others participating in the project, and contribute their own knowledge and observations including photos and other information as a part of sample collection. This approach has been significantly expanded into a powerful new Arctic-wide “Inuit Knowledge Wiki and Social Mapping Platform” called SIKU (based on the Inuktitut word for sea ice; [www.siku.org](http://www.siku.org)) that includes a mobile app, and expanded mapping, ice imagery, social media and interactive capabilities with diverse services and tools to facilitate Inuit self-determination in research, ice safety and systematically documenting environmental observations, hunting stories and traditional knowledge. A new NCP funded program is leveraging the SIKU platform to document Inuit observations of ecosystem trends and processes that can contribute to contaminants processes. The project is documenting body condition, diet, environmental conditions (e.g., sea ice and oceanography) and other conditions associated with contaminants sampling and harvesting of species for which long-term contaminants monitoring programs are in place. The open concept platform is being created so that it can be easily adapted and used by communities and researchers across the north. This approach is providing a compelling way to meaningfully incorporate Inuit observations and knowledge into contaminants research, to engage communities and interested parties in ongoing projects, and to manage data and communications on large multi-community and multi-partner projects.

Community-based research is generating novel information on contaminants in the marine food web of East Hudson Bay and James Bay. Northern partnerships in the study region are informing the direction of the research and allowing for incorporation of local knowledge and observations in the project. Information on metal levels in locally harvested animals will be made available to regional health professionals to assess human exposure to metals through consumption. Study findings will also highlight environmental processes that control the accumulation and transfer of metals in the food web. Ultimately, this science will support environmental stewardship initiatives including tracking future impacts from environmental change, long-range atmospheric transport, and regional human activities on contaminants in East Hudson Bay and James Bay.

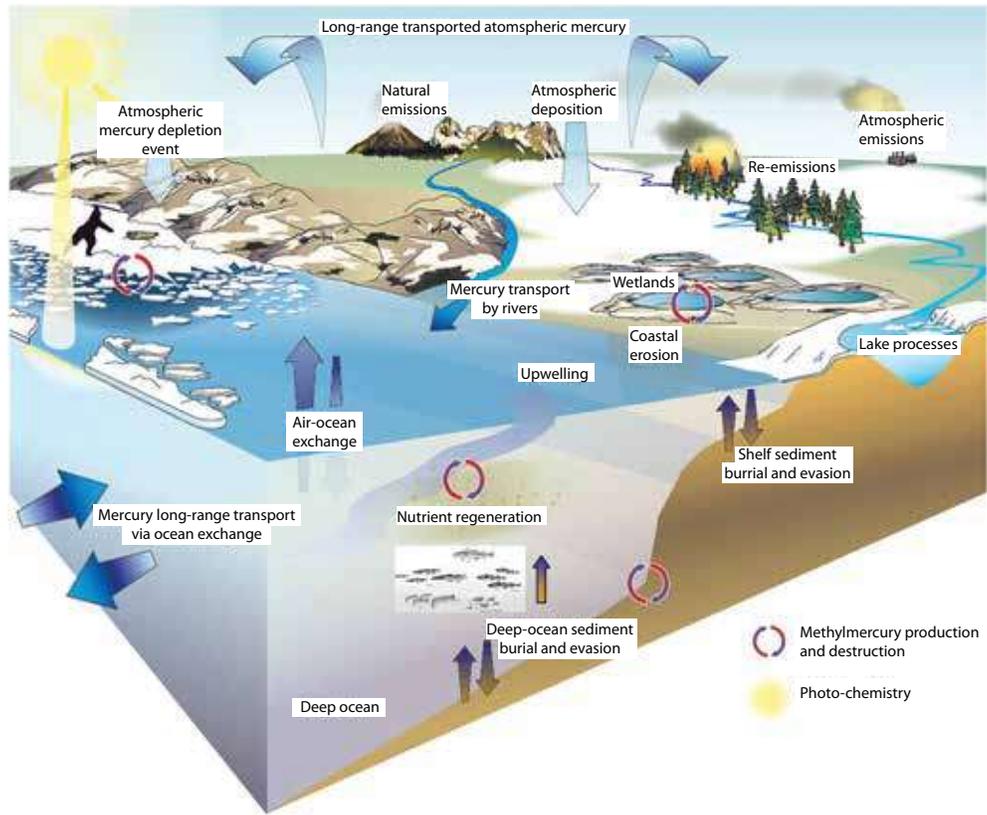
In western Hudson Bay, relatively high mercury concentrations in Qamanirjuaq caribou in comparison to other Arctic herds prompted action by community members, who were concerned the caribou were exposed to mercury through a diet of seaweed. These concerns led to the development of a new NCP project not only investigating the dietary sources of mercury to the caribou, but also interviewing Elders in the communities of Arviat, Baker Lake, Rankin Inlet and Chesterfield Inlet, providing Traditional Knowledge on the habits of Qamanirjuaq caribou (Gamberg 2017).

### 3. How do contaminants get to Hudson Bay?

#### 3.1. Mercury

Mercury naturally occurs in the earth’s crust and is present in the surface environment in trace amounts by weathering of rocks and as a result of volcanic and geothermal activities. Human activities can increase the emission of mercury to the atmosphere and its deposition in the surface environment. Examples of these mercury-emitting activities are artisanal and small-scale gold mining, smelting, production of plastics and cement, burning of coal and the flooding of land associated with hydroelectricity generation. For example, the Hudson Bay Mining and Smelting operations based in Flin Flon, MB were one of the largest mercury sources in North America until the mid-1990s, and current reports indicate the surrounding land area continues to re-emit previously deposited mercury (Environment and Climate Change Canada 2016; Wiklund et. al 2017). In its elemental form, mercury can stay in the atmosphere for more than one year. This allows mercury to be transported in the atmosphere over long distances from its source region, making it a global contaminant. Other transport pathways for mercury include river discharge, oceanic circulation, inland riverbank and coastal erosion, and sedimentation (Figure 1).

One source of methylmercury, the type of mercury which is bioavailable, toxic and accumulates in organisms throughout the food web, is bacterial production in wetlands or flooded soils. This is especially pertinent to Hudson Bay with its many rivers and watersheds. The flooding of terrestrial vegetation associated with reservoir creation for hydroelectric generating plants advances the production and downstream export of methylmercury in freshwater across northern Canada, peaking within the first three years after a reservoir is flooded and returning to baseline concentrations after several decades (e.g., St. Louis et al. 2004; Bodaly et al. 2007; Anderson 2011). However, although concentrations in downstream fish species appear to peak from two to nine years after impoundment, these can take longer than two decades to decrease back to baseline



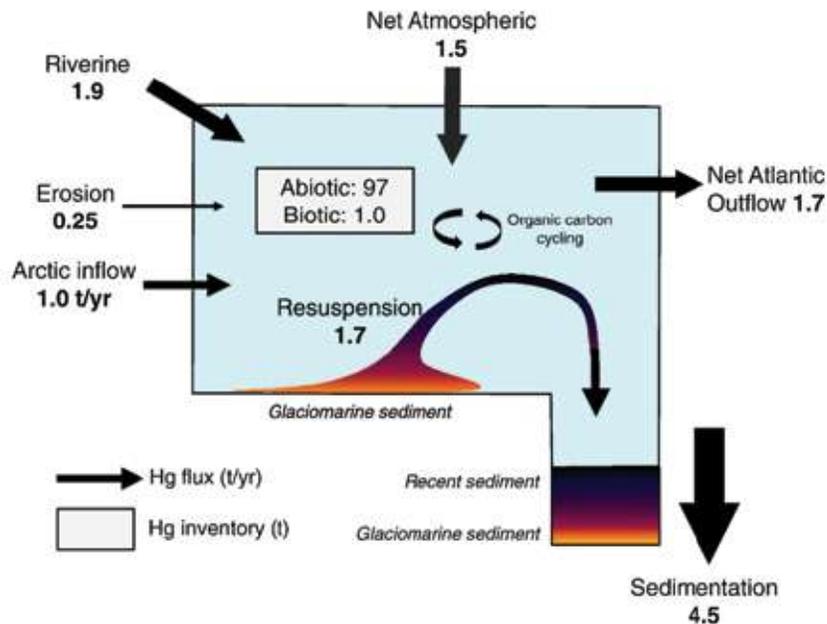
**FIGURE 1.** Illustration of mercury cycling through the Arctic marine and terrestrial ecosystem. Modified from AMAP (2011).

concentrations (St. Louis et al. 2004; Bodaly et al. 2007). Calder et al. (2016) projected a 10-fold and 2.6-fold increase in methylmercury levels from the downstream river and estuary waters, respectively, of the completed Muskrat Falls hydroelectric plant in Labrador. Additional ecosystem modelling illustrated 1.3- to 10-fold increases in aquatic wildlife methylmercury concentrations after flooding, with some species such as lake trout, brook trout, tern eggs and seal kidney, liver and muscle exceeding the Health Canada guideline of 0.5 micrograms per gram. Eleven other hydroelectric sites across Canada were estimated to have equal or higher methylmercury concentrations in water, relative to Muskrat Falls (Calder et al. 2016).

Based on extensive studies over the past decade, the present-day mercury inventory in Hudson Bay is estimated to be ~98 tonnes (Figure 2). Mercury is transported into Hudson Bay via river discharge from its vast watershed, including the Churchill River ( $37 \pm 28$  kg total mercury per year) and Nelson River ( $113 \pm 52$  kg total mercury per year) (Kirk and Louis 2009), atmospheric deposition, and oceanic inflow from the High Arctic Ocean, with a smaller contribution from coastal erosion (Hare et al. 2008). Mercury is removed from the Bay primarily

via sediment accrual and burial and via outflow to the Atlantic Ocean. Despite dramatic increases in river and atmospheric mercury input since preindustrial times (>150 years ago), mercury inventory in the Bay increased by only 30% over the same period, as much of the modern mercury loading to the system is buried in the sediments. Hudson Bay is unusual in that its seafloor is continuously undergoing postglacial rebound, causing a large amount of sediment to become re-suspended from shallow areas and ultimately to be re-deposited at deeper locations. This sediment 'recycling' process facilitates the scavenging and burial of mercury from the seawater (Hare et al. 2008, 2010).

From 2000 to 2009, atmospheric mercury concentrations, in the form of gaseous elementary mercury (GEM), decreased approximately 2% per year at Kuujuaupik in the sub-arctic (NCP 2012). This rate was higher than for the High Arctic, in which mercury decreased by 0.9% per year at Alert. The difference in rates between the High Arctic and sub-arctic is likely explained by the contributing atmospheric sources of mercury to the two regions. The High Arctic is more influenced by East Asian sources of mercury, whereas North American sources,



**FIGURE 2.** Mass balance model for mercury in the Hudson Bay marine system in present times. Units are in tonnes (t) unless otherwise stated. From Hare et al. (2008).

which have decreased over the last few decades, are more important to the sub-arctic (Dastoor 2011).

Atmospheric mercury depletion events (AMDEs) also deposit atmospheric mercury in the Arctic. An AMDE is a chemical reaction process occurring in the spring that transforms GEM from the lower atmosphere into reactive gaseous mercury (RGM), depositing either onto Arctic surfaces or atmospheric particles. Although some of the deposited RGM is quickly reduced to GEM and returns to the atmosphere, snowpacks with bromine and other halogens, typically in close proximity to coastlines, appear to retain mercury after AMDEs (Carignan and Sonke 2010; NCP 2012). Therefore, AMDEs could be an important, seasonal source of depositional mercury in coastal regions.

### 3.2. POPs and plastics

There are many organic contaminants in the environment, all with various physicochemical properties influencing transport and occurrence in different media. Persistent organic pollutants (POPs) include such chemicals as pesticides, industrial by-products and flame retardants (Table 1). "Microplastics", a term used to describe plastic particles two to four times smaller than a grain of sand, are also persistent, can bioaccumulate in the food web, and some, such as plastic pellets, contain toxic additives like polychlorinated biphenyls (PCBs).

#### **Indirect sources**

Unlike mercury, POPs are substances that do not occur naturally. Historically POPs were used mostly in agriculture and industry (Table 1), but these have been severely restricted on a global scale today. New, emerging industrial chemicals such as polybrominated diphenyl ethers (PBDEs) and perfluoroalkyl chemicals (PFCs) have shown evidence of persistence, uptake by organisms and toxicity in the Arctic (NCP 2013). The major pathway in which POPs are released into the environment is by air emissions, but watershed discharge and ocean circulation are also transport mechanisms, such as for some hexachlorocyclohexanes (HCHs) and perfluoro-octane-sulfonic acid (PFOS). For instance, in 2008  $\alpha$ -HCH concentrations measured in Hudson Bay seawater were reported between 480-804 picograms per litre, more than two orders of magnitude higher than concentrations observed for hexachlorobenzene (HCB), between 4.48-11.8 picograms per litre (Wong et al. 2011, Supporting Information).

Some POPs bind to organic matter, settle on the seafloor and become buried in sediment. Chlorinated, brominated and fluorinated POPs have all been detected in Hudson Bay sediments (e.g., Kelly et al. 2007-2009; Kuzyk et al. 2010). In a study by Kuzyk et al. (2010), concentrations of total PCBs in Hudson Bay marine sediment cores varied between 0.04-0.15 nanograms per gram (dry weight). The authors also found that PCB concentrations were correlated to organic matter produced under eutrophic conditions (i.e., nutrient-rich, oxygen-depleted waters).

**TABLE 1.** Summary of uses of the indirectly-sourced POPs to the Arctic discussed in this report. All contaminants listed are persistent, bioaccumulative and potentially toxic substances. Adapted from Bidleman et al. (2013) and sources therein.

	Contaminant	Manufactured use	Global history (units in kilotonnes)
Historical "Legacy" POPs	DDTs (dichlorodiphenyl-trichloroethanes)	Insecticide	Production: 4,500 (1940-2005) Usage: 2,600 (1950-1992) Emission: 1,030 (1940-2005)
	PCBs (polychlorinated biphenyls)	Industrial chemical	Production: 1,326 (1930-2000) Usage: 1,200 (1930-1992)
	CBz (chlorobenzenes)	Fungicide and industrial chemical	Emissions: 0.012-0.092 kt/yr (mid 1990s) (Hexachlorobenzene specifically)
	CHLs (chlordanes)	Insecticide	Usage: 78 (1945-1988)
	Toxaphene (chlorobornanes)	Insecticide	Production: 1,330 (1950-1993) Usage: 1,330 (1950-1992) Emissions: 407 (1947-2000)
	Dieldrin	Insecticide	Usage: 34 (1950-1992)
New/Emerging POPs	HCHs (hexachlorocyclohexanes)	Insecticide	α-HCH Usage: 4,300 (1945-2000) Emissions: 6,000 (1945-2000)
			β-HCH Usage: 850 (1945-2000) Emissions: 230 (1950-2000)
			γ-HCH (Lindane) Usage: 720 (1950-1993) Soil residue: 13.6 (2005)
	PBDEs (polybrominated diphenyl ethers)	Flame retardant	Production: 67 (2001)
POSF (perfluorooctane sulfonate), used to make compounds containing PFOS (perfluorooctane sulfonic acid)	Flame suppressant, surfactants, industrial chemical (PFOS and precursors, specifically)	Production: 96-122 (1970-2002) Emissions: 6.8-45 (1970-2002)	

In other words, the drainage of productive, organic-rich lakes, mostly in the Bay's watershed to the east, accounted for much of the spatial variability of total PCBs along the Bay's seafloor.

Plastic debris is a relatively new phenomenon observed in the Arctic, yet it is a bigger issue in other global regions, e.g., plastics contribute 60-80% of total marine debris in the Southern Hemisphere (Gregory and Ryan 1997). Before their transport to the ocean via rivers and winds, microplastics start out as particles small enough to pass through wastewater treatment plants (e.g., polyester fibres from laundered clothes, microbeads originating in hygiene products). Another source is landfills, where particles from plastic litter (e.g., plastic bottles, bags, straws, packaging, cigarettes) can be blown into rivers and washed out to sea. Heavier microplastics sink and settle to the seafloor, while buoyant (i.e., floating) particles can travel far distances by ocean currents, such as to the Arctic.

Plastics, including microplastics, have been measured in the Arctic seas (e.g., Lusher et al. 2015), in melting sea ice (e.g., Obbard et al. 2014) and in the stomachs of Arctic birds (Provencher et al. 2010, 2014; Trevail et al. 2015; Avery-Gomm

et al. 2017). In 2007-2008, some thick-billed murres (*Uria lomvia*) in the Greater Hudson Bay region were observed to contain plastic pieces in their stomachs, including those feeding at Coats Island (4% of birds sampled), Digges Sound (17% of birds sampled) and Akpatok Island (23% of sampled birds), with the average weight of plastic debris falling between 0.0015-0.0032 grams per bird (Provencher et al. 2010). With the exception of one Common eider out of 100 sampled at Cape Dorset, no other seabirds in the area showed signs of plastics ingestion (Provencher et al. 2014 and references within). Preliminary research has identified fibers in seawater and sediment in the Canadian Archipelago (L. Jantunen (ECCC), Chelsea Rochman (U of T) and Patricia Cororan (UWO), personal communication). Although much is unknown about the types, frequencies and fate of plastics in the Canadian Arctic, let alone Hudson Bay, this is a topic of growing interest and research.

**Direct sources**

One potential source of pollution to the marine ecosystem is petroleum products (e.g., oil, gas, diesel). Petroleum products

are composed of thousands of types of petroleum hydrocarbons. One class of these hydrocarbons, the polycyclic aromatic hydrocarbons (PAHs), are of most concern since they are globally distributed, environmentally persistent and toxic to fish like Arctic cod (Keith 2015; Nahrgang et al. 2016). However, since PAHs are easily metabolized (i.e., eliminated by the body) by fish and some invertebrate species, PAHs generally do not accumulate up through the food web, and thus do not reach high levels in high trophic-level species such as marine mammals (review by Hylland 2006).

Although hydrocarbons can be transported indirectly to the Arctic (e.g., forest fires), it is the risk of direct pollution such as from shipping vessels in the Arctic that is of greater ecological concern (Arctic Council 2009). The Hudson Bay region has seen an increase in the number of marine vessels over the last two decades, although with considerable inter-annual variability (Theme III, Chapter ii, Figure 2). Currently the only oil shipped through Hudson Bay is fuel oil for Kivalliq communities (requiring safe transport to shore from the oil tankers,

see Theme III, Chapter ii.), however it is possible that port and shipping companies may expand operations to include oil shipments through Hudson Bay by 2030-2050 (Andrews et al. 2016). Assessments of Hudson Bay have revealed promising potential for hydrocarbon exploration in the Hudson Bay Lowlands and mineral mining south of Wager Bay in Ukkusiksalik National Park (Jefferson et al. 1993; Nicolas and Lavoie 2012; Theme III, Chapter ii.). Anticipated mobilization of mineral and hydrocarbon resources in Hudson Bay requires further research to enhance understanding of sea-ice processes and their interactions with oil (see Box 2), which is currently poorly understood (Barber et al. 2014; Andrews et al. 2016). One study conducted by researchers at the University of Manitoba, in collaboration with the Parks Canada Agency and Government of Nunavut, is evaluating the baseline concentrations of hydrocarbons within the sedimentary record of Wager Bay (Ukkusiksalik National Park) and Chesterfield Inlet, NU. The work is also investigating possible sources of hydrocarbons to the areas.

### Box 2. Ice and oil

**The most significant threat of marine shipping** in the Arctic is oil spills (Arctic Council 2009). To minimize the uncertainty and impacts of oil spills to the Arctic ecosystems, two state-of-the-art research facilities are helping scientists in their study of sea-ice processes and their interactions with oil.

#### **Sea-ice Environmental Research Facility**

The first of its kind in Canada, the Sea-ice Environmental Research Facility (SERF) at the University of Manitoba is an outdoor experimental laboratory that can “grow” sea ice under varying conditions. Since its opening in 2012 researchers at SERF have been studying how sea ice forms and melts, along with the associated air-sea exchanges of energy and matter. Among the major research outcomes from SERF so far include 1) successful detection of ‘frost flowers’ by remote sensing techniques; 2) the evolution of pH, a measurement of acidity, of the sea-ice environment; and 3) the discovery of minerals such as ikaite and gypsum in sea ice. SERF has also aided in the development of several new technologies for the study of the sea-ice environment.

For more information visit the SERF website at <http://home.cc.umanitoba.ca/~wangf/serf>

#### **Churchill Marine Observatory**

On July 5, 2015 the federal government announced \$22.1 million to build the Churchill Marine Observatory (CMO)



Sea-ice Environmental Research Facility (SERF).

at the Port of Churchill. Research at the innovative, multidisciplinary facility will centre on Arctic issues pertinent to marine transportation and hydrocarbon exploration and development. CMO components will include an Oil in Sea Ice Mesocosm (OSIM), an Environmental Observing system and a Logistics Base. Specifically OSIM will investigate how hydrocarbon contaminants affect the ocean, sea ice and atmosphere, with the overall objectives of enhancing detection techniques, understanding impacts, and establishing or verifying mitigation regimes. The observatory will open in 2019.

*(Continued on following page)*

One of the core research programs to make use of CMO is *GENICE*, short for “Microbial Genomics for Oil Spill Preparedness in Canada’s Arctic Marine Environment”. The 4-year project will study naturally-occurring microorganisms that biodegrade (i.e., break-down) oil in seawater, under various scenarios (e.g., with various types of sea ice). *GENICE* aims to develop baseline microbial genomics (e.g., DNA) data, identify best practices for oil spills in the Arctic, and share generated information with decision makers for policy development.

For more information visit the following web pages:

- CMO: <http://umanitoba.ca/faculties/environment/departments/ceos/research/CMO.html>
- *GENICE*: <http://umanitoba.ca/faculties/environment/departments/ceos/research/GENICE.html>
- *GENICE*: [www.genice.ca](http://www.genice.ca)



PHOTOS BY D. CHIRKOVA AND D. DESMOND, UNIVERSITY OF MANITOBA. CAPTION BY D. CHIRKOVA.

Above photos illustrate a multidisciplinary study of crude oil behaviour in a sea ice environment which took place at SERF’s oil pool during January – February 2017. A light crude oil was injected underneath young sea ice. The ice was sampled during the month with state-of-the-art analytical chemistry instrumentation at the University of Manitoba’s Petroleum Environmental Research Lab (PETRL), providing a spatial and temporal mapping of the oil composition. Pictures on the right demonstrate the pool’s evolution: the top photo was taken a week after oil addition, the central photo illustrates the pool appearance after the first core samples were taken, and the bottom photo depicts the influence of the crude oil’s presence on the ice structure.



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## 4. How are wildlife exposed to contaminants?

### 4.1. Biogeochemical processes

In addition to their physicochemical properties, contaminants' bioavailability is controlled by biogeochemical conditions of the environment such as temperature, salinity, pH, the availability of sunlight, the content of organic matter, and microbial activities. For instance, the mercury that is initially deposited in Hudson Bay (and elsewhere) exists almost exclusively in inorganic forms. However, in the presence of certain bacteria, a fraction of this inorganic mercury is converted to an organic soluble form known as methylmercury.

Some contaminants are highly attracted to organic particles such as organic carbon either produced by marine phytoplankton and algae or introduced by terrestrial runoff. The organic-bound contaminants then either settle to the seafloor for eventual burial or uptake by benthic organisms, or are consumed and passed on to other organisms in the pelagic food web. Other POPs which are more water soluble (e.g., HCHs) and do not adhere to particulate organic carbon remain in the water column, where they can either be taken up by aquatic respiration in plants, invertebrates and fish, or return to the atmosphere.

### 4.2. Up the food chain

Bioaccumulation is the process of a contaminant concentration increasing in an individual organism over time. Because

some contaminants, such as mercury and some POPs, break down slowly (or not at all) in the body, the rate of uptake in organisms such as birds, fish and marine mammals far exceeds the rates of biological detoxification or elimination. Therefore, these long-lived organisms typically accumulate elevated, even high concentrations of contaminants in their bodies relative to background levels. Biomagnification takes the concept of bioaccumulation from a species to a food-web level. The contaminant load of species at the bottom of the food web (e.g., ice algae and phytoplankton) is passed on to zooplankton when eaten. The contaminants accumulated within zooplankton are then transferred to their predators, fish. This process continues with each larger predator (i.e., higher trophic level) in the food web, resulting in significantly higher concentrations in beluga and seals relative to other marine organisms. For example, the concentration of methylmercury in algae relative to seawater is about 10,000 times higher, and this rate of increase is about four to six times with each progressive trophic level (Stern et al. 2012a). Therefore the diet of top marine predators has a significant effect on their contaminant burden (Loseto et al. 2008a; McKinney et al. 2009).

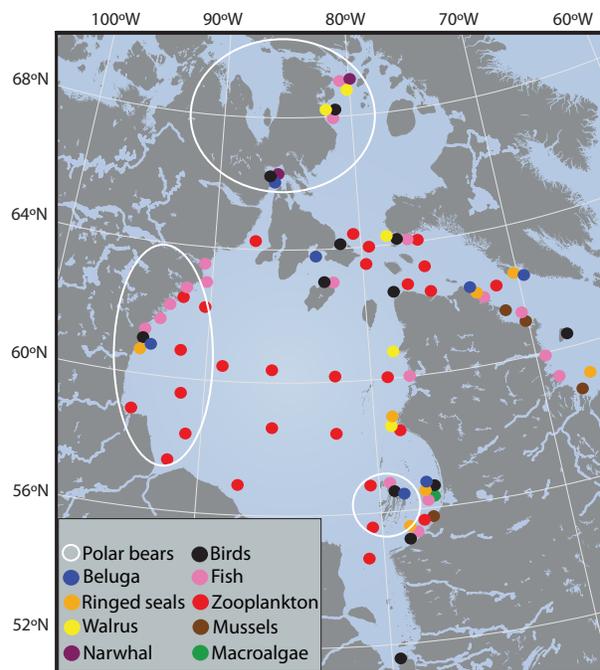
Mercury and POPs have shown various rates of biomagnification in Hudson Bay organisms. For instance, methylmercury was observed to biomagnify nine-fold from the lowest to the highest trophic level among zooplankton species alone (Foster et al. 2012). PCBs and dichlorodiphenyl-trichloroethanes (DDTs) appear to biomagnify highly in marine food webs (Kelly et al. 2007, 2008; Braune et al. 2014a), and PFOS biomagnifies in sea

ducks and marine mammals but not in aquatic organisms (Smithwick et al. 2005; Butt et al. 2008; Kelly et al. 2009; Braune et al. 2014a). Whereas more water-soluble contaminants such as  $\beta$ -HCH typically do not biomagnify up through invertebrates and fish, they do show high accumulation rates in marine mammals and seabirds due to the efficiency of their digestive tracts (Kelly et al. 2007). Although PBDEs bioaccumulate in some species (excluding polar bears; McKinney et al. 2011a), the majority of PBDEs do not appear to biomagnify strongly in Arctic marine food webs, probably due to biotransformation capabilities and rates (Kelly et al. 2008; Braune et al. 2014a).

POPs and PBDEs have a tendency to bind to lipids and thus accumulate in blubber, but PFCs (e.g. PFOS) bind to proteins and thus accumulate in blood, liver and kidneys (Martin et al. 2003; Kelly et al. 2009). Mercury is distributed throughout blood and tissues in the body, and ultimately congregates in the liver of birds and mammals. Total mercury concentrations can be 30 times higher in liver relative to muscle tissue (Wagemann et al. 1996; Dehn et al. 2005; Braune et al. 2015a). With respect to microplastics pollution, the bigger issue is not with the chemicals that can leach from the plastic, but rather their interference with hormone systems when ingested by organisms (e.g. review by Thevenon et al. 2014).

## 5. What are the levels of contaminants in Hudson Bay marine life? How are these changing over time?

Presented here are the spatial and temporal trends of contaminant concentrations in marine wildlife in and adjacent to Hudson Bay as determined from long-term and key studies. Figure 3 illustrates the locations from which samples were collected for contaminant analysis over 30 years. Where limited or no information of specific contaminants exists in Hudson Bay, we have supplemented the review to include neighbouring regions, such as Prince Leopold Island in the Canadian Archipelago. For simplicity, only a few common contaminants and some of the estimates for summed POP groups (i.e., total concentration of all DDTs= $\Sigma$ DDT) are presented in this section (see Table 1). Caution should be taken when studying the values of summed estimates for contaminant groups because (1) the number of individual contaminants per summed group can deviate between studies and (2) within each summed contaminant group the individual contaminants can have different physicochemical properties. With that said, estimates for summed contaminant groups are reported here for a general qualitative comparison only within the region, with the exception of PFOS. Since PFOS is the major PFC in wildlife (Giesy et al. 2001; Smithwick et al. 2005; Martin et al. 2004; Butt



**FIGURE 3.** Wildlife samples collected from within the greater Hudson Bay area from 1985-2015. Polar bears were harvested in locations within the white circles, depicting polar bear subpopulation ranges.

et al. 2007) and there are sufficient data covering trends of this specific PFC, the reporting of the summed estimate of total PFCs (i.e.,  $\Sigma$ PFC) was avoided.

When referring to the unit values of contaminants, mercury is commonly reported in micrograms per gram (parts per million), denoted as  $\mu\text{g/g}$ . One part per million can be visualized as one drop of food dye in 60.5 litres of water, which is the approximate size of a carry-on suitcase for flights. POPs on the other hand, which are typically observed in smaller concentrations, are usually reported in nanograms per gram (parts per billion), denoted as  $\text{ng/g}$ . One part per billion can be visualized as one drop of liquid in a railroad tanker car.

### 5.1. Primary producers, invertebrates, fish and birds Spatial trends

#### *Marine primary producers and invertebrates*

Contaminants concentrations are generally very low in algae, mussels and zooplankton. Total mercury concentrations in mussels (or bivalves) averaged 0.01-0.02  $\mu\text{g/g}$  as measured in Hudson Strait (Muir et al. 2000) and 0.16  $\mu\text{g/g}$  at Kuujuaapik (Mickpegak and Chételat 2015). Zooplankton sampled across Hudson Bay, Foxe Basin and Hudson Strait (2003-2005, 2010) contained average total mercury concentrations within the range of 0.01-0.08  $\mu\text{g/g}$ , whereas mean methylmercury

concentrations measured below 0.03 µg/g (Foster et al. 2012). Generally, species of higher trophic levels contained higher proportions of methylmercury. Total mercury in amphipods (shrimps) collected near Arviat, NU contained, on average, 0.02 µg/g (Pedro et al. 2017).

With respect to POPs, one analysis of contaminants in macroalgae near Umiujaq (1999-2002) revealed low mean concentrations of POPs (<9 ng/g, except ΣHCH at 27 ng/g), but ΣPBDEs were surprisingly higher at 324 ng/g (Kelly et al. 2007-2009). In mussels, the highest mean concentrations observed were ΣPCBs (46 ng/g), with all other contaminant groups averaging below ~8 ng/g between 1998-2002 in Hudson Strait and Umiujaq (Muir et al. 2000; Kelly et al. 2007, 2008). Pedro et al. (2017) observed in Arviat amphipods with relatively high concentrations of ΣPCBs (510 ng/g), total chlordane (ΣCHL) (420 ng/g) and ΣPBDEs (303 ng/g), which authors explained may have been linked to the amphipods' benthic diet.

#### Fish

In marine and anadromous (i.e., living in seawater but returning to freshwater to spawn) fish in Hudson Bay, average total mercury was reported as less than 0.5 µg/g (Braune et al. 2014b; Mickpegak and Chételat 2014; Evans et al. 2015; Pedro et al. 2017). Total mercury in anadromous Arctic char (*Salvelinus alpinus*) has historically been measured at very low levels, between 0.03-0.08 µg/g in muscle tissue at sites in Hudson Bay, Foxe Basin and Hudson Strait between the 1970s to late 2000s (Evans et al. 2015, Supporting Information and sources therein). Higher mean values were detected in some benthic

species at Coats Island (2007-2009), particularly fourline snake blenny (0.3 µg/g) (Braune et al. 2014b), but this value was still six times lower than the average total mercury concentration in their predator, thick-billed murre, at this location (Braune et al. 2014a).

Mean concentrations of POPs in sea-run Arctic char (2004-2009) did not vary significantly between Arviat, Sanikiluaq, Puvirnituq, Cape Dorset, Hall Beach, Igloolik and Kangirsuk, and generally fell within the ranges of concentrations measured from other locations in the Canadian Arctic (Muir et al. 2013, Annex Table A4-1). Typically, mean toxaphene concentrations were highest (<24 ng/g), followed by ΣPCBs (<17 ng/g). However, concentrations were higher in other types of fish. For instance, ΣPCBs were higher in capelin (*Mallotus villosus*) for both eastern Hudson Bay (183 ng/g; Kelly et al. 2007) and western Hudson Bay (138 ng/g; Pedro et al. 2017). Sand lance (*Ammodytes* spp.) was also in this ballpark (113 ng/g; Pedro et al. 2017). However, the highest recorded ΣPCB concentrations in Hudson Bay fish were reported in sculpin (*Myoxocephalus* spp.) near Arviat in 2014, at 234 ng/g (Pedro et al. 2017), which was explained likely as a result of their benthic diet. In northern Hudson Bay, ΣCHL had the highest mean values in fish sampled from 2007-2009 (up to 181 ng/g; Braune et al. 2014b).

Average ΣPBDE concentrations have generally been reported at below 40 ng/g in fish at Coats Island, Arviat, and Umiujaq (Kelly et al. 2008; Braune et al. 2014b; Pedro et al. 2017), although there were higher mean values noted for some benthic species at both locations (as high as 83 ng/g in Arctic shanny; Braune et al. 2014b). Lowest averages of



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ΣPBDE concentrations were observed in sea-run Arctic char throughout Hudson Bay (<1 ng/g; Muir et al. 2013, Annex Table A4-1). PFOS concentrations averaged <6.2 ng/g in the whole body or muscle of fish (Kelly et al. 2009; Braune et al. 2014b), but higher means were observed in the liver of species from the Great Whale River, Kuujuarapik (e.g., 39 ng/g in Brook trout; Martin et al. 2004).

#### *Seabirds*

Thick-billed murres and common eiders from various locations in Hudson Bay and Hudson Strait contained average total mercury concentrations less than 2.5 µg/g of liver tissue (Wayland 1999; Braune et al. 2014b; Mickpegak and Chételat 2015). Braune et al. (2014b) reported little variation in hepatic (liver) mercury concentrations in thick-billed murres from Coats Island, Digges Island (NW Hudson Bay) and Akpatok Island (Hudson Strait) in 2007-2008, but concentrations were half those of thick-billed murres from more northerly locations such as Prince Leopold Island (590 km north of Igloodik) and the Minarets bird cliffs on eastern Baffin Island. Recent analyses of trace metals in female common eiders at Mittivik Island, northern Hudson Bay, revealed blood mercury concentrations averaging 0.20 µg/g, with concentrations falling within the range of 0.08-0.43 µg/g in 193 specimens between 2013-2014 (Provencher et al. 2016). With respect to total mercury concentrations in eggs, essentially all in the form of methylmercury (Weiner et al. 2003), thick-billed murres and common eiders at southeast Southampton Island showed averages of less than 1.8 µg/g (Braune et al. 2006; Akearok et al. 2010).

As part of a larger food-web study, POPs were measured in the liver of eider ducks and white winged scoters (1999-2002) near Umiujaq (Kelly et al. 2007-2009). The highest average value for all contaminant groups measured was ΣPCBs in white winged scoters (2953 ng/g), followed by ΣDDTs (668 ng/g; Kelly et al. 2007). By comparison, liver tissue of thick-billed murres at Digges Island and Akpatok Island collected in 2008 contained much lower concentrations, averaging around 40 ng/g for both ΣPCBs and ΣDDTs (Muir et al. 2013, Appendix Table A4-8). Equivalent mean values for thick-billed murres at Coats Island (2007) were lower still at 9.8-10.7 ng/g, but the eggs contained higher average concentrations (118-139 ng/g; Muir et al. 2013, Appendix Table A4-8). Muir et al. (2013) reviewed ΣPCB, ΣDDT and total chlorobenzene (ΣCBz) concentrations in liver tissues of thick-billed murres from Digges and Akpatok islands and found that, as with mercury, these concentrations were relatively lower than for thick-billed murres at the Minarets and Prince Leopold Island colonies in 2008.

With respect to newer POPs, PFOS concentrations in the liver of seabirds in eastern Hudson Bay averaged 7-25 ng/g in the 1990s to early 2000s (Martin et al. 2004; Kelly et al. 2009).

By comparison, the equivalent concentrations in thick-billed murres from northern Hudson Bay and Hudson Strait (2007-2008) were 104-230 ng/g, although average concentrations in eggs (2009) were lower (30 ng/g; Muir et al. 2013, Appendix Table A4-11). There was no significant difference in PFOS concentrations in liver samples from Digges Island, Akpatok Island, the Minarets and Prince Leopold colonies (Muir et al. 2013). From the same group of birds, average concentrations of penta-BDEs (sum of BDE-47, -99 and -100), were highest in eggs (2.49 ng/g) and lower in liver (<0.9 ng/g; Muir et al. 2013, Table A4-10), considerably lower than mean ΣPBDE concentrations in white winged scoter liver tissue at Umiujaq (71 ng/g; Kelly et al. 2008).

#### **Temporal trends**

##### *Fish*

Evans et al. (2015) reviewed trends of total mercury in anadromous Arctic char muscle tissue across the Canadian Arctic. An analysis of the data revealed significant increases in concentrations at Hall Beach (1978-2007) and Arviat (1992-2008), and furthermore total mercury analyzed in the last two years of collection at Arviat (2005, 2008) appeared to be influenced by the variation in autumn air temperature (i.e., concentrations were higher when fall temperatures were lower).

##### *Seabirds*

No trends of total mercury were observed for thick-billed murre eggs at Coats Island from 1993-2009. However, when adjusted for trophic position using analyses of data for stable isotope ratios of nitrogen ( $\delta^{15}\text{N}$ ), an indicator of trophic level, mercury concentrations showed a significant increasing trend (Braune 2010). In this same collection from 1993-2013, decreasing trends for six contaminants were reported. Furthermore, when adjusted for  $\delta^{15}\text{N}$ , significant temporal trends remained for *pp'*-DDE, hexachlorobenzene, dieldrin and ΣPCBs but at near or smaller rates of decline (Braune et al. 2015b). Together, these findings suggest that dietary shifts have influenced contaminant concentrations at the Coats Island colony (see 6.2 in this chapter for further details).

Further north at Prince Leopold Island, some POPs, including PCBs, ΣCBz, and ΣDDT, declined in thick-billed murres and northern fulmars from 1975-2011 (Braune 2007). Interestingly, however, in recent years ΣCBz and ΣCHL have increased in these species' eggs, similar to ringed seals from the same region (Muir et al. 2013). In the early 2000s, ΣPBDE concentrations were significantly increasing in these birds but are now currently stable or declining, following the ban of PBDEs in North America (Hale et al. 2003; Law et al. 2003). While PFOS has not shown any significant trends since 1975, total perfluorocarboxylate (PFCA, another PFC) concentrations have increased by

13-14% over 12 years in thick-billed murres and northern fulmars (Muir et al. 2013), although during 2009-2011 both PFOS and PFCA concentrations declined. These PFCA trends are generally following the global production and emissions trends of PFCAs and their precursors (Armitage et al. 2009; Wang et al. 2014).

## 5.2. Marine mammals

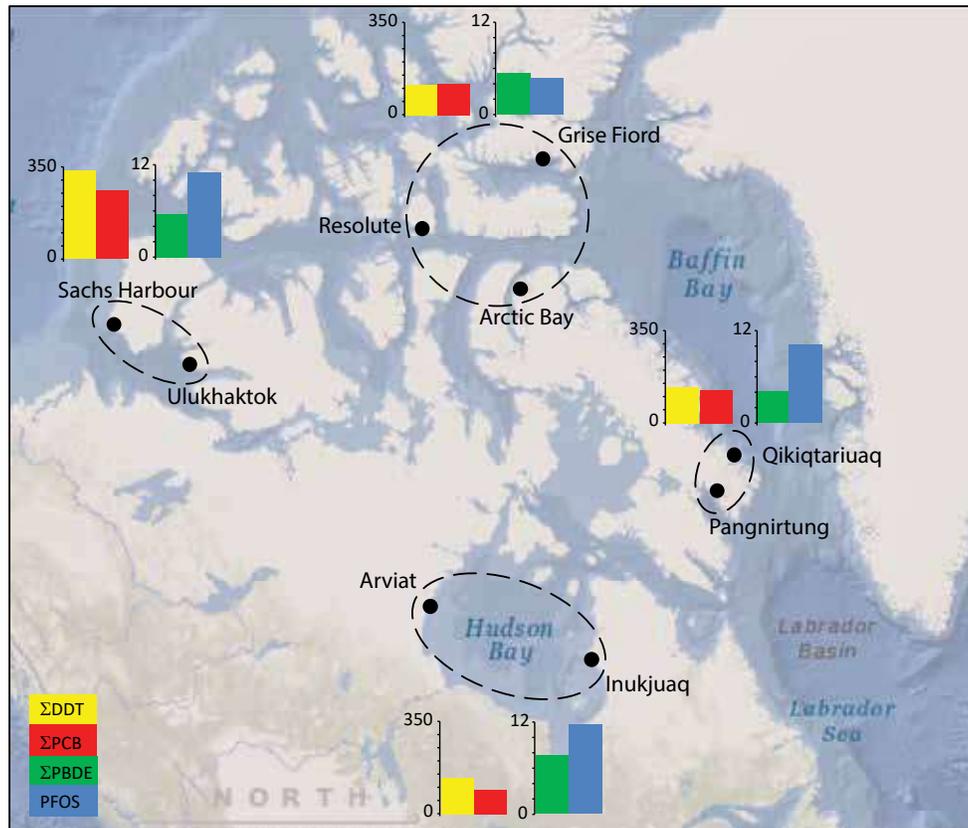
### Spatial trends

#### Seals

An analysis of total mercury in ringed seal liver (1998-2008) and muscle (2000-2010) at twelve Canadian Arctic communities revealed that average concentrations from Inukjuaq samples contained the lowest values (2.74 and 0.13 µg/g, respectively) while Arviat samples were in the mid-range (18.67 and 0.53 µg/g, respectively; Muir 2010). Total mercury concentrations were reported from Kuujuaapik in the winter of 2014, averaging 25.8 µg/g of liver and 0.65 µg/g of muscle (Mickpegak and Chételat 2015). Young et al. (2010) compared total mercury in muscle and liver of ringed, bearded and harbour seals

sampled at Arviat and Chesterfield Inlet by age class (1999-2006). Looking at the adult age class, they found that the two samples of harbour seals had about 10 times more total mercury in muscle and liver tissues relative to the three ringed and two bearded seals.

Typically, ΣPCB and ΣDDT concentrations have made up the majority of the POPs contaminant burden in ringed seals (Muir et al. 1999a; Muir et al. 2001; Kelly et al. 2007). Figure 4 illustrates the spatial variability of common and emerging contaminant groups in ringed seals across the Arctic. The concentrations of many legacy POPs (e.g., ΣDDT, ΣPCB) in ringed seals collected at Arviat and Inukjuak have generally been among the lowest mean values reported across the Canadian Arctic from 2003-2011 (Muir et al. 2013). With respect to ΣPBDE, however, average concentrations were highest in Inukjuak samples (16ng/g; Muir et al. 2009). Butt et al. (2008) also found that PFOS concentrations were relatively high in Inukjuak samples (88 ng/g, liver tissue) relative to samples collected across Canada. The higher concentrations in Inukjuak-sampled



**FIGURE 4.** PFOS and estimates of total (Σ) DDT, PCB and PBDEs in ringed seal blubber tissue across the Canadian Arctic (units in ng/g wet weight). Data are from 2011 and averaged across 2-3 sampling locations in dashed circles (Muir et al. in Table A4-1, NCP 2013). (Basemap credited to Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors.)



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seals may be related to differences in long-range transport of PBDEs and PFOS (Butt et al. 2008). Interestingly, when data were adjusted for  $\delta^{13}\text{C}$ , an indicator of pelagic/offshore and benthic/inshore sources of prey (e.g., Cherel and Hobson 2007), PFCs were statistically higher in Arviat samples, along with Grise Fiord, Qikiqtarjua and Nain samples, suggesting PFC exposure is somewhat related to benthic and inshore prey sources (Butt et al. 2008). For further discussion and illustration of contaminant spatial trends in Canadian Arctic ringed seals, see Brown et al. (2018) in the ArcticNet IRIS 2 report.

#### *Walrus & narwhal*

Walrus typically have smaller contaminant concentrations compared with ringed seals and beluga, likely because of their lower trophic position and the influence of biomagnification (Hobson and Welch 1992, 2002). Mean annual total mercury levels reported from Igloodik, Hall Beach and Inukjuaq have been under  $5\ \mu\text{g/g}$  of liver, and at Inukjuaq  $0.04\ \mu\text{g/g}$  of muscle tissue (Muir et al. 2000; Stern and Lockhart 2007-2010; Gaden and Stern 2010). Average  $\Sigma\text{PCB}$  and toxaphene concentrations in blubber sampled in eastern Hudson Bay (1999) and Foxe Basin (2000s) were generally below  $500\ \text{ng/g}$ , only half to two thirds the concentrations observed in ringed seals (Muir et al. 1999a; Muir and Kwan 2000; Kelly et al. 2007; Stern and Lockhart 2009). Tomy et al. (2004, 2008a) reported that walrus liver from Cape Dorset (1998) contained average PFOS concentrations of  $2.4\ \text{ng/g}$  and  $\Sigma\text{PBDE}$  concentrations of  $0.4\ \text{ng/g}$ , being 37 and 40 times lower, respectively, than the equivalent mean concentrations of ringed seals sampled south of that area (Butt et al. 2008; Muir et al. 2009).

Very little contaminants information has been reported for narwhal in Hudson Bay. With respect to mean total mercury in

liver tissue, samples from Repulse Bay were reported between  $8.9\text{--}12\ \mu\text{g/g}$  during 1993-2001 (Gaden and Stern 2010). Stern et al. (2009) analyzed POPs in Foxe Basin narwhal from 2006 and revealed the highest mean concentrations were of toxaphene ( $8081\ \text{ng/g}$  in females), followed by  $\Sigma\text{DDT}$  and  $\Sigma\text{PCB}$  concentrations ( $\sim 2200\ \text{ng/g}$  each in females). These samples contained lower POPs concentrations than narwhal in Clyde River and Pond Inlet, which was postulated as attributable to a difference in diet and food webs along the migration paths, or even being due to the ages, which cannot be determined accurately for narwhal.

#### *Beluga*

Hudson Bay beluga are less contaminated with mercury than those in the western Canadian Arctic (Lockhart et al. 2005; Stern and Lockhart 2010-2012; Stern and Loseto 2013, 2014). Average total mercury concentrations in liver sampled from Arviat beluga (1984-2012) and Sanikiluaq beluga (1994-2013) have typically been reported under  $20\ \mu\text{g/g}$ , and average muscle concentrations have been under  $5\ \mu\text{g/g}$  (Lockhart et al. 2005; Gaden and Stern 2010; Stern and Lockhart 2010-2012; Stern and Loseto 2013, 2014, 2016b).

Beluga whales in Hudson Bay have tended to have high levels of  $\Sigma\text{PCB}$  and  $\Sigma\text{DDT}$ , followed by chlordane (Muir et al. 1999b; Hobbs et al. 2003; Stern et al. 2005; Kelly et al. 2007). Recent average  $\Sigma\text{PCB}$  and  $\Sigma\text{DDT}$  concentrations in males sampled from Sanikiluaq in 2015 were below  $500\ \text{ng/g}$  (Stern and Loseto 2016a).  $\Sigma\text{PBDE}$  concentrations in Hudson Bay and Hudson Strait beluga populations have generally averaged  $<41\ \text{ng/g}$  (Muir et al. 2004; Kelly et al. 2008; Tomy and Loseto 2014), with higher concentrations at Igloodik ( $40\text{--}72\ \text{ng/g}$ ; Tomy et al. 2004; 2008b). Tomy et al. (2008b) further reported that  $\Sigma\text{PBDE}$  measured in Igloodik beluga samples were higher compared to Hendrickson, Pangnirtung and Resolute samples. With respect to PFOS, mean concentrations in Umiujaq and Sanikiluaq beluga were below  $40\ \text{ng/g}$  (Kelly et al. 2009; Tomy and Loseto 2014).

#### *Polar Bears*

Studies of contaminants in polar bear subpopulations across Alaska, Canada, eastern Greenland and Svalbard have revealed southern Hudson Bay animals have the lowest total mercury concentrations (mean of  $6.96\ \mu\text{g/g}$  liver; 2007-2008) but also the highest concentrations of PFOS and  $\Sigma\text{PBDE}$  (mean of  $1459$  and  $88.5\ \text{ng/g}$ , respectively in 2013-2014 adult females) (Letcher 2010; McKinney et al. 2011a; Routti et al. 2011; Letcher et al. 2018). The relatively lower total mercury values in Hudson Bay bears compared with south Beaufort Sea bears could be explained by the shorter food web and lower methylmercury concentrations in the water column present in Hudson Bay, relative to the south Beaufort Sea (St. Louis et al. 2011). Work by McKinney

et al. (2011b) also suggests that subpopulations of polar bears in Hudson Bay, relative to other circumpolar subpopulations, consume higher proportions of lower trophic level or fresh-water-associated prey in their diet.

The highest contaminant concentrations in polar bears in Hudson Bay are  $\Sigma$ PCB,  $\Sigma$ CHL and PFOS (Martin et al. 2004; Smithwick et al. 2005; Verreault et al. 2005; McKinney et al. 2011a; Letcher et al. 2018), with mean  $\Sigma$ PCB concentrations exceeding 8000 ng/g blubber in some adult animals (2013-2014) (Letcher et al. 2018). Like ringed seals, polar bears sampled from Hudson Bay have had low  $\Sigma$ HCH concentrations but higher  $\Sigma$ DDT, dieldrin and chlordane-related compounds compared to bears in the western and central Archipelago (Muir et al. 2013). Within Hudson Bay, southern polar bears tended to have elevated concentrations of  $\Sigma$ PFAS,  $\Sigma$ PBDE and  $\Sigma$ DDT compared to western bears, which is attributed to the shorter distance to southern, urban and/or recent sources of associated pollution (McKinney et al. 2009; Letcher et al. 2018). On the other hand, western polar bears had relatively higher  $\Sigma$ Cbz and  $\Sigma$ HCH concentrations over southern bears (Letcher et al. 2018). See Figure 5 in the ArcticNet IRIS 2 contaminants chapter by Brown et al. (2018) for further illustration and discussion on spatial trends of POPs in Canadian Arctic polar bears.

### Temporal trends

#### Seals

Total mercury concentrations in the muscle tissue of ringed seals collected at Arviat have declined significantly since the mid-2000s (9% loss per year; Muir et al. 2013, 2014). Between 1990 and 2011, ringed seals at Arviat and Inukjuaq also exhibited significant declining concentration trends of  $\Sigma$ PCB,  $\Sigma$ CBz,  $\Sigma$ HCH,  $\Sigma$ CHL and  $\Sigma$ DDT (more than 5% loss per year), and concentrations of  $\Sigma$ PBDE and PFOS have also decreased since the early 2000s, although not significantly (Butt et al. 2007; Muir et al. 2013). In comparison with ringed seals in the Beaufort Sea, these rates of decline appear to be faster (Muir et al. 2013).

#### Walrus & Narwhal

Total mercury concentrations in walrus sampled at Igloodik and Hall Beach showed no significant temporal trend in concentration from 1982-2009 (Stern 2010). Similarly, length-adjusted total mercury concentrations in liver in Repulse Bay narwhal revealed no trends from 1993-2001 (Gaden and Stern 2010).

#### Beluga

Female beluga at Arviat showed significant decreasing trends of age-adjusted total mercury concentrations in muscle tissue during 1984-2008 (Gaden and Stern 2010). Along with decreasing trends in  $\delta^{13}\text{C}$ , which was also reported in western



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Hudson Bay polar bears from 1991-2007 (McKinney et al. 2009), this decreasing mercury trend was hypothesized to result from a shift in the location of beluga foraging grounds towards more offshore, less contaminated prey. As to why there was no counterpart trend with the males, this could be explained by sexual segregation of foraging and habitat selection (Loseto et al. 2006, 2008b).

With respect to POPs, there are few recent studies investigating temporal trends in the eastern Canadian Arctic populations of beluga. In females from Sanikiluaq, all major groups of chlorinated compounds ( $\Sigma$ CBz,  $\Sigma$ HCH,  $\Sigma$ CHL,  $\Sigma$ DDT,  $\Sigma$ PCB,  $\Sigma$ TOX) and dieldrin significantly decreased between 1994 and 2013, with many compounds declining by an order of magnitude (Stern, unpublished data). The next closest region to the Hudson Bay system with trend data is Cumberland Sound (~330 km north of Hudson Strait).  $\Sigma$ CBz,  $\Sigma$ HCH,  $\Sigma$ DDT and  $\Sigma$ PCB all declined from 1995-2009 in male beluga but the rates were not statistically significant (Stern et al. 2012b; Muir et al. 2013).  $\Sigma$ PBDE concentrations increased significantly in Cumberland Sound beluga from 1982 to 2008 (5.9% per year, Tomy et al. 2011; Muir et al. 2013). PFOS concentrations also increased significantly during 1982-2000 (4.7% per year) but declined significantly from 2000 to 2010 (9.8% per year; Tomy et al. 2011; Muir et al. 2013).

#### *Polar Bears*

While mercury concentrations in Hudson Bay polar bears appeared relatively unchanged during the period of 1982-2008 (Routti et al. 2011), concentrations of  $\Sigma$ HCH and  $\Sigma$ DDT significantly decreased since 1968 (Braune et al. 2005; Rig  t et al. 2011; McKinney et al. 2009, 2010; Muir et al. 2013).

Letcher et al. (2018) recently reviewed various contaminant congeners and groups in both the southern Hudson Bay subpopulation and the western Hudson Bay subpopulation. Comparing concentrations in polar bears from 2013-2014 to those of 2007-2008 (McKinney et al. 2011a), Letcher et al. (2018) reported declines in  $\Sigma$ PCB,  $\Sigma$ DDT,  $\alpha$ -HCH, dieldrin and  $\Sigma$ PBDE for all bears except males from western Hudson Bay.  $\Sigma$ CHL and PFOS concentrations were also lower for all 2013-2014 bears, whereas  $\Sigma$ CBz and  $\beta$ -HCH had increased in western Hudson Bay adult males.  $\Sigma$ PFCA was one group that increased among all bears. Why trends differed for western Hudson Bay male adults compared to other bears in the region was reasoned by differences in diet and behaviour (e.g., McKinney et al. 2009, 2011a, b). Previously,  $\Sigma$ PBDE in western Hudson Bay bears had significantly increased from 1991-2007 (McKinney et al. 2010). A further investigation of dietary indicators revealed that the bears were consuming more harp or harbor seals and fewer bearded seals, and that this change in diet facilitated a faster rate of increase of PBDEs (McKinney et al. 2010).

### 5.3. Biological effects and risks of contaminants to Arctic wildlife

Because many contaminants biomagnify in aquatic food webs, species near the top of the food chain, (e.g., polar bears, beluga, seals and marine birds) can accumulate contaminant concentrations associated with risks of potential health effects. The range of health effects is dependent on species and can include reproductive impairment, neurotoxicity impacts, endocrine (hormone) disruption and immunological suppression.

#### **Mercury**

Relatively high concentrations of MeHg exposure have been linked to lower reproductive success in common loons (Evers et al. 2008). In the Canadian Arctic, only the eggs of Ivory gull (*Pagophila eburnea*) sampled from Seymour Island in 2004 contained MeHg concentrations within the threshold range for reproductive effects (Shore et al. 2011). Liver concentrations of MeHg in Northern fulmar at Devon Island (2003) and Prince Leopold Island (2008) were also within the threshold range of reproductive effects (Shore et al. 2011; NCP 2012). Blood mercury concentrations and the thyroid hormone corticosterone (responsible for responding to stress) were significantly, inversely correlated in northern Hudson Bay female eider ducks (Provencher et al. 2016). In thick-billed murres in northern Hudson Bay, blood mercury concentrations were positively associated with the thyroid hormone triiodothyronine ( $T_3$ , responsible for growth, development, and metabolism) (Fernie et al. 2017).

In marine mammals, high MeHg concentrations are most commonly associated with reduced neurological functions as well as suppressed immune functions. For example, high MeHg concentrations were associated with reduced counts of white blood cells in captive beluga whales at the Vancouver Aquarium (Frouin et al. 2012). Beluga from the western Canadian Arctic contained MeHg concentrations high enough to potentially impact neurological processes (Ostertag and Chan 2010; Ostertag et al. 2013). With respect to liver and muscle concentrations of total mercury, a review of Canadian Arctic beluga and seal samples revealed most populations were likely not experiencing mercury poisoning (NCP 2012). The one population of marine mammals which met the threshold for mercury poisoning was the western Hudson Bay adult harbour seals, having THg concentrations of  $>2.0 \mu\text{g/g}$  in muscle and  $>240 \mu\text{g/g}$  in liver (Young et al. 2010).

#### **POPs**

Organic contaminants, particularly  $\Sigma$ PCB, toxaphene, and some DDT and chlordane compounds, have been linked to reproductive, estrogenic, endocrine and immune impacts, lesions, poor body condition, survival, metabolic and behaviour impacts in

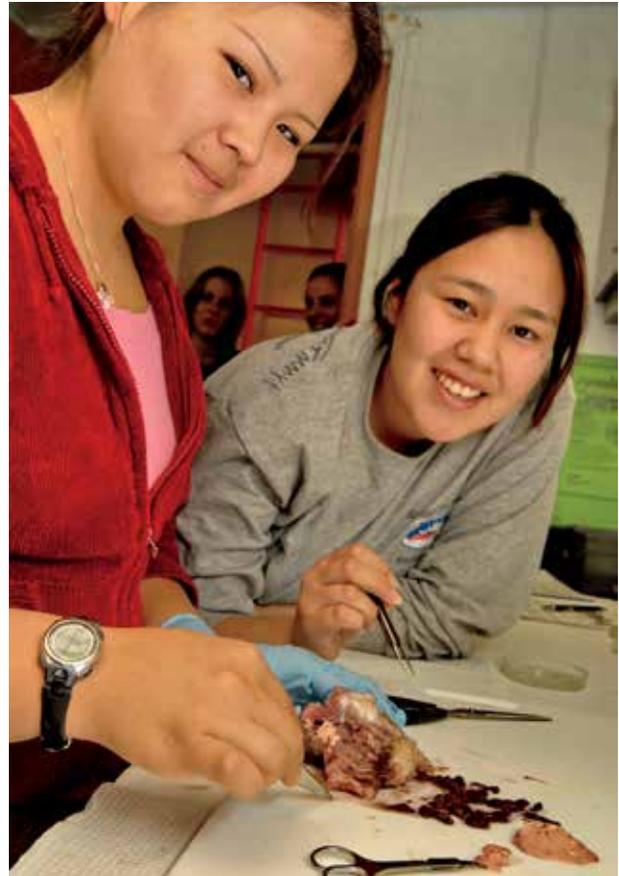
various species (review by Letcher et al. 2010). However, concentrations of POPs in most Canadian Arctic wildlife populations do not exceed threshold levels for biological effects (Letcher et al. 2010). Only a few studies of Canadian Arctic animals have discovered associations between contaminants and displaced thyroid hormones, and/or changes in vitamin concentrations (e.g., Kuzyk et al. 2003; Brown et al. 2013; Desforges et al. 2013). Pertaining specifically to Hudson Bay, Letcher et al. (2010) suggested both western Hudson Bay and southern Hudson Bay polar bears were contaminant exposure “hotspots”; in other words, the organic contaminants recorded in these populations have exceeded 1 ppm (1,000 ng/g), which is considered to be a cautious threshold for high risks of infections and reproductive effects in polar bears.

One of the concerns of POPs with respect to biological effects is their potential for interfering with animal adaptation to climate change. Should hormones responsible for thermoregulation, growth and neurodevelopment be disrupted, the hunting and survival of young marine mammals in the face of extreme environmental change may be impacted (Jenssen 2006).

Although the body of knowledge for POPs biological threshold effect levels is growing, there are some limitations that make it difficult to assess the population health of Arctic animals. Threshold effect levels are typically established for captive animals in controlled environments, and it is difficult to extrapolate these effects to free-ranging animals for which there are knowledge gaps in their biology, physiology, diet, trophic level, cumulative stresses and seasonal changes in contaminants due to fat accumulation/mobilization (i.e., most Arctic species). Add to this the overarching issue that organisms are exposed to a mixture of contaminants which can interact to produce more (or less) serious effects, and it sums up to be a very complicated assessment.

## 6. How will climate change affect contaminant pathways and exposure to marine life?

Climate change and variability have shown complex effects to the pathways and fate of mercury and POPs. In the Arctic, changes observed in the medium (environment), bottom-up processes (e.g., food web) and top-down processes (e.g., animal range and diet) can affect the contaminant concentrations in top-level species such as ringed seals, beluga and polar bears. The following section summarizes some of these impacts as they are currently understood.



SCHOOLS ON BOARD

### 6.1. Environmental changes

Temperature and sea ice play a role in the availability of contaminants in seawater but often in complex ways. For example, while a reduction in sea-ice coverage exposes a higher amount of surface area of seawater, and may allow for an increased entryway for particulate mercury, it may also allow for higher rates of photo-demethylation and evasion (i.e., atmospheric loss) of gaseous mercury (Andersson et al. 2008; Point et al. 2011; Stern et al. 2012a; Braune et al. 2015a). The extent and duration of sea-ice cover also affects the deposition (input) and volatilization (exit) of POPs from different environmental compartments. For instance, in scenarios with higher temperatures and less sea ice, typically volatile contaminants escape from the oceans back into the atmosphere. For instance, one modelling study illustrated that under various warming scenarios air concentrations of  $\alpha$ -HCH increased by up to 25% solely as a result of the contaminant volatilizing from the snow pack from May-September (Ma and Cao 2010). Another modelling study reporting upon projections for the 75-m surface ocean layer between 1995-1999 and 2095-2099 indicated up to 20% increased concentrations of the water-soluble  $\gamma$ -HCH



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but up to 20-40% declines of the more volatile PCB congeners 52 and 153 in the Arctic (AMAP 2016). Results illustrate the importance of the physicochemical properties of each contaminant with respect to responding to climate change. Climate projections for Hudson Bay (2040-2064) indicate significant warming annually (1.5-4.6°C) and seasonally (1.1-3.3°C in summer, 1.8-8.5°C in winter). Sea-ice concentrations are anticipated to continue to decline in the foreseeable future (Theme I. Chapter iii.; AMAP 2017a).

Changes to the hydrological cycle will also affect contaminant distribution. As glaciers and multiyear sea ice melt, large pools of contaminants may be released from previous long-term storage. Furthermore, since precipitation scavenges and deposits atmospheric contaminants to surface media, projected increases in rain and snow would deliver a proportion of contaminants back to the ocean (e.g., Meyer and Wania 2007). As discussed in Theme I. Chapter iii., climate projections for Hudson Bay (2040-2064) indicate increased annual precipitation by up to 0.4 mm/day. Extreme precipitation events are also expected to increase in the Arctic (AMAP 2017a).

As stated earlier, the production of methylmercury in terrestrial environments occurs in wet conditions, whereby

higher rates of methylmercury production occur in years of earlier thaw and later freezing (Stern et al. 2012a). In years of high precipitation, when a larger area of wetlands is flooded, more methylmercury is produced and higher concentrations are discharged from the Churchill and Nelson rivers into Hudson Bay (Mailman et al. 2006; Kirk and St. Louis 2009). Wetter and warmer conditions also influence permafrost thaw and subsequent releases of stored mercury, as well as nutrients in ponds which can stimulate methylmercury production (Givelet et al. 2004; Macdonald et al. 2005; MacMillan et al. 2015). With snowmelt and spring break-up anticipated to continue to occur earlier (Theme I. Chapter ii.), and with the depth of snow and permafrost projected to continue to decline (AMAP 2017a), relatively higher levels of methylmercury could be exposed to and biomagnify in the food web (Stern et al. 2012a).

As mentioned above, forest fires are a source of hydrocarbons to the Arctic. The frequency of fires are expected to increase (AMAP 2017a), suggesting a continued source of organic contaminants to the atmosphere and deposition in the Arctic.

Although climate variation affects contaminant transport and fate, it is important to note here that the regulation of

contaminant emissions is a stronger factor affecting the atmospheric concentrations of POPs in the Arctic in comparison to climate change (Hansen et al. 2015).

## 6.2. Food web changes

Stern et al. (2012) explained that changes in sea ice can affect the bottom-up exposure mechanisms of methylmercury (and POPs) to marine food webs in several ways pertinent to Hudson Bay:

- (1) The amount of organic matter (e.g., phytoplankton, primary production) and energy available at the base of the food web affects contaminant input at the bottom of the food web. Historically, the concentration of phytoplankton in the water column has been relatively low in Hudson Bay (Kuzyk et al. 2010). Ecosystem models estimate annual primary production is relatively higher in the northwestern half of the Bay and particularly for northern Hudson Strait due to better nutrient exchange in the water column (Theme II, Chapter ii.). Yet, due to the expected decrease in vertical mixing of nutrients in the large, central Bay, it is estimated that there may be an overall decrease in productivity for the Hudson Bay System as a whole, with the possible exception of increased productivity in coastal, well-mixed areas (Theme II, Chapter ii.). Scenarios of enhanced marine production have been postulated to result in decreased food-web contaminant exposure as a result of contaminants adsorbing to the increased organic matter and settling to the seafloor (Outridge et al. 2008; Borgå et al. 2010);
- (2) growth rates of low trophic-level organisms (e.g., phytoplankton) as mediated by temperature, carbon, nutrient and energy (e.g., lipid) sources, which affect bioaccumulation rates (Outridge et al. 2008; Borgå et al. 2010; AMAP 2016). Interestingly, one study modelling POP bioaccumulation in an Arctic marine pelagic food web illustrated that biomagnification was more strongly affected by seasonal changes as opposed to variation in climate (AMAP 2016); and
- (3) food-web length (i.e. additions or removals of species), which affects the rates of biomagnification.

A growing number of studies have documented how changes in the underlying food web can affect dietary contaminant exposure in top marine predators (Borgå et al. 2004; McKinney et al. 2009, 2012; Hallanger et al. 2011). Two well-documented contaminant-monitoring projects specific to Hudson Bay exemplify how changes in the food web or species availability can affect contaminant concentrations in (1) thick-billed murres and (2) polar bears.

- (1) Between 1980-2002, thick-billed murres at Coats Island in northern Hudson Bay shifted their diet from Arctic cod to capelin and sand lance, and this transition was suggested to have resulted from warmer, longer ice-free periods (Gaston et al. 2003, 2012; Theme II, Chapter v.). Although capelin and sand lance contained lower contaminant concentrations than Arctic cod, these species showed higher rates of contaminant transfer to their predators (Braune et al. 2014b). After adjusting for trophic position (using  $\delta^{15}\text{N}$ ) in this colony's eggs, results indicated that the dietary shift at Coats Island reduced the rate of contaminant decline, suggesting that the shift in diet did in fact affect the temporal trends (Braune et al. 2015b). More recently, research by Pedro et al. (2017) reported higher concentrations of PCBs and many pesticides in sand lance and capelin compared to Arctic cod, but only by up to 2-fold. Authors suggest that the invading species (sand lance and capelin) therefore have a limited potential to introduce more contaminants into the Arctic marine food web. (See 6.3 in this chapter for further examples of invading species.)
- (2) A polar bear study incorporating fatty acids, a type of dietary indicator, determined that western Hudson Bay polar bears fed proportionately more upon harp and harbour seals (open-water seals) and less upon bearded seals (pack-ice seals) in early break-up years from the early 1990s to mid-2000s (Thiemann et al. 2008; McKinney et al. 2009), and furthermore that this change in diet explained a significant amount of variation in the contaminant concentrations in the bears (McKinney et al. 2009). In particular, diet was associated with concentrations of PCBs, chlordanes and PBDEs (McKinney et al. 2010, 2011b). Harbour seals also appear to feed at a higher trophic level and have higher concentrations of mercury in muscle tissue compared with ringed and bearded seals (Young et al. 2010). McKinney et al. (2010) suggests that if polar bears continue to consume proportionately more harp and harbour seal in their diet, then contaminant concentrations will increase relative to an unchanged diet.

## 6.3. Range expansion and condition

Warming waters and longer ice-free conditions may allow for an increase in delivery of contaminants to the Arctic by biological vectors. For example, some invading animal species such as killer whales (Higdon et al. 2012; Theme II, Chapter vi.) and Pacific salmon (Dunmall et al. 2013) are shifting migration and expansion into new Arctic terrain. These animals bring their contaminant burdens with them, which can be transferred into arctic and sub-arctic food webs (Blais et al. 2007; Muir et al. 2013; Pedro et al. 2017). Additionally, the contaminant exposure of

animals can be changed when there are shifts in their temporal or spatial foraging patterns (Loseto et al. 2008a,b; Gaden et al. 2009; Gaden and Stern 2010). As an example of these foraging shifts within Hudson Bay, 18% of participants in the 2004 Nunavik Health Study indicated that beluga were more difficult to hunt because they were in different areas from where they usually resided (Furgal and Rochette 2007).

The stresses from long-term meteorological and ecological changes can also make marine mammals more sensitive to contaminant toxicities. For example, when marine mammals travel farther to find food sources, they expend more of the energy stores in their blubber. As blubber reserves are depleted, leaving behind the stored POPs, thinner marine mammals are exposed to higher contaminant concentrations, and the potential thresholds for biological effects can more easily be exceeded. Research on western Hudson Bay polar bears has revealed that poor body condition of females has been significantly related to early break-up of sea ice (Stirling et al. 1999), and furthermore that high POPs concentrations as observed in these bears (McKinney et al. 2011a; Letcher et al. 2018) could hinder antibody production important for fighting off infections (Lie et al. 2004).



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## 7. Key findings and recommendations

Country foods are a central part of the well-being of Indigenous communities. However, some animal tissues can attain concentrations of persistent and toxic contaminants that pose risks to the health of country food consumers. Environmental monitoring programs serve the dual purpose of providing information to evaluate the safety of country food consumption as well as the effectiveness of global pollution emissions regulations. Herein lie the key findings of contaminants knowledge in Hudson Bay:

### Sources:

- Many contaminants in Hudson Bay are produced externally and arrive in the North by long-range transport through the atmosphere, oceans and rivers. Atmospheric concentrations of mercury appear to be decreasing in the sub-arctic.
- With an anticipated rise in marine shipping traffic to service natural resource industries in and around the Bay, the risk of point source pollution (e.g., oil spills) will increase. Current understanding of sea-ice processes and their interactions with oil is poorly understood.

### Wildlife trends:

- Mercury concentrations in ringed seals from Inukjuaq and southern Hudson Bay polar bears are lowest across the Canadian Arctic with respect to each species. Significant declines in mercury have also been observed for ringed seals and (western Hudson Bay) female beluga up to the mid-2000s. However, increases in mercury have been reported from Arctic char in western Hudson Bay up to 2007-2008, as well as for thick-billed murre eggs from Coats Island (up to 2009). Mercury levels have remained stable for polar bear subpopulations.
- Hudson Bay ringed seals have the lowest measured legacy POPs concentrations across the Arctic. Furthermore POPs levels have significantly decreased in thick-billed murre eggs (*p,p'*-DDE, hexachlorobenzene, dieldrin and  $\Sigma$ PCBs) ringed seals ( $\Sigma$ PCBs,  $\Sigma$ CBz,  $\Sigma$ HCH,  $\Sigma$ CHL and  $\Sigma$ DDT) and polar bear subpopulations ( $\Sigma$ HCH,  $\Sigma$ DDT,  $\Sigma$ PCB,  $\Sigma$ CHL, dieldrin,  $\Sigma$ PBDE and PFOS) in Hudson Bay. However, increasing trends of  $\Sigma$ PFCA, one of the newer, emerging contaminants, have been observed for polar bears in the region. There is currently no information on microplastics data in Canadian Arctic wildlife.
- Concentrations of POPs tend to be relatively high in benthic invertebrates and fish, or species dependent on a benthic diet.

**Climate change:**

- Reduced sea-ice coverage may enable increased losses of mercury and volatile POPs from the ocean to the atmosphere. However, more precipitation may not only facilitate a portion of atmospheric contaminants returning to the ocean, but also increase terrestrial runoff, including wetlands where methylmercury is produced.
- Changes in the food web have the potential to affect contaminant exposure to top predator species.
- Cumulative stresses, such as habitat loss, dietary changes and/or poor body condition, may compound toxicological impacts of contaminants to marine mammals.

**Recommendations**

Much progress has been made to advance the knowledge of contaminants in Hudson Bay and the Canadian Arctic, yet gaps exist in some areas. Listed below are recommended topics of research and calls to action as addressed within this chapter and in other sources.

**Knowledge gaps:**

- Continue environmental monitoring programs to address chemicals from local (e.g., industrial activities, tourism, Arctic communities) and long-range sources (AMAP 2017b). Microplastics pollution requires further study in the Arctic.
- Indigenous communities in the Hudson Bay region lack contaminant exposure data. This is a key knowledge piece in determining the risks of health effects posed by contaminants such as mercury and persistent organic pollutants. It is strongly advised that monitoring studies be developed (or continued) to evaluate human health of Indigenous communities of Hudson Bay and all of the Arctic.
- Research toxicity effects of mercury and POPs accumulation in Arctic marine mammals, where data is limited (Letcher et al. 2010; NCP 2012, 2013; Scheuhammer et al. 2015; Environment and Climate Change Canada 2016).
- Develop/continue long-term monitoring programs for persistent organic pollutants (POPs) to support temporal trend analysis for fish species in Hudson Bay, of which current data is limited.
- Investigate the biogeochemical cycle of mercury in association to climate change scenarios. The difficulty in predicting the fate of mercury lies within the limited knowledge of its behaviour in all environmental compartments, particularly for Hudson Bay (AMAP 2016; Environment and Climate Change Canada 2016).

**Calls to action:**

- Develop regional action plans which will communicate the risks of local pollutants (AMAP 2017b). For example, some pollutants such as microplastics fall outside of global regulatory frameworks. Although Canada has made progress by committing to prohibit the manufacture or import of health products containing microbeads (a form of microplastics) by July 1, 2018 (Canada Gazette 2017), Arctic communities can take a stand to prevent other sources of microplastics (i.e., using less plastic products, banning plastic bags, developing waste management systems to include recycling and/or preventing plastics to escape landfills).
- Encourage participation of Indigenous representatives in international conventions/conferences on climate change and contaminants.
- The engagement of Indigenous partners in projects throughout all project steps (planning to knowledge mobilisation) is encouraged to enhance and complement project outcomes such as knowledge generation and communication strategies. Elders, community-based monitors, hunters, and Traditional Knowledge-holders can channel relevant feedback towards future directions of research. Community-driven approaches and accessible, online tools, such as those provided by the Arctic Eider Society's SIKU.org project, can help facilitate meaningful community engagement. Regional Contaminants Committees, which act as northern representatives of NCP, can also provide advice to contaminants researchers on community issues and engagement (contact information here: [http://www.science.gc.ca/eic/site/063.nsf/eng/h\\_0842AF3B.html](http://www.science.gc.ca/eic/site/063.nsf/eng/h_0842AF3B.html)).

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### III.ii

# Transportation and Community Use of the Marine Environment

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## Summary

**M**aritime activities within the Greater Hudson Bay Marine Region provide a lifeline to northern communities, support mining operations, facilitate the transportation of resources to global markets, support a small commercial fishery and include a small tourism industry. The seasonal ice cover restricts a vast majority of the maritime activity to the open water season that typically runs from July to late-October, however significant trends towards earlier breakup and later freeze-up are prolonging the season and increasing maritime activity into the shoulder months of June, November and even December. Along with this increase in the length of the open water shipping season, winter shipping through the ice has begun to happen regularly within the Region as a few mine sites are visited by polar class vessels capable of operating independently within the ice cover. Overall there has been a considerable increase in vessel activity since 1990 within the Region, with a large jump occurring between 2006 and 2007. Vessel traffic has increased and is projected to continue doing so as both the population and industrial activity continue to increase within the Region. At present there are 4 active mine sites within the Region, though there are up to 89 proposed mines, of which a majority would rely on marine transportation to some extent. While this brings jobs and investment into the Region, it increases the risk of potential accidents and spills while also increasing the potential impact of ship noise, ship-source pollution, and ship-strikes on marine mammals within the Region.

Communities around the region rely on the annual summer sea-lift to re-supply them with fuel, construction materials, vehicles, non-perishable items and other goods at a fraction of the price compared to air transport. With an increasingly long open water season there is the possibility for increased access for sea-lift vessels. One of the issues surrounding community sea-lift operations is the varying degree of infrastructure and support available at each community for the physical transfer of goods from the vessels to the shore and then distribution within the community. Generally there is very little marine infrastructure available in the region, though communities in Nunavik have received considerable investment from the Quebec government to build breakwaters, boat ramps and areas to stage cargo in each community.

Outside of the open water season, communities rely on the landfast sea ice for travel and use the icescape as an extension of their hunting grounds. With changes to the ice cover and increasingly frequent extreme weather events, travel on the landfast sea ice has become increasingly dangerous. Furthermore the emergency response capacity (via the Coast Guard and Canadian Forces) may be insufficient to meet current and projected needs in the Arctic. This will result in significant risks for travellers, vessel operators, rescue personnel, and the environment throughout the Greater Hudson Bay Marine Region.

## Key Messages

- Maritime activity within the Greater Hudson Bay Marine Region is greatest during the summer open water season when vessels need not contend with sea ice. As the open water season has increased in duration, the open water shipping season that historically occurred between August and October, has now spread into the shoulder months and extended to now run from June to November.
- Maritime activity within the Greater Hudson Bay Marine Region is comprised of a mix of vessels exporting grain from the Port of Churchill, re-supplying communities within the region, re-supplying and transporting ore from industrial mine sites, and partaking in research or tourism activity in the Region. Vessels range in size from Panamax bulk carriers down to yachts and fishing boats used by community members within the Region.
- Historically there has been no winter shipping activity within the Greater Hudson Bay Marine Region, however during recent years there have been a few winter sailings to Deception Bay along Hudson Strait to transport ore from the Raglan and Nunavik Nickel mines. There is ongoing discussion of winter shipments to and from the Mary River mine on Baffin Island, either through the port in Milne Inlet or the proposed port in Steensby Inlet that would lead ships through Hudson Strait and Foxe Basin, however at this point there is no imminent start of winter shipping to Mary River.
- At present there are 4 operational mines within the Greater Hudson Bay Region (Mary River, Meadowbank, Raglan, Nunavik), however in northern Quebec there have been 40 proposed mines, and in Nunavut, there are 24 mines in an advanced stage of exploration and 25 more in an early stage of exploration or prospecting. A majority of these proposed mine sites would rely on marine transportation for re-supply and the transportation of ore. Collectively the mining industry represents a significant opportunity for the area surrounding the Region, however the impact of increased shipping on the local wildlife and environment must be considered when developing these proposed sites, especially as winter shipping becomes a reality within the region.
- The level of marine infrastructure within each community varies considerably within the Region and impacts community access to the marine environment and the safety and efficiency with which re-supply to the

community can be conducted. Under the Nunavik Marine Infrastructure program, the communities of Nunavik have all received improvements to their marine infrastructure in the form of breakwaters, stabilized beaches, wharves or boat ramps. Outside of Nunavik the level of marine infrastructure is variable, and as a result re-supply vessels are capable of operating independently with limited infrastructural support. Improving basic infrastructure within communities would enhance the efficiency and safety of the annual summer sealift and is something that the federal government has proposed to improve through their Oceans Protection Plan.

- Increasing risks in the marine environment during the open water shipping season include storm surges, poorly predicted tides, and increased extreme wind events. These may cause significant delays and additional risk to re-supply and fuel-transfer operations. During winter shipping activity, ridged and compressed ice represent hazardous conditions even for Polar Class rated vessels that operate independently within the ice cover during winter.
- As marine access increases throughout Hudson Bay the risks that shipping poses to the environment, wildlife and people of Hudson Bay also increase. Concerns related to the disturbance of marine mammals and increased risk of fuel/oil spills have been raised and will need to be acted upon further as shipping is projected to continue to increase within the Region. Issues with bathymetric information, coastal infrastructure, search and rescue capacity and disaster response must be considered and worked into the broader national Low Impact Shipping Corridors Initiative (previously the Northern Marine Transportation Corridors Initiative).

## 1. Introduction

As climate change continues to drive trends towards warmer temperatures and reduced ice cover throughout the Arctic there has been a lot of attention given to the potential increase in accessibility of northern sea routes and known northern resources. While the fabled Northwest Passage draws a lot of this attention, it remains a risky place for marine activity due to variable ice cover, a lack of navigational aids, and an overall dearth of response capacity, that collectively lead to high insurance premiums for vessels operating in the area. In terms of the effect of climate change on maritime activity within



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Canada's North the greatest change may not be realized along the Northwest Passage but further south within the Greater Hudson Bay Marine Region, where an existing transportation network may have the opportunity to expand its operations and better serve Arctic communities and industries.

In this chapter we focus on marine transportation within the Greater Hudson Bay Marine Region and discuss how documented climatic changes will affect both community- and industry-related maritime activities around the Region. The seasonal sea ice cover of the Region provides the biggest impediment to maritime activities, but the ice cover is very susceptible to small fluctuations in temperature and an overall warming trend across the Region has affected the seasonality and physical nature of the ice pack (see physical environment section for further details). As a result, the open water season has grown significantly longer (Hochheim and Barber 2014; Andrews et al. 2018) and in turn maritime activity has already increased. Both of these trends are expected to persist into the future and represent two important facets of the Region

moving forward. Yet with opportunities presented by a longer ice-free shipping season there are also risks posed by maritime activity to the natural environment, wildlife and northern communities that need to be considered.

The chapter begins with a review of shipping activities and their associated regulations within the Greater Hudson Bay Marine Region. We then move on to discuss the five major facets of marine transportation within the Region; i) The Port of Churchill, ii) community re-supply, iii) industrial shipping, iv) pleasure craft and cruise ships, and v) community based marine access. We then look at the past, present and projected changes of environmental variables that influence shipping activities and the safety with which they can be conducted. Ultimately this leads to a discussion of the opportunities for marine transportation under a changing climate and the potential risks posed by increased maritime activity within the Greater Hudson Bay Marine Region. Finally, we conclude with suggestions and recommendations for future work related to maritime activities within the Region.

## 2. Marine transportation within the Greater Hudson Bay Marine Region

Activities related to marine transportation within the Greater Hudson Bay Marine Region are as diverse as the needs of the stakeholders that they service. To list only a few: maritime activities provide a lifeline to the 33 northern Indigenous communities through the annual summer sealift, they provide supplies to the four presently operating mine sites and facilitate the transportation of resources to global markets from these four mines and the Port of Churchill. Additionally, maritime activities support an eco-tourism industry and fishery throughout the Region, and during the winter the maritime environment provides access to winter sea ice routes and hunting grounds.

The seasonal ice cover within the Region provides a very clear distinction between maritime activities that take place during the ice-free open water period and those that contend with, or even rely on the winter ice pack. The ice-free shipping season has historically existed from late July to late October and permitted non-ice strengthened bulk carriers, eco-tourism ships and re-supply vessels to operate within the Region for up to 11 weeks without the threat of sea ice. Conversely, during winter the landfast sea ice that forms around the coastal areas of the Region fosters local travel routes that are vital for hunting activities. Meanwhile the offshore mobile ice pack necessitates the use of icebreakers for access outside of the open water season to the mine sites and their associated port facilities.

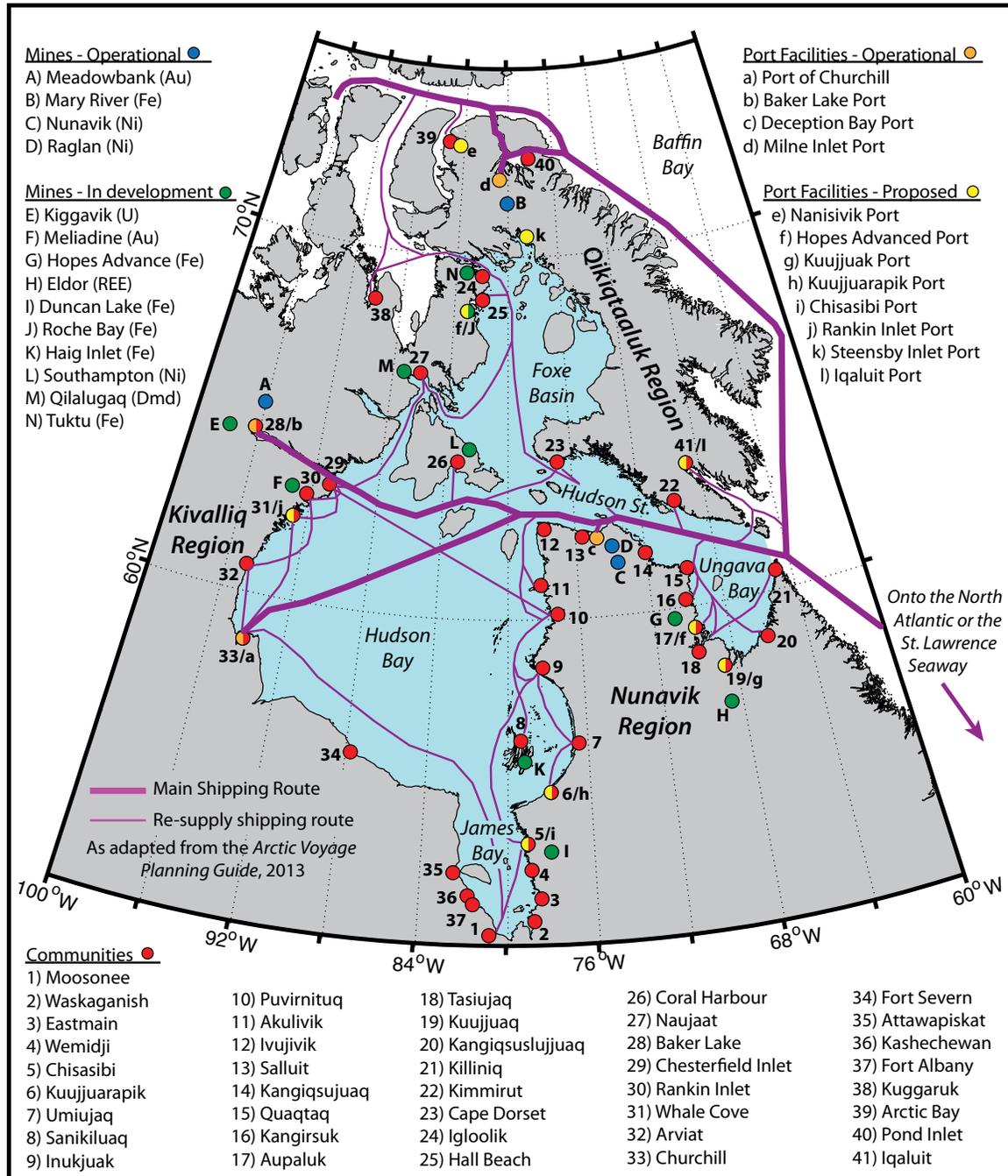
Shipping within the Greater Hudson Bay Marine Region begins and ends at the mouth of Hudson Strait, between the southeast corner of Baffin Island and Cape Chidley, Labrador (Figure 1). Beyond the mouth of Hudson Strait is the Labrador Sea and North Atlantic Ocean, which connects the Region to ports within southern Canada (i.e., Montreal), and global markets for the materials produced at mines within the Region and exported through the Port of Churchill (Figure 1). In terms of shipping, the greatest concentration of vessels has always been located in Hudson Strait which acts as the gateway to the Region. Historically the shipping route then split into two primary corridors that cross Hudson Bay towards the Port of Churchill and Baker Lake via Chesterfield Inlet (Figure 1). The routes and concentration of vessels along those routes is highly dependent on the demand for marine access and are therefore continuously evolving.

Historically the Churchill route was used to export grain to markets in Central and South America, Europe and Africa, however since the closure of the Port in 2015 no grain shipments have gone through the Port. The route to Chesterfield Inlet reflects the open water season re-supply of fuel, bulk materials and heavy equipment to the MeadowBank Gold

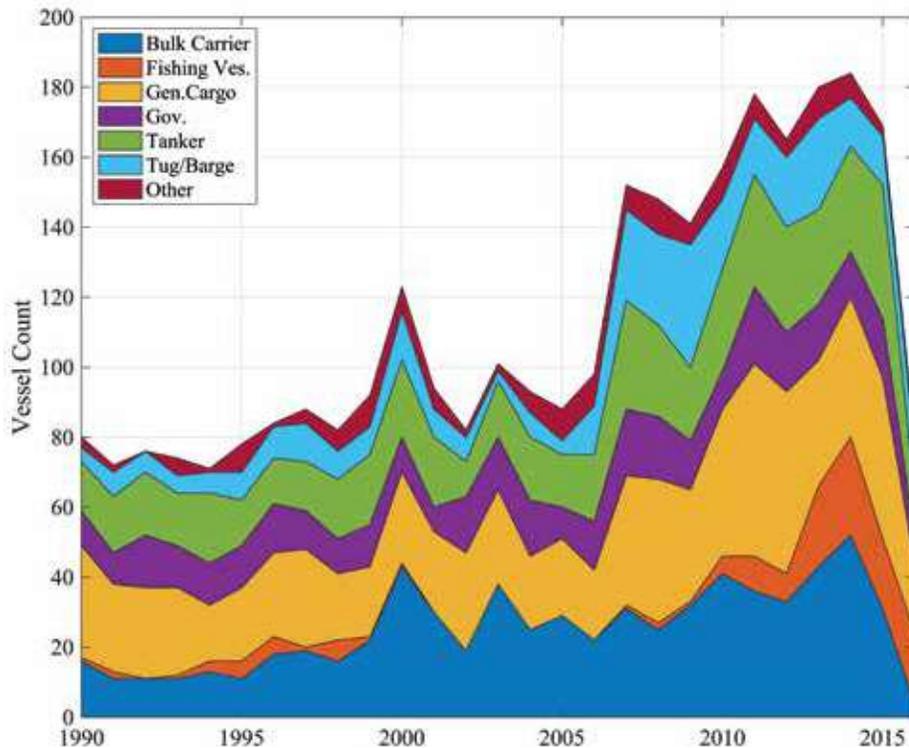
Mine near Baker Lake at the end of the Inlet. The route to Chesterfield Inlet highlights the impact that a single mine can have on vessel traffic within the Region, even a mine that only uses marine transportation for re-supply and transports processed materials via air. The smaller arterial routes reflect the annual summer sealift that re-supplies northern communities and developing mine sites with building materials, vehicles, fuel and non-perishable goods. Re-supply represents a vital lifeline for remote northern communities along the shores in the Kivalliq, Qikiqtaaluk and Nunavik regions. Beyond marine access Mosonoochee, Ontario and Churchill, Manitoba are accessible by rail. In terms of road access, only the communities of Eastern James Bay are accessible by an all-season road. Due to the extremely limited road and rail access to communities within the Region the annual summer sealift is integral to the affordable and reliable delivery of goods and materials to communities and mine sites throughout the Region.

### **Vessel traffic**

Previously there was very limited data available on vessel traffic within the Canadian Arctic. Since 1990 maritime vessels operating within the NORDREG Zone, which encompasses all Canadian waters north of 60°N and all of Hudson, James and Ungava Bays, have been requested to submit daily position reports to the Canadian Coast Guard (Pizzolato et al. 2014). In 2010 it became mandatory for vessels over 300 tonnes (e.g., re-supply vessels, bulk carriers and cruise ships), vessels towing or pushing another vessel with a combined gross tonnage of over 500 tonnes, or vessels carrying a pollutant or dangerous good to submit position reports. However, prior to 2010 it has been suggested that 98% of vessels submitted position reports to the Coast Guard when operating within the NORDREG Zone (Rompkey and Cochrane 2008; Pizzolato et al. 2014). In collaboration with the Canadian Coast Guard, Dr. Jackie Dawson's research group at the University of Ottawa has worked for several years now to quality control the NORDREG data and classify each vessel type (Pizzolato et al. 2014; 2016; Dawson et al. 2017; 2018). The dataset currently provides the most reliable information on vessel traffic within the Canadian Arctic. In terms of the Greater Hudson Bay Marine Region, it is clear that vessel traffic has increased during recent years (Figure 2). From 1990 to 1995 the average annual vessel count was 75, whereas between 2010 and 2015 the average annual vessel count was 172. The greatest shift in the vessel count occurred between 2006 and 2007. Prior to 2007 the average vessel count was 87, with a peak of 123 in 2000 that was associated with a peak in grain exports through the Port of Churchill (Hudson Bay Route Association) and the associated peak of 43 bulk carriers. Following 2007 the mean vessel count rose to 164, with a peak of 184 in 2014. Considering that the Port of Churchill was shut down during the



**FIGURE 1.** The Greater Hudson Bay Marine Region (blue shading), with communities (red), mine sites (both operational (blue) and proposed (green)), ports (both operational (orange) and proposed (yellow)) and shipping routes (purple tracks) presented. Mines and Ports were derived from Gavrilchuk and Lesage (2014), while the shipping routes were adapted from the Arctic Voyage Planning Guide, (2013) and reflect vessel traffic during 2010. Half filled circles denote two features at the location. Mined resources are provided for each mine (Au – Gold, Fe – Iron, Ni – Nickel, U – Uranium, REE – Rare Earth Elements, Dmd – Diamonds).



**FIGURE 2.** Plot of the annual vessel count for each vessel type within the Hudson Bay region from 1990 to 2016. Data from J. Dawson.

2016 and 2017 shipping season, it is likely that the total vessel count declined by up to 20 vessels during these two years.

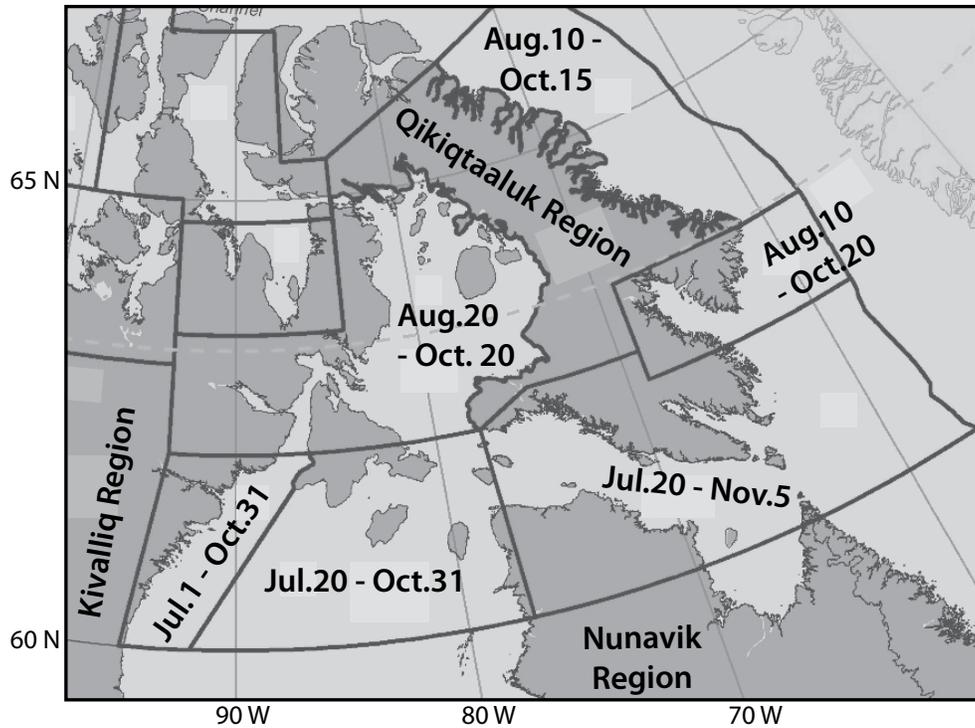
Breaking down the total vessel count into vessel types we can see that bulk carriers are the most common vessel type operating within the Region. Furthermore, bulk carriers in combination with general cargo and tankers consistently comprise a majority of the marine vessel activity. Meanwhile, passenger and fishing vessels consistently have the lowest vessel counts. Each vessel type displays considerable inter-annual variability, though bulk carriers and general cargo have greater variability due to variable demands of mines and the Port of Churchill. Between 1990 and 2015 the presence of government vessels and icebreakers, and passenger ships have remained relatively steady, whereas bulk carriers, general cargo, tanker ships, and tug/barge vessels show notable increases, specifically between 2006 and 2007.

**Seasonality of vessel traffic**

Due to the seasonal sea ice cover that forms annually within the Greater Hudson Bay Marine Region (for more details on sea ice see Theme I. Chapter ii.) and the danger that it poses to ships, Transport Canada regulates the shipping season by vessel type through the *Arctic Waters Pollution Prevention (AWPP) Act*.

Depending on the age and operational plan of vessels operating within the Region, they must comply with the AWPP Zone/Date system, the more recent Arctic Ice Regime Shipping System (AIRSS), or the Polar Operational Limitations Assessment Risk Indexing System (POLARIS) which applies to vessels built after January 1, 2017 – the international entry-into force date of the Polar Code (Stoddard et al. 2016).

The Zone/Date system dictates when vessels may operate within any one of the 16 “Shipping Control Zones” in the Canadian Arctic according to their ice classification (Figure 3, Table 1). These dates were determined from historic ice conditions prior to the AWPP implementation in 1970. They reflect the seasonality and type of sea ice in each zone and vary according to the size, type and ice classification of different vessels (Transport Canada 2010). Specific to the Greater Hudson Bay Marine Region, non-ice-strengthened vessels may operate in Hudson Strait between July 20<sup>th</sup> and November 5<sup>th</sup>, Northwestern Hudson Bay between July 1<sup>st</sup> and October 31<sup>st</sup>, Northern Hudson Bay between July 20<sup>th</sup> and October 31<sup>st</sup>, and Foxe Basin between August 20<sup>th</sup> and October 20<sup>th</sup> (Figure 3). If a vessel is ice strengthened these dates expand (earlier spring, later fall) and if the vessel is an icebreaker these dates expand further to reflect the vessel’s capabilities (Table 1). Note



**FIGURE 3.** The Shipping Control Zones of the Greater Hudson Bay Marine Region and the corresponding access dates for non-ice strengthened ships as defined by the Zone/Date system. Modified from *Minister of Justice* (1985).

that there is no Shipping Control Zone for southern Hudson Bay (< 60°N), though access to this region is limited by transit through the Zones covering Hudson Strait and Northern Hudson Bay (Figure 3).

While the Zone/Date system does provide a general idea of the potential shipping season in an area, the dates are fixed and inflexible to long-term trends or inter-annual variability in sea ice conditions (Transport Canada 2010). Therefore AIRSS was developed as a flexible framework for shipping activities taking place outside of the Zone/Date system (Transport Canada 2010). AIRSS uses a metric to determine if the ice capabilities of a vessel (Table 1) will allow it to safely operate in a given ice cover. In terms of the vessel, AIRSS considers the strength, displacement and power, whereas in terms of the ice cover it considers the ice concentration, thickness, age, roughness and state of decay. Ultimately the AIRSS system determines if a vessel can handle the ice regime along its intended route. If the outcome is positive the ship may proceed, otherwise it must select another route, wait for weather conditions or the ice state to change, request an icebreaker escort, or turn back.

Expanding on the Canadian example of AIRSS, the International Maritime Organization has implemented POLARIS as part of their Polar Code. A major difference between AIRSS

**TABLE 1.** The Canadian Arctic Ice Regime Shipping System (AIRSS) maximum allowable ice type and ice thickness for vessel categories within the Canadian classification system (From Transport Canada 2010).

Vessel Class	Maximum allowable ice type	Ice thickness (cm)
CAC1	No Limit	No Limit
CAC2	Multiyear	No Limit
CAC3	Second year	No Limit
CAC4	Thick first year	>120
Type A	Medium first year	70-120
Type B	Thin first year (stage 1)	50-70
Type C	Thin first year (stage 2)	30-50
Type D	Grey-white	15-30
Type E	Open water/Grey	10-15
Non-Ice Strengthened	Open water	-

and POLARIS is that the latter allows for the consideration of limited speed/escort operations, as well as the seasonal decay of sea ice in terms of ice strength (Stoddard et al. 2016). The inclusion of limited ship speed as a factor in the go/no-go

metric of POLARIS was a result of feedback from operators in the Arctic who found they could navigate an ice cover under reduced speed and due caution (Stoddard et al. 2016). As mentioned, POLARIS only applies to vessels built after January 1<sup>st</sup> 2017, so it will not immediately impact the typically older vessels that presently operate within the Greater Hudson Bay Marine Region. However, as maritime activity increases within the Region and newer vessels, specifically ice strengthened or icebreaker bulk carriers, begin to operate within the area, POLARIS will have a greater impact on maritime traffic within the Region.

As a result of these regulations and the sea ice conditions that dictate them, shipping activity within the Greater Hudson Bay Marine Region has historically been limited to the open water season when vessels do not need to contend with the risk of sea ice (Figure 4). During the early 1990s vessels were only active within the Bay from July to October, with the greatest activity occurring during August and September. However, as the open water season has increased in duration (see Theme I. Chapter ii.) so too has the shipping season. A noticeable change occurred in 1995, when the shipping season expanded to include June, November and December (Figure 4). While shipping during December has only occurred

intermittently since 1995, shipping activity during June and November has persisted and increased significantly at 2.5 and 6.9 vessels per decade, respectively. In fact, monthly vessel counts have significantly increased each month from June to November, with a peak rate of 13.6 vessels per decade during October. Vessel counts in October have increased from only 6 in 1990 to 47 in 2013. Overall vessel counts have significantly increased throughout the Region, due in part to increased summer shipping, but more importantly due to the expansion of the shipping season into the shoulder months of June, October and November. Significant trends towards earlier breakup of the spring ice cover and delayed freeze-up are lengthening the open water season within the region (see Theme I. Chapter ii.) and fostering this expansion of the shipping season.

Outside of the open water shipping season, vessels of a sufficient Polar Class (Table 2), or ice strengthened vessels escorted by an icebreaker (typically provided by the Canadian Coast Guard) may operate within the ice cover. However the added cost associated with winter shipping has proven to be prohibitively expensive for grain shipments through the Port of Churchill and for community re-supply (Andrews et al. 2016). Hence winter shipping has historically been very uncommon

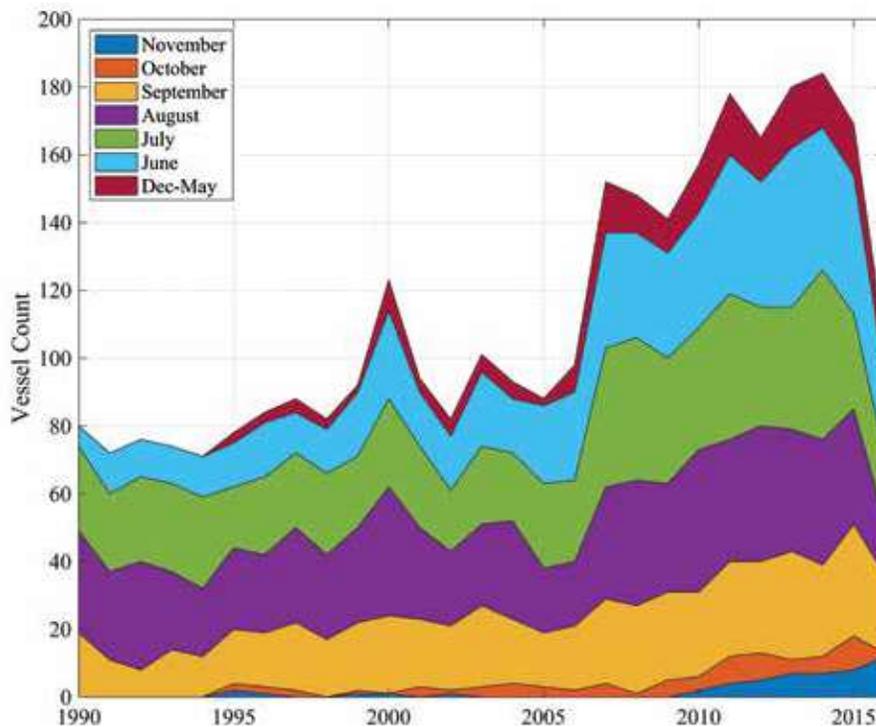


FIGURE 4. Monthly vessel counts in the Greater Hudson Bay Marine Region for the period from 1990 to 2016.

**TABLE 2.** Types of ice that each Polar Class of vessel can navigate in (From Transport Canada 2010).

Polar Class	Ice Description
PC1	Year-round operation in all Polar Waters
PC2	Year-round operation in moderate multiyear ice conditions
PC3	Year-round operations in second year ice, which may include multiyear ice inclusions
PC4	Year-round operation in thick first year ice, which may include old ice inclusions
PC5	Year-round operation in medium first year ice, which may include old ice inclusions
PC6	Summer/autumn operation in medium first year ice which may include old ice inclusions
PC7	Summer/autumn operation in thin first year sea ice, which may include old ice inclusions

within the Greater Hudson Bay Marine Region. However, within the mining industry there has been growing demand for year round access to mines. Historically mines have stockpiled ore during winter and shipped it out during the subsequent open water season, but this limits the volume of ore that can be exported from a mine and thus limits the mine's profitability. Beginning in 2005 the Raglan Nickel Mine in northern Quebec has used a Polar Class 4 bulk carrier to transport two loads of iron ore from Deception Bay to the port of Quebec each winter, and more recently the Nunavik Nickel Mine has also used a Polar Class 4 bulk carrier to transport ore to northern Finland during winter (Gavrilchuk and Lesage 2014). This activity is reflected in the monthly shipping traffic data presented in Figure 4. At this point in time all winter shipping within the Greater Hudson Bay Marine Region has been done by the Canadian company Fednav, which operates two Polar Class 4 ice breakers (Table 2: can operate year round in thick first year sea ice, which may include old ice inclusions), the *Arctic* and *Nunavik*, and the *Umiak*, which is an ICE-15 rated icebreaker (Comparable to Polar Class 3; Table 2). The *Arctic* and *Nunavik* are capable of breaking thick first year sea ice with old ice inclusions, while the *Umiak* is capable of breaking 1.5m thick sea ice. The Raglan and Nunavik Nickel mines highlight the potential for winter shipping within the Region and have lead to other mines (i.e., Mary River) proposing to ship year round from the Canadian Arctic. However it must be restated that the cost and risk associated with winter shipping are considerably greater than during the open water season. Therefore, it comes down to a question of desire and economic feasibility, which is predominantly dictated by insurance costs, that will dictate the future of winter shipping within the Region.



**FIGURE 5.** The Port of Churchill's wharf and shipping berths.

### 2.1. The Port of Churchill

The Port of Churchill is an international port located on the southwest coast of Hudson Bay in Churchill, Manitoba (Figure 1). The Port was built during the 1920's and opened in 1931 following the completion of the Hudson Bay rail line from The Pas to Churchill. Historically Churchill was accessible by ship, rail and air, making it a unique cog of the North American transportation system. The original objective of the Port was to connect the grain-growing provinces of western Canada to world markets and to provide a strategic Canadian claim to the Arctic. The Port and associated railway were owned and operated by the government of Canada from 1931 to 1997 when they were sold to the American company OmniTRAX. Following the sale the Hudson Bay Port Company, a subsidiary of OmniTRAX, operated the Port with continued federal and provincial financial support. During the last decade there has been talk amongst the Port of Churchill's stakeholders about developing the Port into a central player in the trade industries of the Arctic and central Canada (Meredith and Norquay 2013). However, this vision has been slow to materialize and in December 2015, omniTRAX closed the Port and put it and the Hudson Bay Railway up for sale (Winnipeg Free Press 2015). The Port remained closed during the 2016, 2017 and 2018 summer shipping seasons, while the railway continued to service communities in northern Manitoba, including Churchill, until spring 2017 when significant damage to the line during spring flooding caused the line to be closed. As a result of the closure of the Port, there is a clear drop off in shipping activity within the Region during 2016 (Figure 2). Specifically bulk carriers, tankers, general cargo and other types of vessels. Following years of speculation and debate about the future of the Port of Churchill and Hudson Bay railway, it was announced on August 31<sup>st</sup> 2018 that both assets had been sold and repairs

would begin immediately on the damaged rail line (CBC 2018a). Both assets were purchased by Arctic Gateway Group Limited Partnership, which is a private-public partnership that includes Misinippi Rail Limited Partnership from northern Manitoba, Fairfax Financial Holdings from Toronto, and AGT Limited Partnership from Saskatchewan (CBC 2018a).

Regardless of its current ownership situation, the Port of Churchill remains the largest infrastructure within the Greater Hudson Bay Marine Region, and therefore remains worth including within this work. The Port has four loading berths that can each handle Panamax sized vessels (Length: ~290 m, Beam: ~32 m, Draft ~12 m) for the loading of grain, bulk commodities, general cargo and tanker vessels (Figure 5). Historically the Port's primary freight has always been grain. During its first year of operation 14,849 tonnes were handled, while more recently (1997-2014) an average of 500,000 tonnes per year were handled (Hudson Bay Route Association). The peak tonnage to pass through the Port in a single year was 775,024 tonnes in 1976 (Hudson Bay Route Association). The Port typically operated for 11 weeks during the open water season from early August to late October and generally utilized non-ice strengthened bulk carriers (Andrews et al., 2016). In rare instances ice strengthened bulk carriers have been used to extend the shipping season into November, but with already thin profit margins there was little desire for the added expense of hiring ice strengthened vessels (Andrews et al. 2016). In the early 2000s the Port of Churchill was part of the proposed "Arctic Bridge" that would have connected the grain growing regions of central North America to European markets via the North Atlantic and port in Murmansk, Russia (CentrePort Canada 2012). The Port of Churchill had previously exported grain to Russia and in 2002 the Premier of Manitoba signed a letter of intent to further develop the Arctic Bridge Manitoba Government 2002. However, following this, grain was only shipped from Churchill to Russia three times and has not been shipped since 2008. In 2007 Churchill did receive one shipment of fertilizer from Murmansk, but this was a one-off shipment (Pryce 2016). Historically, the Port of Churchill received external assistance in attracting grain shipments, whether this was through the Canadian Wheat Board (CWB) diverting grain to the Port or the Churchill Port Utilization Program that provided a subsidy to grain passing through the Port following the dismantling of the CWB in 2012 (Andrews et al. 2016). The Churchill Port Utilization Program provided a \$9/tonne subsidy to grain shipments passing through the Port (Meredith and Norquay 2013; Andrews et al. 2016) and while the subsidy was set to end in 2017 the Port was closed following the 2015 shipping season. At this point there is no subsidy program in place should the Port re-open, though it is likely that this will be involved in discussions surrounding the future of the Port.

Beyond the extensive grain shipments, a small amount of re-supply cargo (fuel, building materials, vehicles and non-perishable food items) typically passed through the Port as part of the summer sealift to communities within Kivalliq. In this sense the Port of Churchill was used to reload the re-supply vessels that were in turn able to return to the communities of Kivalliq without returning to Montreal to reload. This is an effort that can potentially be expanded in the future to improve the efficiency of re-supply within the Region.

## 2.2. Community re-supply

Every summer during the open water period, remote northern communities throughout the Canadian Arctic are re-supplied with goods and materials from southern Canada through the annual summer sea-lift. The sea-lift provides a vital lifeline to these communities as it re-supplies them with fuel, construction material, vehicles, non-perishable items and other goods at a fraction of the price compared to air transport. A 2005 review of the sea-lift program for the Government of Nunavut found that it was between 8 and 11 times cheaper to transport goods and materials by sea than by air (Government of Nunavut 2005). As of 2016 there are close to 30,000 people living within the communities of the Greater Hudson Bay Marine Region, all of these people rely to some extent on sea-lift services (Nunavut Bureau of Statistics 2016; Nunivaat – Nunavik Statistics Program; Stats Canada 2017).

Beginning in 1959 the Canadian Coast Guard, on behalf of the Federal Government, took over the organizational responsibility of sea-lift operations in the Canadian Arctic and oversaw the awarding of re-supply contracts to private shipping companies (Transportation Plan of Nord-du-Quebec 2002; Pelletier and Guy 2014). In 1979 the Government of Quebec took over organizational responsibility of sea-lift to Nunavik (Transportation Plan of Nord-du-Quebec 2002), and in 2001, two years after its separation from the Northwest Territories, the Government of Nunavut took over organizational responsibility of sea-lift to its communities (Pelletier and Guy 2014). At present there are four shipping companies that provide re-supply to communities in the Canadian Arctic.

1. **Nunavut Sealink and Supply Inc. (NSSI)** – NSSI is a Nunavut based company that is owned through a partnership with Arctic Co-operatives Ltd., Desgagnes Transarctik Inc., Qikiqtaaluk Corporation, Sakku Investment Corporation (owned by the Kivalliq Inuit Association) and Kitikmeot Corporation. A majority of the company is Inuit owned, although Desgagnes Transarctik Inc. is the managing partner. NSSI operates a fleet of seven ice-strengthened vessels (*Rosaire A. Desgagnes, Acadia Desgagnes, Camilla Desgagnes, Claude A. Desgagnes, Sedna*

*Desgagnes, Zelada Desgagnes and the Taïga Desgagnes* that are based out of the Montreal region and service the Kivalliq, Nunavik, Qikitaaluk and Kitikmeot regions of the Canadian Arctic, along with communities in Quebec, Newfoundland and Labrador.

2. **Nunavut/Nunavik Eastern Arctic Shipping Inc. (NEAS)** – NEAS was established in 1998 and is based out of Iqaluit. A majority of NEAS shares are owned by Inuit groups such as the Makivik Corporation, the Inuit Birthright Corporation and Transport Nanuk Inc. (a joint venture between the North West Company and Logistec Corporation). NEAS operates a fleet of seven ice-strengthened vessels (*Mitiq, Umiavut, Avataq, Qamutik, Erasmusgracht, Nunalik and Dolfijngracht*) out of Valleyfield, Quebec that service the Kivalliq, Nunavik, Qikiqtaaluk and Kitikmeot regions.
3. **Northern Transportation Company Ltd. (NTCL)** – Based out of Hay River, NWT and formerly owned and operated by the Inuvialuit Regional Corporation, NTCL declared bankruptcy in December 2016 and was sold to the Government of the Northwest Territories (Government

of Northwest Territories 2016; CBC 2017). NTCL services communities along the Mackenzie River, within the Inuvialuit Settlement Region and within the Kitikmeot region to as far east as Cambridge Bay. Because the Mackenzie River is quite shallow, NTCL relies on a series of tugs and barges instead of larger ice-strengthened vessels like NSSI and NEAS.

4. **Moosonee Transportation Limited (MTL)** – Based out of Moosonee, Ontario in James Bay, MTL has used a tug (*The Nelson River*) and two barges to service coastal communities of James Bay (Attawapiskat, Kashechewan, Fort Albany, Waskaganish, Wemindji and Chisasibi) and southeastern Hudson Bay (Fort Severn, Winisk, Great Whale, Sanikiluaq, Umiujaq and Puvirnituk) since 1989. Distribution facilities are located in Moosonee, Wemindji and Chisasibi. While the latter two communities are accessible by road; Moosonee is only accessible by the Ontario Northland Railway, which connects the community to Cochrane Ontario and the North American transportation network.



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Re-supply vessels must operate self sufficiently with everything from cranes, barges and tractors for the transfer of goods, to mobile offices and flood lights for coordinating deliveries on the beach. The technical study “Overview Networks, Infrastructures, Operations and Management in Nord-du-Quebec” done as part of the Transportation Plan of Nord-du-Quebec in 2002 provides a nice overview of the re-supply process. Because vessels rarely stop at only one community per trip, the cargo must be packed in the reverse order of the sailing schedule so that they can be unloaded in each community as quickly and efficiently as possible. Re-supply vessels anchor at the designated mooring location for each community and begin by unloading the tugboat, barge and tractor that were all brought up north with the vessel. Once the tractor and other land based equipment are set up on the beach the tug will take the barge back to the vessel where it will be loaded with containers, pallets of fuel, crates of goods and other materials destined for the community. Once the barge is loaded the tug will return it to shore,

literally grounding it at the beach where ramps will be set up and the tractor will begin unloading the barge onto the beach. This process will continue until all of the goods destined for the community have been unloaded. Tides may cause a delay in the transfer process, or if inclement weather makes for unsafe conditions the process may also be stopped. Once the goods are onshore the shipping company, a local contractor, or representatives from the community may distribute them.

One of the issues surrounding community sea-lift operations is the varying degree of infrastructure and support for the physical transfer of goods from the vessels to the shore. Large tides, exposed beaches, narrow approaches, and potentially dangerous mooring locations all increase the difficulty and risk of carrying out the summer time re-supply. There is considerable regional variation in the marine infrastructure available to support both local and commercial marine access in each community. In Nunavik the \$88 million Nunavik Marine Infrastructure program began in 1998 with the objective of making access to the sea safe and easy for the local population

while also improving the safety of commercial operations (Transportation Plan of Nord-du-Quebec 2002). The 14 Inuit communities in Nunavik, which are not accessible by road, received new and/or improved marine infrastructures, such as breakwaters, concrete wharves, access ramps, storage areas and floating pontoons that were built according to the existing infrastructure, tidal range, beach stability, and the degree to which the beach was exposed to the open water. The first phase of the program focused on community access to the marine area, though commercial shipping did also utilize these additional infrastructures. The second phase has focused on improving facilities for re-supply operations in the communities with two sets of heavy equipment, including trucks, bulldozers, excavators and crushers, being moved from one community to another to complete access roads and storage areas and further stabilize beaches (Makivik website). Until the 1970's and 1980's, the eastern coastal communities of James Bay and parts of Hudson Bay (from south to north, Waskaganish, Eastmain, Wemindji, Chisasibi and Whapmagoostui) depended on seasonal barge traffic, usually from Moosonee in southern James Bay, for the shipping of construction materials and heavy equipment. With major developments occurring in and around James Bay, all season roads were developed in the 1990's and transformed the role of maritime transportation in this region. A limited amount of maritime transportation by barge still takes place, but the volumes transported have declined considerably.

Beyond Nunavik and Eastern James Bay, communities in Kivalliq and Qikiqtaaluk have historically received very little investment in marine infrastructure. This can make accessing the marine environment more difficult and slow down the re-supply process. However, provided that these communities rely on re-supply, the NSSI and NEAS have figured out how to conduct the re-supply with the existing infrastructure. To help improve this situation, in April 2018 the federal government launched the Safety Equipment and Basic Marine Infrastructure for Northern Communities initiative as part of the Ocean Protection Plan. The initiative will invest \$94.3 million to improve community marine infrastructure and safety equipment in remote northern communities within Northwest Territories and Nunavut (Transport Canada 2018). While the investment is not at the scale of building new ports or large marine infrastructures, it is on the scale of the Nunavik Marine Infrastructure program, which proved that small infrastructural improvements within remote communities can have a large and lasting impact in the safety and efficiency of marine access. The announcement specifically states "Investments in safety equipment and infrastructure across Nunavut and the Northwest Territories to ensure safer sealift and community supply" as one of the programs objectives. The program outlines the creation of Mooring bollards and anchors, cargo

laydown areas, breakwaters and sealift ramps within northern communities. Furthermore, the announcement repeatedly outlines the need to work closely with local communities on issues related to marine transportation, emergency response and environmental conditions related to shipping.

Beyond dry cargo goods that can be crated or packed into containers, there is the issue of safely transporting fuel from a tanker to shore. Once again the Transportation Plan of Nord-du-Quebec (2002) provides an overview. In most northern communities a floating pipeline is used to connect the tanker to a shore-based pipeline that transfers fuel to the community's tank farm. Once again, the tankers must be self-sufficient and launch their own workboat once the tanker has been anchored at the mooring site. The workboat is used to unroll the floating pipeline, which can be up to 1,900 m long, and run it to shore where it will connect with the shore based pipeline. Once the floating pipeline is connected it is flagged with buoys and pressurized with compressed air to check for leaks. Once the connections and pipeline have been inspected and verified to be in proper working order the fuel transfer may begin. Fuel is typically transferred at 70 to 80 m<sup>3</sup> per hour, but even under ideal conditions the transfer may still take approximately two days. The pipeline is inspected every 30 minutes, and constant attention is paid to the weather and tides that can disturb or displace the pipeline (Transportation Plan of Nord-du-Quebec 2002).

There is of course considerable risk involved with pumping fuel through floating pipelines for days at a time, especially during inclement weather, high winds and periods of low visibility. Recently, two spills occurred during fuel transfers within the Greater Hudson Bay Marine Region. On October 7<sup>th</sup>, 2015 high winds caused a leak in the floating pipeline during the annual fuel transfer in Salluit. Between 2,000 to 3,000 L of diesel were spilled into the local marine system, though the vessel quickly deployed booms to contain the spill and began the process of cleaning up the fuel (CBC 2015a). The Canadian Coast Guard vessel *Terry Fox* arrived the next day to inspect the spill and oversee the clean up (CBC 2015a). The other spill occurred near Rankin Inlet on the evening of July 14, 2016 500 L of gasoline were spilled when a local fishing boat hit the floating pipeline during the fuel transfer (CBC 2016). Once again the spill was contained with booms in a small cove near the town (CBC 2016). During both instances the community members were told to avoid the coastline until it was certain that the spilled fuel had been cleaned up.

The only community to not use a floating pipeline is Kuujuaq, which is re-fuelled by barges and tugs because the tanker mooring is located between 12 and 20 km away from the community (Transportation Plan of Nord-du-Quebec 2002). The two barges can each carry just over 200 m<sup>3</sup> of fuel with a

return trip from the tanker taking upwards of 6 hours under ideal conditions. As a result the fuel transfer process in Kuujuaq can extend beyond 20 days depending on weather conditions.

In terms of total re-supply volume, there was 450,000 and 500,000 m<sup>3</sup> of dry cargo shipped during 2014 and 2015, respectively by NEAS and NSSI to the communities within Kivalliq, Nunavik, Qikitaalik and Kitikmeot (Government of Nunavut 2014; 2015). Between one-quarter and one-third of this cargo was destined for mines, specifically Meadowbank, Mary River, Meliadine and those serviced through Deception Bay (Raglan and Nunavik), while a majority of the remaining cargo was destined for communities. Note that 100,000 m<sup>3</sup> of the cargo delivered during 2015 was destined for the new airport being built in Iqaluit, while part loads were delivered to Nanisivik for the future Canadian Naval base. In 2015 four NEAS and six NSSI vessels completed three return sailings each from the St. Lawrence seaway to northern destinations for a total number of 30 sea-lift related sailings. In 2014 NEAS chartered an additional vessel *Erasmusgracht* for a direct delivery to Iqaluit for a total of number of 31 sailings (Government of Nunavut 2015). Sailing schedules are available online from each company and provide updated arrival and departure dates for each community. During the 18 sailings conducted by NSSI during 2014, communities within the Greater Hudson Bay Marine Region were visited 103 times. Some communities received as many as eight to ten visits (e.g., Rankin Inlet, which in part reflects the development of the nearby Meliadine Gold Mine), while others received as few as one (e.g., Hall Beach). In total, NSSI vessels visited communities in western Hudson Bay 38 times between July 11<sup>th</sup> and October 28<sup>th</sup>, communities in eastern Hudson Bay 8 times between July 8<sup>th</sup> and October 16<sup>th</sup>, communities in Foxe Basin (including Nauyasat) 5 times between July 26 and October 13<sup>th</sup>, and communities in Hudson Strait 49 times between July 7<sup>th</sup> and October 29<sup>th</sup> (shipping schedules courtesy NSSI). According to NSSI staff, the company now begins shipping two weeks earlier during spring than it did in the past, though the fall timing has remained much the same (Andrews et al. 2016). Of course there remains a level of interannual variability with the timing of sea ice breakup that can delay access to communities that may still be blocked by a remnant ice cover. Such was the case in 2015 when the ice cover in Eastern Hudson Bay didn't break up until mid-August and the Coast Guard icebreaker *Amundsen* was called in to escort re-supply vessels through the ice to communities (CBC 2015b). A similar delay in ice breakup occurred in north eastern Hudson Bay during 2018 and once again required coast guard ice breakers to provide escort services for re-supply vessels (NEAS personal communication 2018). Delays can be critical for communities as it shortens the window for them to receive fuel and other goods before the end of the season and subsequent winter.

### 2.3. Mining related re-supply and transport

The terrestrial area surrounding the Greater Hudson Bay Marine Region contains a rich and diverse endowment of natural resources, and under a changing climate these resources are becoming increasingly accessible. Historically the Paleo- and Thule-Inuit ancestors exploited local copper, iron and stone resources as far back as 2,500 BP (Farrell and Jordan 2016). Modern mineral exploration in the region began in the 18<sup>th</sup> century when British Explorer Samuel Hearne travelled from the Prince of Wales Fort (now Churchill) in search of copper deposits (Tetu et al. 2015). The first industrial mining activity didn't begin until 1957 when the North Rankin Nickel Mine opened and fostered the creation of Rankin Inlet as a permanent settlement in 1950 (Cater and Keeling 2013). The North Rankin Nickel Mine was the first industrial mine in Canada's Arctic and was considered a successful experiment in northern development (Cater and Keeling 2013). Even though the mine closed after 5 years due to declining nickel prices and depletion of the ore body, it did provide strong support for Arctic mining and specifically the success of hiring Inuit workers, which accounted for 70% of the mines workforce (Cater and Keeling 2013). Following the North Rankin Nickel Mine, other mines such as Nanisivik (1979-2002) and Polaris (1981-2002) zinc mines opened further north within the Canadian Arctic on northern Baffin Island, near Arctic Bay, and Little Cornwallis Islands, near Resolute, respectively. In terms of mining activity within the Greater Hudson Bay Region, following the closure of the North Rankin mine in 1962, it didn't return to the area until 1997, when the Raglan Nickel mine opened in Nunavik. At present there are four active mine sites within the Greater Hudson Bay Region (Blue dots - Figure 1) that rely to some extent on marine access:

- i. Meadowbank Gold mine
- ii. Raglan Nickel mine
- iii. Nunavik Nickel mine
- iv. Mary River Iron mine.

Meadowbank Gold mine is located 110 km north of Baker Lake at the western end of Chesterfield Inlet on a deposit that was first identified in the 1980s. The Canadian company Agnico Eagle acquired the mine in 2007 and began commercial production of gold in March 2010. The 45,000 ha area had an estimated initial reserve of 3.45 million oz that would be extracted through a series of open pit mines (Werniuk 2008). The raw ore is processed on site and poured into doré bars that are then transferred south by air. While neither the raw nor processed materials are transported south via marine transport, the mine does rely on marine re-supply for things such as fuel, vehicles, building materials, other equipment and non-perishable items. By the end of 2015 the mine had

produced over 2 million oz of gold, leaving enough proven reserves to operate to the end of 2018 and potentially into 2019. Building on their experience at Meadowbank, Agnico Eagle is developing the Amaruq and Meliadine Gold mines in Kivalliq, both of which are expected to open in 2019 (Bell 2017). Amaruq is located 50 km from Meadowbank and is expected to produce 1.98 million oz. of gold over 6 years, all of which will be processed at the existing Meadowbank processing plant. The Meliadine gold mine will cover an area of 111,358 hectares and is located 25 km north of Rankin Inlet. The project has estimated reserves of 3.4 million oz. of gold and an estimated life of 14 years. The Meliadine and Amaruq projects are expected to create work for 2,000 people, roughly 700 of which will be Inuit, and generate \$66 million worth of payroll per year within the Kivalliq region (Bell 2017).

The Raglan and Nunavik Nickel mines in Northern Nunavik both use docking facilities in Deception Bay to receive re-supply and export nickel concentrates and copper. The Raglan Nickel mine opened in 1998 and covers 70 km<sup>2</sup> on a sulphide nickel deposit in northern Nunavik (NRCan 2007). Exploration in the region began in back in 1957, though due to a decline of the stock market in the 1970s the mine wasn't pursued until 1990 (Raglan website). In 1991 the *MV Arctic* completed a test winter navigation to Deception Bay to prove that winter shipping was feasible, and in 1994 Raglan purchased the Port facilities at Deception Bay that would be used during the start of mine construction in 1995 (Raglan website). In 1997 the concentrator and power plant for the mine were transported by sea from Quebec to Deception Bay and installed at the mine site for the start of commercial mining in 1998 (Raglan website). In 2007 the Port facility at Deception Bay was renovated and during the subsequent year the Raglan mine reached an annual production of 1.3 Mt (1,300,000 tonnes) of ore (Raglan website). Four underground mines (Katinniq, Mine 2, Kikialik, and Qakimarjurq) produce the ore that is then crushed, ground and processed on site into 37,000 tonnes of nickel-in-concentrate per year. The nickel concentrate is trucked 100 km to the port facilities in Deception Bay where it is stored in a dry cargo dome until bulk carriers transport it south to the Port of Quebec. While most of the ore is transported during the open water season, there are two winter transports with FedNav's *MV Arctic* (Polar Class 4 bulk carrier; Mussels et al. 2016). From Quebec the concentrate is transported to Glencore's smelter in Sudbury, Ontario, and then the cast nickel is shipped to Norway for its final processing into high quality metal (Tetu et al. 2015). As of 2011 the Raglan mine had paid the host communities of Salluit and Kangiqsujuaq over \$100 million as per the Raglan agreement that was signed in 1995 with the Makivik corporation. Raglan's current operations are part of Phase I of the implementation of the mine and



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are expected to cease production shortly after 2020 (Raglan website). As a result, the company has launched the Sivumut project to ensure continued production from the Raglan mine beyond the year 2040. Phase II of the Raglan mine will run from 2020 to 2035 and rely on two new underground mines (Mining Project 14 – 850,000 tonnes per year; Mining Project 8 – 500,000 tonnes per year). Phase III will run from 2035 and beyond, and see the development of three new underground mines (Mining Project Donaldson – 450,000 tonnes per year; Boundary Area and the West Boundary are mines for which there is no projected output available). Ore from the 5 new underground mines will be processed in the current facilities and transported to Deception Bay in the same manner as the ore from Phase I (Sivumut Project 2017).

The Nunavik Nickel mine is located 30 km south of Raglan and is structured around a similar business plan with the intent of shipping 150,000 tonnes of nickel concentrate annually through Deception Bay to Finland (Tetu et al. 2015). Very little information is available on the mine, but the Canadian based Canadian Royalties has owned several deposits within the Nunavik Nickel project since 2001. Development of the Nunavik Nickel project halted during the 2008 financial crisis, but in 2010 Canadian Royalties was purchased by the Chinese based Jilin Jien Nickel Industry Co. Ltd. At the time a budget of \$122.5 million was outlined to restart construction and resume exploration of the deposits with the goal of producing nickel and copper concentrate by mid-2012. Similar to Raglan, ore was to be concentrated onsite and then transported 120 km to a temporary barge docking system in Deception Bay that was located 1.5 km from the Raglan port (Canadian Royalties website). The first batch of copper ore was shipped from the



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Nunavik Nickel mine in 2013. In 2014, through a partnership with Fednav the new vessel *MV Nunavik* (Polar Class 4 bulk carrier) began operation with the intention of completing 7-8 voyages per year, with 2 during winter, from Deception Bay to global markets, specifically Finland and China (Tetu et al. 2015). In September 2014 the *MV Nunavik* became the first unescorted commercial vessel to navigate the Northwest Passage as it transferred 23,000 tonnes of nickel concentrate from the Nunavik Nickel mine to China (CBC 2014).

The Baffinland Mary River Iron Ore mine is located on Baffin Island, Nunavut and represents one of the most northern mines in the world. Baffinland Iron Mines Corporation is jointly owned by ArcelorMittal, a multinational steel manufacturing company based out of Luxembourg, and Nunavut Iron Ore. The company is based out of Oakville, Ontario, but has a northern headquarters in Iqaluit and community liaison offices in five communities that are located close to the mine (Arctic Bay, Clyde River, Hall Beach, Igloolik and Pond Inlet) (Baffinland website). The Mary River mine covers an area of 17,000 hectares and contains 9 high-grade iron ore deposits. In 2008 three trial

shipments of iron ore were sent to Europe for test processing (CBC 2008). Officially the mine began operations during summer 2014; stockpiling ore until the first shipment of 53,000 tonnes departed Milne Inlet on August 8, 2015 (Nunatsiaq Online 2015b). In 2016 the mine shipped 2.7 million tonnes of iron ore and in 2017 it shipped 4.1 million tonnes, which is just below its current permitted capacity of 4.2 million tonnes per year (CBC 2017b). To this date all shipments to and from the Mary River mine have gone through Milne Inlet on the north side of Baffin Island, near the community of Pond Inlet. Over the 75-day shipping season during 2017, 56 ships departed Milne Inlet for refineries in Germany, the United Kingdom and Japan (CBC 2017b). During 2017 there were 37 reported spills at the port facility in Milne Inlet, and while most were treated sewage and greywater, there were several thousand liters of raw sewage and several hundred litres of fuel spilled into the local environment (CBC 2017b)

The port at Milne Inlet is connected to the mine by a 100 km long tote road and has two shiploader assemblies that are capable of each loading 4,500 tonnes of ore per hour

(Baffinland website). In 2014 Baffinland had proposed to ship ore over a 10 month shipping season that would extend from June to March and require ice breakers to be used during the sea ice season (CBC 2014b). However, in 2016 following a review process with local communities where significant concerns over ice breaking were raised, the plan was abandoned and Baffinland committed to “*make every effort to ship ore during the open water season*” (CBC 2016b). At the time the open water shipping season was defined as the period between June and October, however in the same article Baffinland expressed interest in extending the shipping season until December 31<sup>st</sup> (CBC 2016b). The original plan for the Mary River mine, and one that is still referred to on the Baffinland website, was to ship ore on a 150 km long train line from the mine to a new port to be built in Steensby Inlet, which is on the south side of Baffin Island and connects to Foxe Basin. From Steensby Inlet a fleet of icebreaker bulk carriers would transport the materials through Foxe Basin, along Hudson Strait and on to global markets. The railway and Steensby Inlet port would cost an estimated \$5 billion and were thus not included in the Early Revenue Phase of the mines operations. Instead the Steensby Inlet plan was pushed to the second phase of the mines operations and though there is limited information available on the intentions of the Steensby Inlet port, there is evidence from a Nunavut Planning Commission Public Hearing on the Baffinland Iron Mines from January 13, 2017 that shows Baffinland is still interested in developing the southern rail route to Steensby Inlet (Nunavut Planning Commission 2017). Beyond the price of the Steensby Inlet option, there were significant concerns raised by local communities related to the wildlife and archaeological sites located around Steensby Inlet (CBC 2012). In 2012 the mayors of Igloolik and Hall Beach softened their stance on Steensby Inlet, suggesting in exchange for housing, paved roads and a new fish processing plant the communities could deal with the Steensby Inlet port (CBC 2012). The Steensby Inlet option would drive a large increase in vessel traffic within Foxe Basin and contribute to even greater vessel traffic through Hudson Strait. Under the Zone/Date system the open water shipping season within Foxe Basin exists from August 20 to October 20, though Baffinland has proposed using ice strengthened or Polar Class rated bulk carriers for all of its shipping needs, which would extend the shipping season under the Zone/Date and AIRSS regulatory systems.

Beyond these four active mine sites there are a large number of proposed mines for the area surrounding the Greater Hudson Bay Marine Region. Gavrilchuk and Lesage (2014) show that there are 40 proposed major mining projects in exploration or development phase within Quebec, three of which (Hopes Advance, Eldor and Duncan Lake – Figure 1) plan to export ore via northern deepwater ports. Within Nunavut,

the Nunavut Planning Commission expects over 10 major mineral projects to enter production between 2013 and 2020 (Nunavut Planning Commission 2011). Of these 10 projects, 4 would rely on marine transport through the Greater Hudson Bay Marine Region; i) The Mary River mine, which is already in production, ii) Meliadine Gold mine located 25 km Northwest of Rankin Inlet, iii) Kiggavik Uranium mine located 80 km west of Baker Lake, and iv) The Roche Bay Iron mine located on Melville Peninsula in Foxe Basin. Note that in 2016 the Nunavut Impact Review Board and Federal Government denied the application for the Kiggavik Uranium mine due to the lack of a defined start date and work schedule (CBC 2016c). The French company Areva that lead the proposal, acknowledged that declining uranium prices may have delayed construction and production at the mine for up to two decades (CBC 2016c). Beyond these 4 projects, there are an additional 24 projects in advanced exploration stages, and 25 projects undergoing early stage exploration and prospecting throughout Nunavut (Gavrilchuk and Lesage 2014). Within the Region, the proposed Haig Inlet Iron mine on the Belcher Islands, Southampton Nickel and rare earth metal mine on Southampton Island, Qilalugaq Diamond mine near Naujaat, Tuktu Iron mine 60 km north of Roche Bay (Figure 1) and up to 28 other projects in Kivalliq would all rely on marine transportation. Additionally, a portion of the 40 proposed projects in Quebec, most of which are in Nunavik, would rely on marine transportation through the Greater Hudson Bay Marine Region. In order to meet the projected demand of northern mines the government of Quebec has begun a profitability study on a deep-water port in Whapmagoostui-Kuujuarapik, while the Makivik Corporation and Kativik Regional Government have expressed desire for a deep-sea port in Kuujuuaq (Gavrilchuk and Lesage 2014; Figure 1). At the same time, the development of a deepwater port in Rankin Inlet has been identified as a key priority in order to facilitate northern mine activity in the Kivalliq region (Canadian Northern Economic Development Agency 2012). The proposed port facility in Rankin Inlet would compliment the proposed all-season road connecting Rankin Inlet to Churchill and the rest of the North American transportation network (Government of Nunavut 2010).

While a longer open water season increases accessibility to these mine sites there are several other considerable conditions required for a mine to be viable. These conditions include, but are not limited to, access to capital and foreign direct investment for infrastructure, international market conditions, and shifting demands that dictate commodity prices and ultimately the profitability of a project (Tetu et al. 2015). The existing mines in the Region have all required vast amounts of investment and taken decades to come to fruition. In 2015, Jean-Marc Seguin, Makivik Corporations mining coordinator said that mining

exploration is slowing down in Nunavik due to the declining global market (Nunatsiaq Online 2015a). Seguin suggested that the added constraint of higher operating costs and a short window of time to conduct fieldwork and transport goods makes projects within Nunavik more difficult. But ultimately it is the international markets that dictate whether a project can be profitable and worth the added difficulty of operating in the north. Within the area, iron ore and nickel concentrate are the two most common materials mined, and over the last 5 years the price of both of these materials has declined substantially. Projects that may have been profitable in 2012 when prices were between 1.5 to 2 times what they are now, may no longer be profitable. However, land claims and exploration rights can be maintained on a back burner by mining companies until the global markets dictate that it may once again be profitable to access the materials.

#### 2.4. Expedition cruise ships and pleasure craft

Expedition cruise ships, or passenger vessels, have been operating in the Canadian Arctic since 1984, when the *Explorer* became the first passenger vessel to transit the Northwest

Passage during an unusually low ice year (Johnston et al. 2016). Between 1984 and 1991 passenger vessel activity was sporadic within the Canadian Arctic, but stabilized between 1992 and 2005 (Stewart et al. 2010) and has increased during recent years (Dawson et al. 2014; 2017; Pizzolato et al. 2014). The recent increase has been driven by improved accessibility to formerly inaccessible areas of the Arctic as a result of climate driven changes to the Arctic ice pack. This, in turn, has given rise to the phenomenon known as Last Chance Tourism which provides tours through Arctic waters where sea ice, ice bergs and ice-supported wildlife (e.g., polar bears, walrus, seals and whales) are still available to be witnessed by tourists (Lemelin et al. 2010; 2013). Provided that passenger vessels operating in the Canadian Arctic are typically only ice strengthened to 1A on the Finnish-Swedish classification system (Comparable to PC7; Table 2) and can therefore only handle melting first year ice during summer and fall, they have historically only operated during the open water season within the confines of the Zone/Date system. Historically this meant that Arctic tours were confined to Hudson Bay and Baffin Bay between July and October, however as the Northwest Passage and other



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locations further north have become increasingly accessible the tourism industry has moved further north (Stewart et al. 2010; Dawson et al. 2017) beyond the Greater Hudson Bay Marine Region.

In their analysis of the tourism industry in Hudson Bay, Stewart et al. (2010) studied passenger vessel activity during 2006, 2008 and 2009 and identified 7 communities (Cape Dorset, Churchill, Inukjuak, Kangiqsujuaq, Kangirsuk, Kimmirut and Kuujuaq) and 3 shore sites (Akpatok Island, Diggs and Mansel Islands, Quaqtaq) within Hudson Bay and Hudson Strait where vessels visited at least once. Even over the three years of their study the authors found that the number of visits declined in 8 of the 10 locations with only Churchill and Quaqtaq maintaining the number of visits across the three years. Inukjuak, the lone site visited in eastern Hudson Bay, had 4 ships visit in 2006 followed by none in 2008 and 2009, essentially representing the end of passenger vessel tourism in eastern Hudson Bay. The same thing had occurred in the Nunavut communities of Arviat, Rankin Inlet and Chesterfield Inlet in western Hudson Bay prior to the start of the study in 2006. During the study period Cruise North's *Lyubuv Orlova* began its Hudson Bay tour in Churchill and transited across the Bay to Walrus, Diggs and Mansel Islands where polar bears and walrus could usually be seen. Subsequently she would sail to Cape Dorset, the "Capital of Inuit Art", and make its way along Hudson Strait towards Kuujuaq where the tour would end. Perhaps due to diminishing interest in Hudson Bay tours, Cruise North, which was the first Inuit owned and operated cruise business, decommissioned the *Lyubuv Orlova* in 2010 and closed its operations.

Within Hudson Strait the communities of Kuujuaq, Kangirsuk, Kangiqsujuaq and Kimmirut all saw the number of passenger vessel visits decline during the study period of Stewart et al. (2010) and are no longer listed on Arctic tour itineraries. The number of shore visits to non-community sites near the mouth of Hudson Strait such as Akpatok, Killiniq and Button Islands declined during the study period but not as much as the community visits did. This is likely because the three islands provided good wildlife viewing opportunities for marine mammals, polar bears, walrus, thick-billed murres, and several species of whales, making the islands popular with passenger vessels. However, similar to the communities of Hudson Strait, none of these islands are listed on any current Arctic cruise itineraries. Instead tours now typically begin further north where participants embark the vessel in Iqaluit, Resolute, Kugluktuk, or Cambridge Bay, or in the communities of Nuuk or Kangerlussuaq, Greenland (Quark Expeditions; One Ocean Expeditions; Zegrahm Expeditions). One of the issues that passenger vessels faced within Hudson Bay was geography, essentially the distances between sites were too great. Furthermore, because tourism vessels operated during the



open water season and only entered the Region once the ice cover had melted, they were unable to provide sights of sea ice and ice dependent wildlife. Comparatively, further north within the NWP vessels can operate during the open water season but approach the summer ice edge and provide sights of sea ice and wildlife that attract tourists to the north.

Another aspect of marine tourism beyond passenger ships is the non-commercial group of pleasure craft. Pleasure craft are characterized as recreational vessels that do not carry passengers for remuneration, and are most commonly yachts, sailboats or row boats (Arctic Council 2009). It's important to note that pleasure craft are not required to report their locations within the NORDREG zone, as a result only pleasure craft that self-report their positions are represented within the shipping dataset. However, vessels that do self-report receive support in the form of weather and ice reports, and search and rescue services. Dawson et al. (2016) found that between 1990 and 2013 the number of pleasure crafts operating in the Canadian Arctic increased at a rate of 20 vessels per decade, making it the fastest growing marine sector in Arctic Canada with a specific increase in activity along the Northwest Passage. Within the Greater Hudson Bay Marine Region, between 1990 and 2013 pleasure craft only self-reported to NORDREG twice, during 1993 and 2013 (Dawson et al. 2016). In 1993 1 vessel reported to NORDREG as it traversed Hudson Bay to Churchill with stops at Rankin Inlet, Cape Dorset and Kimmirut along its journey (Dawson et al. 2016). In 2013, pleasure craft reported from Hudson Strait and northern Hudson Bay, transiting between South Hampton and Walrus Island before entering Roes Welcome Sound (Dawson et al. 2016). In the broader realm of yacht tourism in the polar-regions, Stonehouse and Snyder (2010) note that it is difficult to regulate and monitor pleasure craft because they operate independently, are self-reliant and become widely dispersed, as part of the appeal is to visit remote locations where few others have been. Pleasure craft offer the potential for economic support in the communities

they visit, however there is also the potential for adverse environmental and cultural impacts, along with risks in terms of safety and security that warrants management of pleasure craft (Johnston et al. 2017). The role of pleasure craft in Arctic tourism and their associated regulations are being considered and part of future research efforts.

### 2.5. Community based marine access

Access to the maritime routes within the Greater Hudson Bay Region plays a significant role for Inuit communities. Making use of the open water and coastal landscapes during the warm summer months, in addition to the frozen sea ice throughout the winter, Inuit communities maintain both general routes and traditional trails representing significant channels of communication and exchange (Aporta 2009). Knowledge of these trails has been transmitted orally for centuries and only recently have some begun to be conventionally mapped and stored in digital databases with the permission of the knowledge holders (see the Pan-Inuit Trails).

During summer months, communities make use of the open water of Hudson Bay and its tributary systems for transport, trade, communication, and subsistence hunting purposes. Water craft are still widely used today to access neighbouring communities, including island harbours such as Coral Harbour (Salliq) on Southhampton Island, and Sanikiluaq. During the summer months, ATV's are used to travel land routes, and smaller watercraft, such as seadoos, kayaks, small boats, and freighter canoes tend to commute near the coastlines and along major river routes, where they can avoid the more hazardous open waters. As the marine environment freezes over during the winter months, snowmobiles become a primary source of transportation across the landfast sea-ice and along coastal trails. Landfast sea ice forms in coastal areas and is anchored to either the coast or seafloor, thereby representing a stable platform for seasonal travel. (See Theme I. Chapter ii.)

#### **Historic community maritime access and use**

Maritime transportation, dating back to the 17<sup>th</sup> century, played a key role in the historical evolution of the fur trade in what is now Northwestern Québec. Trading partners made use of the major estuaries as routes for the inland transport of furs and the shipping of merchandise from Britain, in turn, resulting in the locations of contemporary coastal Cree First Nations. Similar trading practices took place along the Kivalliq coast of Hudson Bay, and further south along the coast of what is now the Churchill region where commercial whaling and trade became a predominant means of contact between traders and local communities (Arima 1994).

Many of the trade routes in the Hudson Bay and Foxe Basin region date to a long history of pre-existing traditional

trails 'iglinit' established and kept in the social memories of communities throughout generations (Aporta 2004). Access and use of the sea ice and snow trails provided opportunity to hunt seal and walrus along the floe-edge and through sea mammal breathing holes, and importantly, was a reliable means to visit relatives and friends in surrounding communities.

For many communities, the development and maintenance of these semi-permanent sea ice features (i.e., trails) was inextricably linked to the environment and was a good way to monitor changes to the landscape, climate, and local conditions. As such, access to, and movement along these routes is both historically, and remains presently an important part of Inuit community life, identity, and knowledge (Aporta 2009).

#### **Modern community maritime access and use**

Access and use of open water, and sea ice routes and trails continues to be an important part of community life within the Hudson Bay Region, as it provides a means for shipping and travel, allows for access to specific animals and engagement with modern subsistence practices including commercial hunting and harvesting, and can provide a sense of enjoyment and leisure among friends and families (Laidler et al. 2008; 2010; Carter et al. 2017). The sea-ice enables transportation to communities and harvesting sites that are either difficult to reach or inaccessible when landfast ice is not present (Krupnik et al. 2010). It has been reported that the entire extent of landfast ice in Nunavut is utilized by the Inuit people (Aporta 2011). During summer the Cree communities in eastern Hudson Bay and James Bay make extensive use of freighter canoes for travel along the coast. Visitors to the coastal communities will be well aware of the large numbers of canoes drawn up along the shores of the estuaries, and the ramps and related facilities available to support such local transportation. Canoes and skidoos are the means of transport available to support camps along the James Bay and Southeastern Hudson Bay, and to some extent continue to provide transportation links for families, linking the coastal communities.

Local knowledge of travel routes among the islands, headlands and shoals along the coast is indispensable. Knowledge of the coastline is an important element of 'Local Ecological Knowledge'. The loss of the intimate knowledge of coastal and sea-ice routes, and of the vagaries of weather along the coast, is a source of concern and remains a critical issue in the transmission of local knowledge between generations. In Nunavik and northern Quebec, trail networks remain a vital system for linking communities without existing roads or runways (Tremblay et al. 2008). The use of trails for hunting, fishing, and trapping remains important for the social, cultural, and nutritional values of these communities.



M. KAMULA

Within the Kivalliq and Foxe Basin regions, traditional summer and winter trails continue to connect coastal and small island communities with the mainland (ex. Melville Peninsula) and Baffin Island (Laidler et al. 2008; Pan-Inuit Trails; Carter et al. 2017). Modern means of travel (i.e., boats and planes) and communication have created new opportunities to reach some of these neighbouring communities, yet as the ocean surface freezes in late October, early November, community trailbreakers continue to maintain traditional sea-ice routes passed down through generations, and new routes that are being adapted in response to the rapid changes to the environment (Aporta 2004). Winter travel routes have been documented around Igloolik and Nauyasat in Foxe Basin (Aporta 2004) and around Arviat in western Hudson Bay (Carter et al. 2017). These trails are used predominately for travel by snowmobiles, and facilitate faster and easier travel and trade between communities, provide opportunities to reach new hunting and fishing grounds. Ringed seal (natsiq) and walrus (aiviq) are particularly important means of subsistence to those in this region, while harbour seal (qasigiq), bearded seal (ujjuk), narwhal (allanguak), beluga whale (qilalugaq), and bowhead whale (arviq) are also occasionally harvested (Laidler et al. 2008).

### ***Climate change impacts on community based marine access and transport***

Changes to the local and regional climate have had an overall negative impact on community based marine access to Hudson Bay and surrounding waterways. This has been noted both by local citizens and elders, as well as by local and academic researchers (Laidler et al. 2008; Aporta 2004; Tremblay et al. 2008). According to observations from community hunters across the Region, including reports from Cape Dorset, Igloolik, Churchill, Hall Beach, Chesterfield Inlet, and Coral Harbour, the sea ice has become more dynamic, less predictable, and thinner with more snow accumulation, making navigation difficult, and dangerous (Krupnik and Jolly 2002; Laidler et al. 2010; MacDonald 2004; Ford et al. 2006, 2008; Tremblay et al. 2008). In addition, changes to the environment have compromised trails leading to specific hunting grounds, and have affected the overall health and availability of some fish and wildlife species used for subsistence (Ford 2007; Ford et al. 2006, 2008; Gearheard et al. 2011). Scientific data collected across Hudson Bay regions support these local assessments as trends have been found in changing ice, temperature, and wind conditions that in turn impact the sea ice extent, distribution, snow fall, and some subsistence sources (Theme I. Chapter ii; Berkes and Jolly 2002;

Pearce et al. 2010; Ford and Pearce 2012; Andrews et al. 2018). The reductions in sea ice, particularly the timing of landfast sea ice, throughout the Greater Hudson Bay Marine Region will impact the feasibility of ice travel. Together, the analyses of Gagnon and Gough (2006), Ford et al. (2008), and Laidler et al. (2010) provide evidence of significant declines in landfast ice duration in Hall Beach, Chesterfield Inlet, Coral Harbour, Churchill, and Igloodik. Moreover, Yu et al. (2014) report a significant decline in the annual duration of landfast ice throughout the Canadian Arctic.

In response to these kinds of changes, it is noted that residents in Nunavik have been adopting and making use of new routes during the winter to adapt to increasingly risky areas or inaccessible traditional trails, and hunters and trailbreakers in the Kivalliq region are said to be forced to make unnecessary detours to avoid dangerous sea ice conditions during winter months (Aporta 2004; Tremblay et al. 2008). This is especially necessary during the early freeze and melting periods when hunters need to identify and locate safe routes to ice flow edges (Laidler et al. 2008). In addition to these dangers, rising temperatures, and an increased frequency and intensity of

extreme weather events which alter seasonal patterns have worsened hazards associated with travel on the land, at sea, and on the ice (Pearce et al. 2015). Similar assessments have been noted by members across Nunavik and northern Quebec communities (Tremblay et al. 2008).

The east coast of James Bay and southeastern Hudson Bay is also exposed to, and experiencing the impact of these environmental changes. This coastline is associated with strong storm surges and considerable rafting of shelf ice – important factors in the coastal ecosystem processes in this region, including the growth and decay of extensive seagrass beds in the shallow waters of the bays along this coast (A. Penn 2017 personal communication). Here, community members use water routes closer to the shore to mitigate the hazards of less predictable climate conditions on the sea (Tremblay et al. 2008). In addition, communities across Nunavik have developed an integrated community-based monitoring (ICBM) program in order to help in the transmission of safe travel routes and trails as well as to track significant changes to the climate and environment over time (Tremblay et al. 2008).

**Box 1. An innovative solution to transportation in the Subarctic: Drone Delivery Service Tested in Moose Cree First Nation**

*(Printed with permission from CBC News – original can be found at <https://www.cbc.ca/news/canada/sudbury/drone-deliver-service-testing-1.4408126>)*

**Toronto-based company Drone Delivery Canada** travelled to the James Bay Coast in 2017 to run tests, for a partnership with Moose Cree First Nation.

The goal of the partnership was to establish a drone delivery service that would bring food, medical supplies and other necessities to the island of Moose Factory. The company said the drones will be able to travel up to 10 kilometres and carry up to 10 pounds.

Moose Factory is often isolated from the mainland during the spring and fall, when it's not safe to drive across the ice, but the water is still too icy for boats.

Tony Di Benedetto, the CEO of Drone Delivery Canada, said this technology will have a positive impact on similar isolated communities.

"It's really about trying to service communities that lack infrastructure, where basic goods are very difficult

to obtain, and when you can obtain them it is very, very expensive," he said.

Drone Delivery Canada CEO Tony Di Benedetto says the technology can help remote northern communities that lack infrastructure.

Di Benedetto says the company wanted to test the technology to better understand how it would work in a real-world environment.

"Climate was a big aspect that we were looking to understand, and we were faced with different extremes during our testing," he said.

The tests also looked at flight duration and terrain, as well as other air traffic in the area.

"When we look at this technology and how it will move forward, we have to be able to demonstrate how this technology safely operates in an existing sky."

Di Benedetto also had the chance to meet with community leaders and local high school students to discuss how they might be able to use the technology in the future.

"They're very fascinated with this type of technology, and they see innovation, they see technology as a way that they can better themselves and solve problems that they face on a day-to-day basis," he says.

Drone Delivery Canada plans to run further tests in Moosonee and is working with regulators, including Transport Canada, to get the delivery service up and running.



N. THERIAULT

Overall, Hudson Bay communities as a whole, are dealing with uncharacteristically longer summers, later freeze-up in the fall, a more dynamic sea ice during the winter months, and earlier melt onset in spring (Laidler et al. 2008; Andrews et al. 2018). One potential benefit to these longer open water summer seasons is that it leads to more opportunity and accessibility to fishing, transport, and shipping (Andrews et al. 2017; Pearce et al. 2015). However, there is also the consideration that these changes are significantly shortening the time for safe passage to winter hunting grounds and travel to other communities throughout the remainder of the year.

Traditional knowledge systems continue to serve a long-term role in supporting and developing local adaptations to climate changes through transmission of hunting ground information, safe routes, and maintaining open communication lines between communities (Tremblay et al. 2008). However, as traditional coping mechanisms are strained by rapid changes to the environment, and the transfer of traditional land skills necessary for safe and successful hunting become more difficult, it is important to note that new technologies have been implemented into community based marine transport systems to help alleviate some of these stresses (Ford et al. 2006; Laidler et al. 2009; Pearce et al. 2010; Aporta 2011). Specifically, Global Positioning Systems (GPS), satellite phones, Very High Frequency (VHF) radios, and distress beacons are being integrated into the traditional transport and movement systems of communities, and have helped many to access, and safely traverse traditional and modern open water, land, and sea ice routes and trails (Pearce et al. 2015).

### 3. The future of marine transportation under a changing climate

#### 3.1. Shipping

Why do shipping vessels travel into the Greater Hudson Bay Marine Region? As discussed earlier in this chapter, the drivers of shipping in the Region include community re-supply, trade (e.g., Port of Churchill), resource extraction (mining), commercial fishing, tourism, and research. Ultimately, the volume of shipping in the Region in a given year is mostly a product of the socio-economic drive for shipping and the environmental constraints imposed by sea ice. Therefore, efforts to predict future shipping volumes must consider the many different economic and cultural factors influencing shipping in the Region as well as the enormously complex ocean-atmosphere dynamics influencing sea ice. This makes *quantitative* prediction of future shipping volumes in the Region extremely challenging, and the few projections available have a high degree of uncertainty. That said, some more simple, *qualitative* predictions for future

shipping can be made with a greater degree of confidence: put briefly, a growing population and increased mining activity will increase the demand for shipping in the Region, while a longer open water (ice-free) season will facilitate this demand with a longer open water shipping season, specifically increased shipping during the shoulder months of June and November. Furthermore the advent of winter shipping through Deception Bay for the Nunavik and Raglan Nickel mines may prompt other mines to examine the option of winter shipping. Ultimately, the positive trend in vessel counts identified by Dawson et al. (2018) and presented within this chapter are likely to persist into the future as maritime activity increases throughout the Greater Hudson Bay Marine Region.

#### **Sea ice timing**

Sea ice is the main environmental determinant of marine transportation within the Region. During the open water season the Region is accessible to all vessels, whereas outside of the open water season ice strengthened vessels have a longer operational period, while ice breakers of a sufficient polar class may operate unassisted year round. Over the period of routine spaceborne observations the ice cover has shown significant trends towards earlier breakup and later freeze-up, which have fostered a lengthening of the open water season throughout much of the Region (Andrews et al. 2018; see also Theme I. Chapter ii.). In an analysis of maritime traffic in the Canadian Arctic completed for the Canadian Government Etienne et al. (2013) suggested that shipping traffic will “spread” across the calendar as the open water season grows longer. The results presented in Figure 2 confirm that as the open water season has grown longer the shipping season has in fact “spread” across the calendar and into the shoulder months of June, November and December. Climate projections predict that the ice cover within Hudson Bay will continue to change in the coming years and prolong the open water season even further. While this provides the opportunity to further spread the shipping season across the calendar, it is ultimately the demand for re-supply and industrial shipping that will dictate how the future of shipping activity.

#### **Sea ice and winter shipping**

To date, there has been very little winter shipping done within the Region. This has been predominantly due to narrow profit margins associated with re-supply activity and international grain shipments through the Port of Churchill. However the growth of the mining industry throughout the Region has brought increased desire for year-round shipping from mines and led the Canadian company Fednav to operate one ICE-15 (*Umiak*) and two PC4 (*Arctic and Nunavik*) ice breakers for the purpose of providing year round access to mines within the Canadian Arctic. Presently winter shipping is limited to a few

transits through Hudson Strait to port facilities in Deception Bay, and while the ice cover in the area is seasonal it is very dynamic, leading to pressured and ridged ice that can impede ships and beset them for days at a time (Mussels et al. 2016; Landy et al. 2018). Regardless of the ice conditions, winter shipping has been proven to be feasible and as a result there is growing discussion of expanding winter shipping activity within the Region. Specifically the Mary River mine has routinely expressed interest in gaining year round access to their port facilities in Milne Inlet and their proposed port in Steensby Inlet that would bring vessels through Hudson Strait to the northern end of Foxe Basin. However the viability of winter shipping is dependent on the resource market, which dictates whether exporting ore during winter is profitable compared to stockpiling during winter and transporting to markets during the open water season. Furthermore there has been considerable pushback on winter shipping from communities and environmental groups who worry about the disruption to the environment and increased risk associated with winter shipping at a time of year when the coast guard is not present in the area to respond to an accident.

#### **International trade**

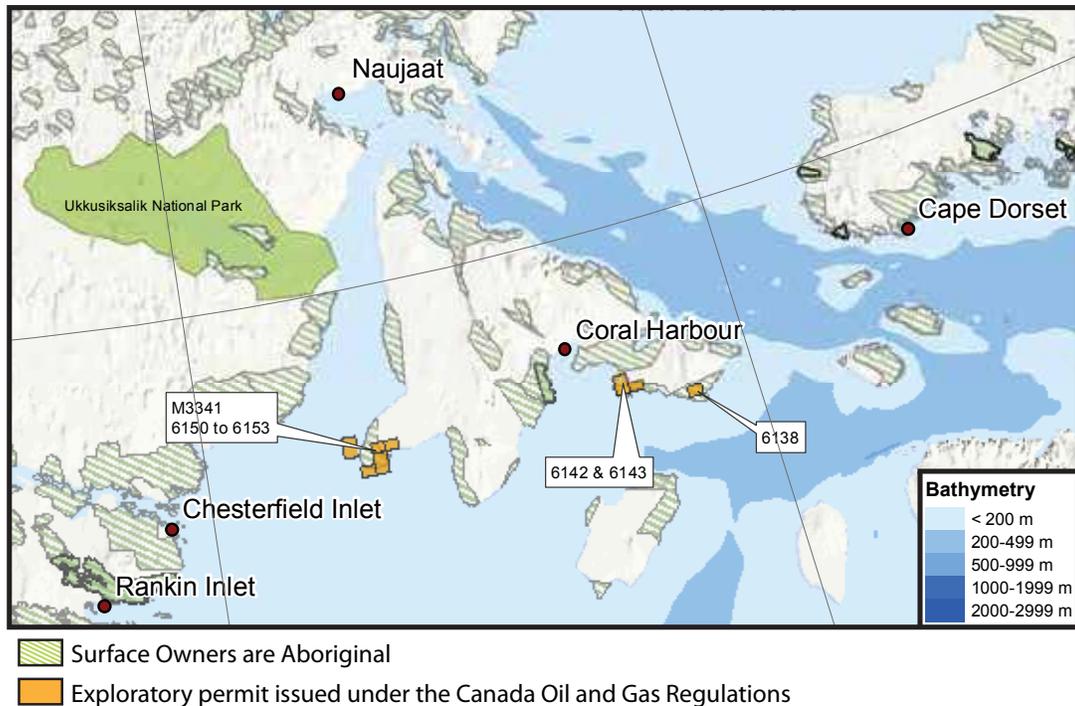
The future of international shipping in the Region is difficult to predict at present. Grain shipments from the Port of Churchill have typically been responsible for the majority of international shipping traffic in the Region, but the Port closed during the summer of 2016. In 2018 Arctic Gateway Group purchased the Port and the railway in Churchill. Although the future of the Port and the amount and type of shipments are unclear the Town of Churchill remains optimistic (CBC 2018a). It is important to note that the Port of Churchill typically had 15-20 shipments per year (Andrews et al. 2016). Historically this represented a large portion of vessel traffic within the Region, however in recent years this proportion has declined as re-supply and mining related shipping has increased (Figure 2).

The prospect of new, or newly viable, Arctic trade routes has been garnering significant media coverage of late. One route of interest is the Northwest Passage, which represents an alternative to the Panama Canal for travel between the Pacific and Atlantic, however sea ice and shipping projections for the Northwest Passage remain variable and uncertain (e.g., Rogers et al. 2013; Stephenson et al. 2013; Engler and Pelot 2013; Melia et al. 2016). Furthermore, the future of the Northwest Passage may not be particularly relevant to the Greater Hudson Bay Marine Region as the routes for the Passage do not enter the Region but rather run north of Baffin Island. There is the potential for vessels to transit through Hudson Strait and Foxe Basin en route to Fury and Hecla Strait, and into the Gulf of Boothia, which connects to the Northwest Passage. However this route

is considered more circuitous than the route through Baffin Bay to Lancaster Sound, so it has very rarely been used and is not commonly discussed as a future route for shipping traffic.

#### **Community re-supply**

Sealift traffic is expected to continue to “spread” across the calendar and to increase in volume in the future. This is because populations are growing in the Region and because marine re-supply is more cost effective than re-supply by plane (e.g., Brooks and Frost 2012; Engler and Pelot 2013). Essentially all of the communities in the Region are experiencing considerable population growth (Statistics Canada 2016 Census 2017; Nunatsiaq News 2017). The population of Kivalliq (Arviat, Baker Lake, Chesterfield Inlet, Coral Harbour, Naujaat, Rankin Inlet and Whale Cover) increased from 7,942 in 2001 to 10,528 in 2016, a 33% increase (Nunavut Bureau of Statistics 2016). The population of Nunavut communities on coastal waters of the Greater Hudson Bay Marine Region (Cape Dorset, Hall Beach, Igloodik, Kimmirut and Sanikilluaq) increased from 4,364 in 2001 to 5,760 in 2016, a 32% increase (Nunavut Bureau of Statistics 2016). The population of Nunavik (Akulivik, Aupaluk, Inukjuak, Avujivik, Kangiqsualujjuaq, Kangiqsujuaq, Kangirusk, Kuujjuaq, Kuujjuarapik, Puvirnituq, Quaqtaq, Salluit, Tasiujaq and Umiujaq) increased from 9,632 in 2001 to 13,204 in 2016, a 37% increase (Nunivaat – Nunavik Statistics Program). With a growing population comes a growing need for building supplies, fuel, and other materials; sealift is often the only option for bringing these heavy items to communities in the Region. With a growing population also comes a growing demand for food. Typically, perishable food items must be brought in by plane, but communities attempt to maximize their delivery of non-perishable foods by sealift. The demand for food may increase even further as current trends suggest declining consumption of locally-harvested food that is being offset by increased consumption of food provided from southern markets (Kuhnlein et al. 2004; Kolahdooz et al. 2014). At present re-supply vessels typically make three round trips from the St. Lawrence Seaway to the Canadian Arctic. A longer open water season may permit a fourth round trip during the open water season, or perhaps more re-supply vessels may be required to satisfy demand. Furthermore, depending on the future of the Port of Churchill it may be possible to use it as a re-supply hub for communities in Kivalliq and throughout the Region. Historically a limited amount of re-supply has passed through the Port, preventing a return trip to Montreal to reload the re-supply vessels and therefore increasing the efficiency with which the sealift can be conducted.



**FIGURE 6.** Exploratory permits for oil and gas within the Greater Hudson Bay Marine Region. Adapted from Indigenous and Northern Affairs Canada (June 2016).

### 3.2. Resource extraction

#### **Mining**

Predicting future mining activity can be challenging because the activity level is dependent on fluctuating commodity prices. As a result, projected timelines for mining projects should be treated with caution. In general, mining activity in Canada's North was projected to nearly double between 2011 and 2020 (Canadian Northern Economic Development Agency 2015). With regards to shipping, more than 25 resource development projects (not just mining) with a marine component could be operational by 2020 in Canada's north (Gavrillchuk and Lesage 2014).

#### **Oil and gas**

At present, there are no active oil and gas projects in the Region and no projects are under development (Gavrillchuk and Lesage 2014; Indigenous and Northern Affairs Canada 2018). Though as of 2015, there were 8 exploratory permits issued for two different sites on southern Southampton Island (Figure 6), totalling an area of 126,376 hectares (Indigenous and Northern Affairs Canada 2016). For comparison, there were 63 licences totalling nearly 3 million hectares in the Beaufort Sea as of 2015.

It is difficult to predict whether the existing exploratory permits in the Region will lead to development and what the

pace of development would then be. Oil and gas development in the Arctic is based on a volatile mixture of economic (e.g., price of oil) and social (e.g., environmental regulation, public pressure) factors and at present oil companies are showing relatively low interest in developing their Arctic holdings. In an analysis of Arctic oil and gas prospects, the Oxford Institute for Energy Studies found that environmental concerns (despite "tight" environmental regulations) and high costs are constraining Arctic oil and gas activity in Canada; the authors concluded that "Canada will not begin exploiting its Arctic [oil and gas] reserves in the near or medium term" (Henderson and Loe 2014).

#### **Commercial fishing**

The number of fishing vessels active in the Greater Hudson Bay Marine Region has grown in recent years (Figure 4). According to the dataset compiled by Dawson et al. (2016), only 35 fishing vessels were present in the Region from 1990 – 2010, while 89 vessels were present in the following five years from 2011 – 2015; over the past three years (2013 – 2015) fishing vessels accounted for 12 – 15% of vessel traffic in the Region. Almost all traffic from fishing vessels appears to occur in August (Figure 4), and it is likely that the majority of this traffic is restricted to Hudson Strait (Étienne et al. 2013).

Interestingly, Zeller et al. (2011) report a decline in Canadian Arctic fish catch between 1950 and 2006. Moreover, Engler and Pelot (2013) report that the number of commercial fisheries in the Hudson Bay Region decreased from 209 in 2005 to 42 in 2009. These findings are difficult to reconcile with the growing fishery traffic in the Region reported by Dawson et al. (2016). The statistics on commercial fishing landings and licenses in the Arctic are not currently available on the Department of Fisheries and Oceans website alongside the statistics for Pacific and Atlantic provinces (Fisheries and Oceans Canada 2016).

### **Tourism**

Tourism-related maritime activity (expedition cruise ships and private yachts) is one of the fastest growing maritime sectors in the Canadian Arctic and is expected to continue to grow as the declining ice cover increases accessibility to areas that were previously ice covered (Engler and Pelot 2013). However within the Canadian Arctic the Northwest Passage is drawing a greater proportion of tourism activity and actually pulling tourism out of the Greater Hudson Bay Marine Region as many tours through the Canadian Arctic now begin north of Hudson Strait in Iqaluit, Kugluktuk or Nuuk, Greenland. Historically there was a small cruise tourism industry in the Region that contributed only a small proportion of the total vessel traffic. Between 2006 and 2009, Stewart et al. (2010) observed what can seemingly be described as the end of cruise tourism in Hudson Bay. The subsequent period from 2011 to 2015 shows diminished tourism activity throughout much of the Region, with pleasure craft only transiting through Hudson Strait to western Hudson Bay or north to Fury and Hecla Strait en route to the Canadian Arctic (Dawson et al. 2018). Around this time there was a focus on Arctic tourism pushing further north into the Northwest Passage that resulted in increased tourism traffic, specifically through Lancaster Sound and Barrow Strait (Dawson et al. 2018). While tourism activity is expected to increase in the Canadian Arctic (Engler and Pelot 2013), it is difficult to predict how tourism activity will change within the Greater Hudson Bay Marine Region. At present it seems as though the cruise tourism industry and private yachts have moved north, beyond the Region, towards the Northwest Passage and other previously inaccessible areas of the Canadian Arctic. While a portion of these vessels may enter Hudson Strait, or perhaps even transit through Hudson Strait and Foxe Basin towards Fury and Hecla Strait en route to the Canadian Arctic, it is currently unknown if in the future cruise ships and private yachts will visit the areas of eastern and western Hudson Bay.

## **4. Risks associated with marine transportation**

Travelling on sea ice in the Greater Hudson Bay Marine Region is becoming more dangerous as ice regimes change and become less predictable under the influence of climate change. Meanwhile, the growing volume of shipping traffic in the Region must navigate carefully in a region with relatively few bathymetric data and navigation aids, and very little emergency response capacity. Furthermore, because of the limited response capacity and because of the potential sensitivity of the ecologically- and culturally-important ecosystems in the Region, a shipping accident could be particularly environmentally damaging in the Region.

### **4.1. Risks of ice travel in a changing climate**

Evidence suggests that travel over sea ice is becoming more dangerous as the ice season changes in the north. Ford et al. (2008) considered the risks of ice travel in Churchill and Igloodik: The authors concluded that shorter ice seasons, thinner ice, and changing ice dynamics have resulted in greater hazard exposure for residents of the study communities. The authors also noted that risk-taking behaviour, with regards to ice travel, is becoming more common as locals attempt to make up for reduced hunting or travel opportunities caused by shorter ice seasons and non-traditional employment (Ford et al. 2008). Finally, the authors reported that vulnerability to dangerous ice conditions varies between communities depending on the local geography and ice environment, and tends to increase in communities with relatively high numbers of harvesters and relatively low availability of store bought foods or gainful employment (Ford et al. 2008). Laidler et al. (2009) continued with the work of Ford et al. (2008) in Igloodik, and the authors noted that vulnerability to changing ice conditions is not only variable between communities but also within them. Within the community, hazard exposure depends on an individual's use of sea ice, their level of engagement in harvesting, and their reliance on traditional foods (Laidler et al. 2009). Anecdotal reports from Chesterfield Inlet suggest that community members increasingly avoid travelling near the ice edge due to decreasing stability and increased risk of the "highway" (land-fast sea ice) breaking off.

### **4.2. Risks for shipping**

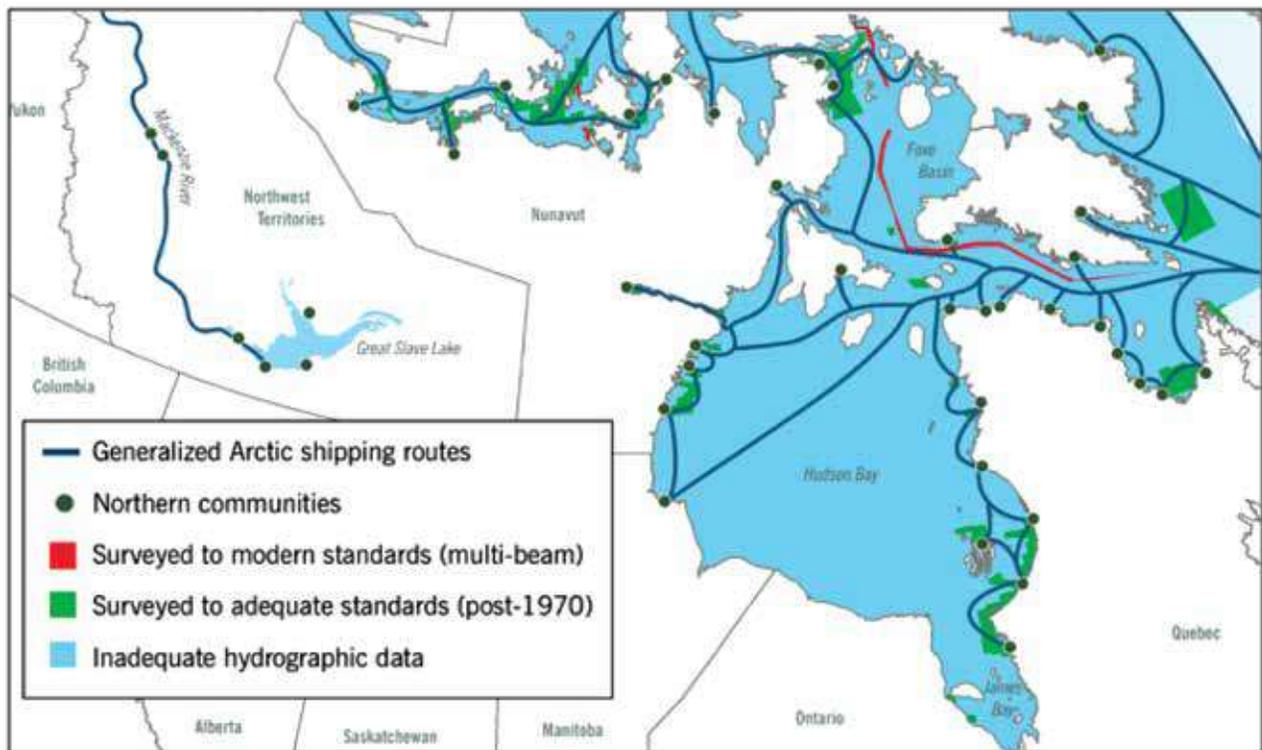
The Greater Hudson Bay Marine Region is a challenging environment for shipping. Seasonal sea ice, cold temperatures, and adverse weather can all present difficulties for vessel operators. Moreover, the region has few navigational aids, little shipping infrastructure, and limited emergency response capacity.

**Navigational aids and hydrographic data**

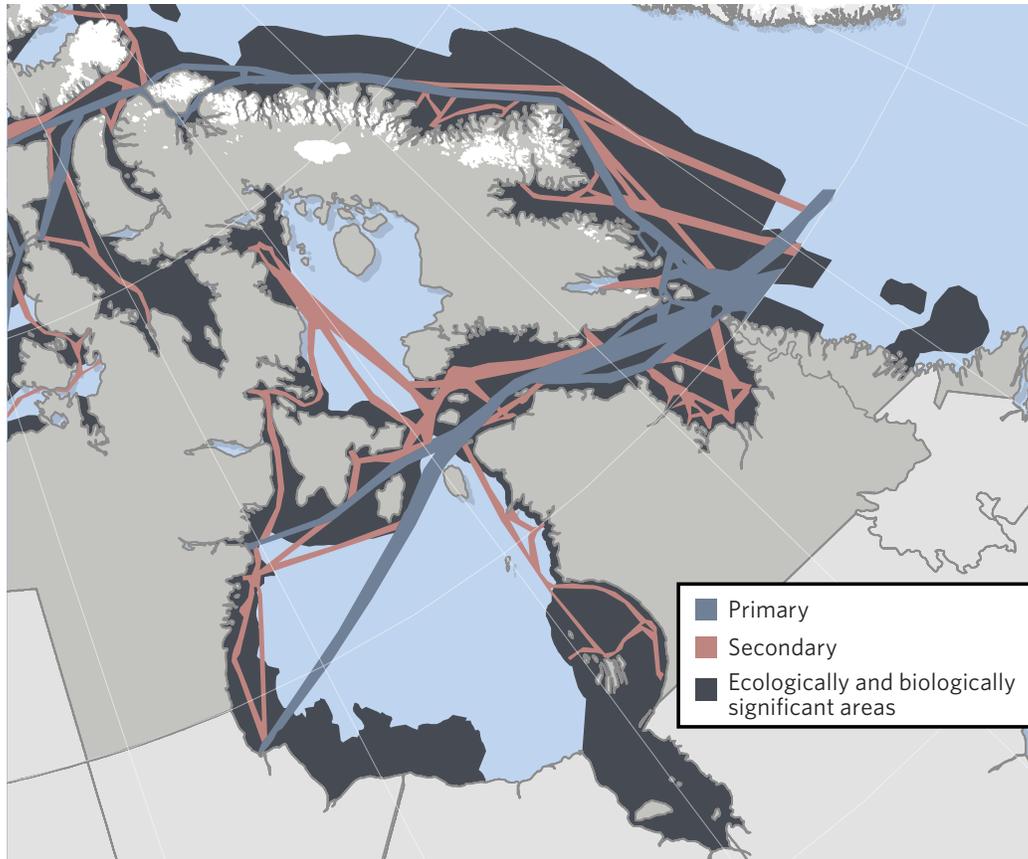
The Commissioner of the Environment and Sustainable Development (2014) recently completed a review of marine navigation in the Canadian Arctic for the Office of the Auditor General. The report concluded that Canadian Arctic waters are inadequately surveyed and charted, including some of the main shipping corridors and inshore waters near communities (Figure 7). According to the report, the shortage of hydrographic data increases operating risks for shipping vessels and emergency responders (Commissioner of the Environment and Sustainable Development 2014). Within the Greater Hudson Bay Marine Region only the route to and from Steensby Inlet, the potential future site of Mary River mines port facility, has been surveyed with a multibeam. The issues of insufficient bathymetry and navigational aids were also raised by the community of Arviat during community discussions related to the proposed maritime corridors (Carter et al. 2017).

The Canadian Coast Guard is aware of the challenging shipping conditions in the Canadian Arctic and in 2012 the Canadian Coast Guard began the 'Northern Marine Transportation Corridors Initiative', which is now often referred to as the 'Low Impact Shipping Corridors Initiative'. As part of

the program the Canadian Coast Guard aims to focus navigational support along high-traffic corridors so as to create a network of safer shipping routes (PEW 2016; Porta et al. 2017). As of winter 2018, a set of prospective corridors has been identified based on existing traffic patterns and these are shown in Figure 8. However the low impact corridors continue evolve based on best available scientific information and local knowledge. Furthermore, initiatives are underway to establish shared leadership (i.e., federal and territorial and Indigenous governments) approaches to governing shipping through a corridors approach. A new initiative is also being established by the Arctic Council to internationalize the corridors concept across Arctic regions to ensure safe shipping among all Arctic nations. Thus far the low impact corridors have received a mixed response as rights holders and stakeholders (e.g., local communities, shippers, researchers, environmental advocacy groups) are pleased to see new Arctic shipping policy in development but have concerns about the Canadian Coast Guard's corridor selection process. Specifically within the Greater Hudson Bay Marine Region there is concern about whether the primary corridor connecting Chesterfield Inlet and Hudson Strait will go between Somerset and Coats Islands, which is an important



**FIGURE 7.** Shipping routes, communities and the status of hydrographic charting within the Greater Hudson Bay Marine Region as of 2014. From the Office of the Auditor General of Canada (2014).



**FIGURE 8.** Preliminary map of the proposed primary (blue) and secondary (red) corridors of the Low Impact Shipping Corridors Initiative within the Greater Hudson Bay Marine Region. Black areas denote Ecologically and Biologically Significant Areas as defined by the Department of Fisheries and Oceans Canada. Adapted from Pew Charitable Trusts (2016).

area for the local walrus population, or if the route will go south of Coats Island towards central Hudson Bay. Furthermore there is no defined shipping corridor south of the Belcher Islands into James Bay, which has limited maritime activity but is known to be a shallow, risky area for ships to operate.

As part of a larger project focused on identifying Inuit and northern perspectives on the corridors initiative, Carter et al. (2017) present results from interviews with key knowledge holders from the community of Arviat in western Hudson Bay. Overall the community was concerned that increased maritime activity through the corridors will disrupt local wildlife, increase levels of contaminants within the local environment, increase coastal erosion and increase the risk of a potential oil/fuel spill, of which they have insufficient capacity to respond to (Carter et al. 2017). The community suggests that the proposed corridors be widened and moved further offshore, while the approach to Arviat and other communities receive improved charting and the installation of permanent lighted navigational markers,

and nearby ecologically important areas be defined as “no-go” or “restricted-use” zones (Carter et al. 2017). The community, as we’re sure many communities would, would like to see improved communication and notification of changes made to the corridors initiative as they continue to evolve (Carter et al. 2017).

#### **Shipping infrastructure**

Shipping infrastructure within the Greater Hudson Bay Marine Region varies widely from community to community and port to port. The Port of Churchill is the largest infrastructure in the Region, with four large berths capable of handling multiple bulk carriers at a time (Andrews et al. 2016). Port facilities at Baker Lake and Deception Bay are basic, but facilitate the handling of re-supply and ore concentrate from the Meadowbank, and Raglan and Nunavik mines, respectively. To accompany the proposed increase in mine activity throughout the Region there have been eight new Ports proposed, all of which align with a nearby mine site and are typically near

a community (Figure 1). Due to the remote location of the communities around the Region, each community relies on the annual summer sea-lift and while the route from the St Lawrence seaway to each community's mooring location may be long, the final ship to shore transfer has been described as the most difficult portion of the operation. The coastal infrastructure available in each community varies considerably throughout the Region, with some communities having suitable breakwaters and levelled beaches to deliver goods to, while others have almost no supporting infrastructure, which can cause delays or present dangerous conditions. In Nunavik, the Nunavik Marine Infrastructure Program systematically improved the marine infrastructure in each of the 14 Inuit communities (Transportation Plan of Nord-du-Quebec 2002). However, outside of Nunavik, other communities have very little marine infrastructure and there has been limited investment. Regardless of the infrastructure, or lack thereof, re-supply vessels are capable of operating independently and have developed routines for transporting goods to shore in each community. However, as growing populations increase demand for re-supply, and a changing climate changes the weather conditions that may lead to delays in the shoreward transfer of goods, it may be reasonable to mimic the Nunavik Marine Infrastructure Program in other portions of the Region. Such a program would not only improve the efficiency and ensure the safety of the re-supply process, but would also improve the communities' access to the marine environment.

### **Emergency response capacity**

The Canadian Government's emergency response capacity (via the Coast Guard and Canadian Forces) appears to be insufficient to meet current and projected needs in the Arctic. The Canadian Coast Guard currently has a fleet of six icebreakers (Canadian Coast Guard 2016a) that are responsible for supporting shipping activity and providing emergency response within the Greater Hudson Bay Marine Region. According to the Canadian Coast Guard (2016b), an icebreaker will be present, or nearby, to Foxe Basin between August and September and in Hudson Bay and Strait between July and October. The Canadian Coast Guard states that during the summer months when icebreakers are present in the Arctic, and under "average ice conditions", a Canadian Coast Guard icebreaker will be on the scene of an emergency within 10 hours (Canadian Coast Guard 2016a). However outside of the window when icebreakers are present in the Region the nearest icebreakers are on the Labrador Coast (Oct – Dec and May – July) or further south along the St. Lawrence seaway (Jan – April; Canadian Coast Guard 2016b). As a result the Canadian Coast Guard does not outline a response time for shipping emergencies taking place in the Arctic outside of

summer and may be in a difficult position to respond to any shipping accident occurring outside of the open water shipping season. In April 2018, as part of the Ocean Protection Plan, the federal government announced a commitment to increase the Canadian Coast Guard's presence, and extend its season in Arctic waters (Transport Canada 2018). The announcement states that this change will support community re-supply, emergency response, and support industry in the north. Interestingly the announcement refers to Canada's proposed new polar ice breaker, the CCGS *Diefenbaker* (Polar Class 2), which has a mandate of operating in the Arctic for 9 months per year. However as of March 2018 there is no timeline for the launch of the *Diefenbaker* (The Chronicle Herald 2018).

Search and Rescue aircraft are also available to respond to emergencies in the Greater Hudson Bay Marine Region. Rescue aircraft serving Hudson Bay and western Foxe Basin are based in Winnipeg, Manitoba and Trenton, Ontario, while aircraft serving Hudson Strait and eastern Foxe Basin are based in Gander, Newfoundland and Greenwood, Nova Scotia (National Defence and the Canadian Armed Forces 2016). Following the grounding of the Akademik Ioffe in August 2018 near Kugaaruk as part of a One Oceans Expedition tour, Dr. Michael Byers from the University of British Columbia proposed that a SAR Helicopter be repositioned to the Arctic during summer in order to provide faster response times to the growing number of calls in Canada's north (CBC 2018b). However, within the same article, Dr. Adam Lajeunesse from St. Francis Xavier University said that while Arctic marine traffic is increasing there is insufficient search and rescue incidents in Canada's north to warrant relocating search and rescue assets.

A considerable number of media reports, research documents, and opinion pieces in the gray literature have suggested that Canadian Arctic emergency response capacity is insufficient for current demands, that demands will likely grow, and that the current shortcomings in capacity result in significant risks for vessel operators, rescue personnel, communities, and the environment (e.g., Lajeunesse et al. 2011; Goegebeur 2014; Zerehi 2016; Carter et al. 2017). The risk is elevated when you consider the introduction of winter shipping within the Region. While the bulk carriers operating during winter are icebreakers, they do contend with compressed, deformed sea ice (Mussels et al. 2016) that can beset the ships for days at a time and represent a potentially dangerous situation. If there ever were an accident during the winter, the nearest icebreaker would be in Newfoundland or the St. Lawrence seaway and at least several days from reaching the damaged vessel and crew onboard.

### **4.3. Environmental concerns**

One could argue that shipping is the most environmentally significant industrial activity in the Greater Hudson Bay Marine

Region. Everyday shipping operations and a potential shipping-related accident could have considerable environmental consequences. The Department of Fisheries and Oceans assesses the ecological risk of maritime operations through a “Pathways of Effects” (POE) analysis (Canadian Science Advisory Secretariat (CSAS) 2014a). Within a POE, an activity such as shipping is broken down into its various components, and the ecological “stressors” and consequent “effects” of each activity are then examined (CSAS 2014a).

There are three primary environmental concerns related to shipping in the Region. These are: pollution, the disturbance of marine mammals, and the introduction of invasive species. Before discussing the potential environmental impacts of shipping, it is important to note that shipping-applicable federal, provincial, and territorial legislation exists to protect the marine environment. Examples include federal legislation such as the Arctic Waters Pollution Prevention Act, the Marine Liability Act, the Canada Shipping Act, the Canadian Environmental Protection Act, and the Oil and Gas Operations Act, as well as territorial legislation such as the Nunavut Environmental Protection Act. Shippers are legally required to comply with existing regulations. Moreover, some vessel operators may undertake further environmental-impact mitigation measures either voluntarily or as required by a regulatory body (e.g., Agnico Eagle 2018). Under the current regulatory regime, the shipping operator may be liable if the marine environment is negatively impacted by a shipping-related incident.

### **Pollution**

As described by Andrews et al. (2016), shipping can generate marine pollution through (A) operation-associated discharge of pollutants or (B) accident-associated spills.

#### *A. Operation-associated discharge of pollutants*

During regular operations, shipping vessels may discharge pollutants such as sewage, solid waste, ballast water, anti-foulants, and hydrocarbons into the marine environment (CSAS 2014b; Agnico Eagle 2016). These pollutants can have adverse impacts on the local environment (CSAS 2014b; Cumberland Resources Ltd 2005). For example, severe hydrocarbon or anti-foulant toxicity can result in poisoning, immunosuppression, and other health effects in marine organisms (CSAS 2014b).

#### *B. Accident-associated discharge of pollutants*

There are a variety of scenarios where a shipping accident could result in the release of a considerable quantity of pollutants into the marine system. Recent occurrences in the Greater Hudson Bay Marine Region provide two examples: First, an accident during the transfer of fuel from re-supply vessel to community has led to a spill at least twice in the Region

since 2015. “Thousands of litres” of diesel fuel were spilled in the waters off Salluit in October 2015 (CBC 2015a) and an estimated 500 litres of gasoline were spilled into the waters off Rankin Inlet in July 2016 (CBC 2016). Second, the tanker *Nanny* ran aground in Chesterfield Narrows in October 2012 (Transportation Safety Board of Canada 2012); although there was no pollution reported after the *Nanny* grounding, a similar accident could conceivably produce a pollutant spill on another occasion. Despite these recent examples, it should be noted that Judson (2010) reported a considerable decline in shipping accident rates in the Canadian Arctic between 1987 and 2010.

Local people, scientists, and environmental groups are concerned about the possibility of more frequent or larger pollutant spills in the Region as shipping traffic increases (see Theme III. Chapter i. Box 2). As suggested in Figure 8, many of the areas receiving relatively high shipping traffic are ecologically and culturally important ecosystems.

### **Disturbance of marine mammals**

Shipping noise, ship-source pollution, and ship-strikes can all impact marine mammals. Research indicates that shipping typically has a negative impact on *local* populations of marine mammals in the Arctic, but it remains difficult to estimate the current and future impact of shipping on marine mammals at a *regional level*. In other words: while it has been quite well established that the noise and physical threat produced by shipping vessels tends to disturb marine mammals, it is less clear how these stressors may affect the mammal populations within the Region.

Marine mammals of particular concern include beluga, narwhal, bowhead whales, walrus, ringed seal, harp seal, and others; these species are thoroughly discussed in Theme II. Chapter vi. Whales, Seals and Walrus. Some of the potential (A) local and (B) regional scale impacts of shipping are discussed below.

#### *A. Local impacts of shipping*

Shipping vessels continuously produce noise from their propulsion systems. Icebreakers also produce considerable noise when actively breaking ice (Lawson and Lesage 2012). The frequency range of vessel noise often overlaps with the frequency range of the noises used for communication and hunting by whales such as beluga, narwhal, and bowhead (Tyack 2008; Lawson and Lesage 2012). At low to moderate intensities vessel noise could interrupt whale communication or hunting behaviour, at greater intensities vessel noise could additionally cause acute physical stress or hearing damage (Tyack 2008; Lawson and Lesage 2012; Reeves et al. 2014). According to reports and modelling, the noise of shipping vessels can travel great distances (sometimes more than

100km) in the ocean (e.g., Tyack 2008). But at what distance does this noise begin to disturb marine mammals? There may be no simple answer to this question, as responses to ship noise appear to vary depending on the noise, the species of mammal, the availability of alternative habitat, the animal's degree of habituation, and many other factors (Tyack 2008; Lawson and Lesage 2012). Of course, the threat of ship-strikes or pollution-caused toxicity grows as the distance narrows between shipping vessels and marine mammals.

Peer-reviewed articles and local reports have both documented marine mammals responding to shipping. For example, the belugas in Cooke Inlet, Alaska have repeatedly been observed moving away from anthropogenic (man-made) noise originating from varying distances (Carter and Nielsen 2011). Various responses from bowhead whales have been observed, with the whales actively moving away from ship noise on some occasions and seemingly oblivious to noise on others (Finley 2001). Note: while lower response to noise could indicate that whales may be more resistant to disturbance, it could also mean the whales are at greater risk of ship-strikes. Higden and Ferguson (2010) express concern that increased shipping noise could result in further disruption and increased ship-strikes for the bowhead population in the Region. Finally, the local people of Chesterfield Inlet have repeatedly reported that the increased shipping through the Inlet produced by the Meadowbank Mine in Baker Lake has substantially disturbed the local marine mammal population, resulting in lower beluga and seal numbers throughout the open water season (Bernauer 2015; Zerehi 2016).

### *B. Regional impacts of shipping*

As discussed, the noise and physical presence of shipping vessels can sometimes injure marine mammals or cause them to change their behaviour, habitat use, or location (e.g., Finley 2001; Tyack 2008; Lawson and Lesage 2012). While these relatively "acute" (short-term) and local effects are quite well established, it is difficult to gauge what impact they may have on regional marine mammal populations. A local population's short term response to human activity in an area does not necessarily indicate the resultant consequences for that animal's regional population; research suggests that regional population effects can be more severe or less severe than the effects suggested by short-term, local interactions (Gill et al. 2001; Bejder et al. 2006). The regional-level effect usually depends on the availability of alternative habitat and a species' ability to relocate, amongst other factors (Gill et al. 2001). Therefore, the consequences of shipping for the marine mammal populations of the Region should be considered on a species-by-species basis. One cause for concern about the potential Region-wide impact of shipping is the considerable



overlap between the areas of greatest traffic density and the key areas for marine mammals.

### **Introduction of invasive species**

Shipping vessels often carry marine species in their ballast water or attached to their hull. This can sometimes result in the release of "non-indigenous" species (species not naturally present) into the marine environment, despite the existence of regulations designed to prevent such an occurrence (Chan et al. 2012). Many non-indigenous species do not persist (i.e., die out) when released into non-native environments, but a small proportion survive and propagate and are thus "introduced" in the new environment (Chan et al. 2012). Newly introduced species can have a range of impacts on their new ecosystems: many introduced species have relatively little effect, while others may have a considerable impact and become "invasive" (Chan et al. 2012). Invasive species can affect their ecosystems through directly-caused disease and mortality of native species or through more subtle ecosystem changes initiated by competition, predation, or habitat alteration (Chan et al. 2012).

The authors of a 2012 assessment of ship-mediated species introductions in the Canadian Arctic found no record of shipping-introduced invasive species in the region; however, species introductions have been reported in other Arctic regions (Chan et al. 2012). Moreover, researchers have suggested that the risk of ship-mediated introductions in the Arctic is growing for two reasons: First, international shipping traffic in the Arctic is on the rise, increasing the number of vessels that could be transporting non-indigenous species into new Arctic environments (Ware et al. 2014; Miller and Ruiz 2014). Second, climate change is altering Arctic marine ecosystems, often producing more mild conditions that are more conducive to the survival of non-indigenous species from

temperate regions (Ware et al. 2014; Miller and Ruiz 2014). Both of these processes are taking place in the Greater Hudson Bay Marine Region. Finally, it is worth noting that Chan et al. (2012) conclude that ports and regions with more international traffic, such as Churchill, are at relatively greater risk of species introduction than other regions in the Canadian Arctic.

## 5. Key findings and recommendations

Within the Greater Hudson Bay Marine Region, the marine environment is used for a variety of activities that range from international grain export from the Port of Churchill, community re-supply, industrial mine site re-supply and ore transport, research and tourism, and finally local community activities. Vessels operating within the Region range in size from Panamax bulk carriers down to yachts, fishing boats and freighter canoes used by community members. Most maritime activity occurs during the ice-free open water season, however a warming climate is lengthening the open water season. Overall shipping activity is increasing within Hudson Bay and spreading out from the typical open water shipping months of August, September and October, into the shoulder months of July and November. Additionally, a small number of icebreaker bulk carriers now operate within the Region during winter as they service the Raglan and Nunavik Nickel mines along Hudson Strait. Winter shipping directly contends with the seasonal ice cover of Hudson Bay, whereas shipping during the open water season directly avoids ice interactions.

The level of marine infrastructure within each community varies considerably within the Region and impacts community

access to the marine environment and the safety and efficiency with which re-supply to the community can be conducted. Increasing risks in the marine environment during the open water shipping season include storm surges, poorly predicted tides, and increased occurrence of extreme wind events. These may cause significant delays and additional risk to re-supply and fuel-transfer operations. During winter shipping activity, ridged and compressed ice represent hazardous conditions for even Polar Class rated vessels that operate independently within the ice cover and sometimes become immobilized for several days at a time.

As shipping activity increases, and is projected to continue to increase throughout Hudson Bay the associated risks to the environment, wildlife and people of Hudson Bay also increase. Concerns related to the disturbance of marine mammals and increased risk of fuel/oil spills have been raised and will need to be acted upon further. Issues with bathymetric information, coastal infrastructure, search and rescue capacity and disaster response must be considered and worked into the broader national Low Impact corridors initiative (previously the Northern Marine Transportation Corridors initiative).

Recommendations for the Greater Hudson Bay Marine Region include:

- Improve marine infrastructure within communities, which would both enhance the efficiency and safety of the annual summer re-supply and improve the safety and accessibility of the marine environment for the community members. Nunavik communities have received significant investment from the Quebec government for improved marine infrastructure, and more recently the federal government has proposed to invest in infrastructure in other northern communities through their Oceans Protection Plan.
- Increased shipping activity also increases the risk of negative environmental impacts. Disturbance of marine mammals and the risk of oil/fuel spills have been raised as major concerns. These risks must continually be monitored, assessed and studied to reduce the risk that shipping imposes on the environment.
- Regulations and protocols related to major transportation corridors and cruise ships should be regularly reviewed with communities.
- As with all areas of the Arctic, bathymetric mapping in the Greater Hudson Bay Marine Region is sparse. Significant investments should be made to improve the bathymetric information in the Region, particularly along the approach to each community.



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- The Canadian Government's emergency response capacity (via the Coast Guard and Canadian Forces) appears to be insufficient to meet current and projected needs in the Arctic. The Greater Hudson Bay Marine Region is large; to improve the response capacity regional and local search and rescue capabilities and coordination must also be improved. Risk reduction and emergency preparedness plans must be a priority.

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### III.iii

# Parks and Protected Areas: Current Landscape and Future Opportunities

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## Key Messages

- Many coastal areas are presently protected by national, provincial, and territorial parks, and by other designations such as bird sanctuaries. However, there are currently no marine protected areas in the Greater Hudson Bay Region. Concerted efforts are required by planning partners to identify and move forward with proposals for marine protected areas that protect marine biodiversity and ecosystems and reflect areas that are considered important by Inuit and Cree.
- Resources are required to conduct research into the role of protected areas in mitigating and adapting to climate change.
- Governance in the Greater Hudson Bay Marine Region is complex and the challenges of planning and marine protection should not be underestimated. Concerted efforts will be required to coordinate with levels of governments, rights-holders and planning and management authorities under land claims agreements.
- Indigenous protected areas should be explored as a new conservation tool that would advance reconciliation, share decision-making, and involve indigenous peoples and their knowledge in national conservation objectives.

## 1. Introduction

The development of area-based conservation measures to protect oceans is gaining significant momentum in Canada and around the world. At the 10<sup>th</sup> meeting of the Conference of the Parties to the United Nations Convention on Biological Diversity (CBD) in 2010, Canada and other nations committed to meet twenty biodiversity targets by 2020 (the Aichi Targets), including conserving 17% of terrestrial and inland water areas and 10% of coastal and marine areas (Aichi Target 11) (CBD 2010). In 2015, the Canadian federal government announced the 2020 Biodiversity Goals and Targets for Canada, with targets for freshwater and marine conservation that echo Aichi Target 11 (Canada 2016).

These commitments have spurred progress on developing *gazetted* protected areas in Canada's oceans (i.e., protected areas that are recognised under statutory civil law), including marine areas



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in Inuit Nunangat (the Inuit homeland in Canada). For years, marine conservation has lagged behind terrestrial conservation in the Arctic with less than 1% of the waters of Inuit Nunangat under any form of recognized protection. There have been expressions of general support for Canada’s marine conservation goals among Indigenous peoples of the Canadian Arctic, with the caveat that protected areas must not just protect ecological integrity and conserve biodiversity, but also build and maintain strong and healthy communities. These goals are being realized in new and in-progress protected areas within the Arctic. For example, the Anguniaqvia niqiqyuam Marine Protected Area (MPA) in the Inuvialuit Settlement Region was established in 2016; it is the first *Oceans Act* MPA to have a conservation objective based solely on Indigenous knowledge. The 109,000 km<sup>2</sup> Tallurutiup Imanga National Marine Conservation Area (NMCA) in Nunavut is in progress; final boundaries have been agreed upon, and an Inuit Impact Benefit Agreement is in negotiation. Currently, the QIA, Government of Nunavut and Government of Canada are developing an interim management plan. Once established, the Tallurutiup Imanga NMCA will contribute about 1.9% to Canada’s marine conservation targets.

Despite the advancement of MPAs in some parts of the Arctic—meaning any kind of formal, area-based conservation measure and not just MPAs under Canada’s *Oceans Act*—the Greater Hudson Bay Marine Region remains a gap in Canada’s MPA network. As of 2018, there are no established gazetted protected areas within its marine waters. The lack of gazetted MPAs does not mean that waters are not managed. There is a complex governance landscape involving three provinces and a territory, three comprehensive land claims and the institutions established by them, Inuit rights organizations and multiple federal departments, and conservation aims factor into existing management plans and decisions. There are also a number of terrestrial parks and protected areas around the Marine Region

that provide some coastal protection. Nonetheless, government, Indigenous bodies and communities are increasingly recognizing the gap in formal marine protection in the Greater Hudson Bay Marine Region and exploring options and opportunities. Interest in MPAs in the Marine Region is being spurred on by the steady intensification of industrial and commercial activities, accelerating environmental change, and the interacting impacts of these pressures in the context of significant local dependence on the marine ecosystem for harvesting. There are 40 coastal communities in the Greater Hudson Bay Marine Region, the large majority of which are Inuit and Cree communities, and all of which depend to varying degrees on marine and coastal resources for food and cultural identity.

Prior to the settlement of land claims around the region, Indigenous groups generally viewed protected areas with great scepticism. At the time, conservation groups promoting protection were associated with animal rights activism, and protected areas were viewed as yet another way to limit access, harvesting and control over ecologically important territories. The settlement of land claims in Nunavut and the marine regions of Nunavik and Eeyou Istchee has changed the context of these discussions, by creating governance systems that enshrine the primacy of Indigenous rights and roles within decision-making. Self-determination through land claims has meant that protected areas are being increasingly seen by Indigenous leadership and communities as a useful tool to protect biodiversity, safeguard the exercise of harvesting rights into the future and promote emerging economic opportunities through tourism. Harvesting and related activities by beneficiaries of land claims agreements are allowed in all gazetted protected areas, regardless of the designation. In addition, the requirement to negotiate impact and benefits agreements as a prerequisite for a protected area provides an opportunity for both indigenous rights holders and governments to clearly set out management arrangements and benefits. This has led to the creation of a number of national parks and other forms of protected areas which will be further discussed in this Chapter.

Protecting the Arctic environment is one of four pillars of *Canada’s Northern Strategy*. The *Arctic Policy Framework*—which will replace *Canada’s Northern Strategy*—is currently being co-developed by the federal government with Indigenous representatives, territorial governments and relevant provincial governments and will set the long-term direction for Canadian Arctic policy. Marine conservation is an important component of the framework. There has also been a surge of momentum and visioning around developing a new form of protected area—Indigenous Protected Areas (IPA)—which are “based on the idea of a protected area explicitly designed to accommodate and support an Indigenous vision of a working landscape... [to] usher in a broader, more meaningful set of northern

benefits and bring definition to the idea of a conservation economy” (Simon 2017: 23). Further, in 2017, the Government of Canada funded work to consider the feasibility of establishing new NMCA’s within the Hudson Bay and James Bay marine regions. Thus, while there are currently no MPAs within the Marine Region, increasing needs and opportunities may bring significant changes over the next decade.

This chapter explores the current landscape of marine protection within the region and key marine protection needs, opportunities, and challenges. The chapter reviews:

- Existing and potential future mechanisms for marine protection in Canada
- Current status of marine and coastal protected areas and parks in the region
- Key ecological and biological protection needs in the region
- Key challenges with regards to governance and coordination
- Future marine and coastal protection plans and opportunities

## 2. Protected areas: a primer

### 2.1. Defining protected areas

Canada has adopted the International Union for the Conservation of Nature (IUCN)/World Commission on Protected Areas (WCPA) definition of a protected area for its national MPA network:

*A clearly defined geographical space recognized, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.* (Dudley 2008)

To be included in Canada’s MPA network, an MPA must have conservation of nature as its main objective, although it does not have to be the only objective, and it must also fall within IUCN categories I-VI (Canada 2011) (Table 1). Long-term conservation in the context of the MPA definition is the, “*in situ* maintenance of ecosystems and natural and semi-natural habitats and of viable populations of species in their natural surroundings” (Dudley 2008: 9), intended to continue in perpetuity. Ecosystem services are understood to include non-material benefits, such as spiritual benefits.

Inuit harvesting and access rights protected under land claims are compatible with any IUCN category. For example, the Polar Bear Pass National Wildlife Area in Nunavut is categorized as a strict nature reserve [IUCN category 1(a)]. No public access or use is permitted, except for Nunavut beneficiaries and people with appropriate permits. MPAs are thus consistent with the Inuit perspective of their being part of the natural ecosystem.

According to DFO (2017), localized benefits of MPAs can include:

- Maintaining the ecological processes that generate ecosystem services
- Protecting marine ecosystem structure, functions and recovery
- Improving ecological resilience through restoring structures, increasing productivity and increasing food web complexity
- Protecting specific areas containing important biophysical features and processes
- Protecting habitats important for providing refuges (for example, for endangered or depleted species), breeding and nursery grounds, rearing and foraging

TABLE 1. IUCN protected area categories

IUCN Category		Description
I(a)	Strict nature reserve	Human visitation/use is strictly controlled and limited
I(b)	Wilderness area	No permanent human habitation; area protected to preserve natural condition
II	National park	Protects ecosystems and species on large scale; allows for compatible activities (e.g., cultural, recreational, tourism)
III	Natural monument or feature	Protects a specific, usually small natural feature (e.g., landform, geological feature, ancient trees)
IV	Habitat/species management area	Protects particular species or habitats
V	Protected landscape/seascape	Protects area and human relationship to an area that gives it a distinct character; area has significant ecological, biological, cultural and scenic value
VI	Protected area with sustainable use of natural resources	Generally large area with a portion under sustainable natural resource management (low-level, non-industrial use)

Source: Adapted from Dudley (2008)

- Enhancing the ability of nearby areas to recover from disturbances, by exporting larvae and adult organisms to those areas
- Supporting increased size, abundance and diversity of marine species
- Supporting economic activities that are compatible with MPA objectives, such as fishing, aquaculture, transport, recreation, tourism and education
- Providing sites for marine research and monitoring and
- Maintaining areas with important spiritual or cultural heritage value

Further, an MPA network, if designed strategically, may enhance the benefits of individual MPAs by scaling benefits up to the bioregional level.

### 2.2. Marine protected area designations under Canadian legislation

Within Canada there are several different types of protected areas, each associated with a different federal department. These different federally protected area programs typically share a common objective: to conserve and protect Canada’s marine biodiversity, ecosystem function and special natural features. However, each program has a distinct focus and the designation of each type of protected area occurs under different legislative mechanisms (Table 2).

Fisheries and Oceans Canada (DFO), the Parks Canada Agency (PCA) and Environment and Climate Change Canada (ECCC) all have mandated responsibilities to create protected areas in the marine and/or coastal environments. The *Oceans Act* assigns the Minister of Fisheries and Oceans with a leadership role for coordinating the development and implementation of a federal MPA network. Canada’s Federal

Marine Protected Area Strategy (2005) clarifies the roles and responsibilities of federal departments and agencies with MPA mandates and describes how federal MPA programs can collectively be used to create a cohesive and complementary network of MPAs. Within all types of MPAs, management is a shared responsibility; for example, commercial fishing and navigation remain under the jurisdiction of Fisheries and Oceans and Transport Canada, necessitating coordination among various departments.

*Oceans Act* MPAs, administered by DFO, are established by regulation to conserve and protect: commercial and non-commercial fishery resources and their habitats; endangered or threatened marine species and their habitats; unique habitats; and areas of high biodiversity or biological productivity. *Oceans Act* MPAs include zoning and the prohibition of classes of activities, and the kinds of activities that will be prohibited within a given MPA depends on what purpose it has been established for. The National Framework for Establishing and Managing Marine Protected Areas describes DFO’s MPA program and outlines a step-by-step approach to designation, which includes the selection of Areas of Interest, assessment and evaluation of an Area of Interest as a potential MPA and formal establishment of the MPA by regulation under the *Oceans Act* followed by the on-going management of the MPA.

The *Canada Wildlife Act* provides the authority for the acquisition of nationally significant habitats by the Minister of Environment and Climate Change for the purposes of wildlife research, conservation and interpretation. The *Act* provides for the establishment and management of National Wildlife Areas (NWA) and Marine National Wildlife Areas, by regulation, to ensure the conservation and protection of key breeding, feeding, and migration and overwintering sites for birds, species-at-risk and other wildlife of national importance. NWAs are managed following a ‘protection first’ approach. The

TABLE 2. Summary of marine protected area designations under Canadian legislation

Type of Area	Legislation & Department	Purpose
<b>Oceans Act Marine Protected Area</b> (“Oceans Act MPA”)	<i>Oceans Act, 1996, c.31</i> , administered by Fisheries and Oceans Canada (DFO)	Conserve and protect at least one of commercial and non-commercial fish, marine mammals, and their habitats; endangered or threatened marine species and their habitats; unique habitats; or areas of high productivity or biological diversity.
<b>National Marine Conservation Area</b> (NMCA)	<i>Canada National Marine Conservation Areas Act, 2002, c. 18</i> , administered by Parks Canada Agency	Protect and conserve representative marine areas for the benefit, education, and enjoyment of the people of Canada and the world.
<b>National Wildlife Area</b> (NWA), including Marine Wildlife Area	<i>Canada Wildlife Act, R.S., 1985, c. W-9</i> , administered by Environment and Climate Change Canada (ECCC)	Protect wildlife and wildlife habitat for the purposes of conservation, research, and interpretation.
<b>Migratory Bird Sanctuary</b> (MBS)	<i>Migratory Birds Convention Act, 1994 (S.C. 1994, c. 22)</i> , administered by ECCC	Conserve and protect migratory birds and their habitat.



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*Wildlife Area Regulations* prohibit numerous activities in an NWA unless a permit has been granted or a public notice has been issued authorizing that particular activity (e.g., a posting at the entrance to the area). General prohibitions include hunting or fishing by non-beneficiaries of land claims; plant or animal damage or destruction; agricultural activities; recreational activities; and any commercial or industrial activities.

*The Canada National Marine Conservation Areas Act* provides the Minister of the Environment and Climate Change Canada and Minister responsible for Parks Canada, with the authority to establish and manage National Marine Conservation Areas (NMCAs). The objective of establishing NMCAs is to protect and conserve marine areas that are representative of the country's ocean environments and Great Lakes, and to encourage public understanding, appreciation and enjoyment of Canada's marine heritage. NMCAs are established through legislation, and the boundaries are

scheduled under the Act by Parliament. The Act prohibits exploration and exploitation of hydrocarbons and minerals, and strict restrictions on ocean dumping. Management plans, including zoning, are a legislative requirement and are tabled in Parliament and reviewed on a 10-year cycle. The establishment process follows five steps, namely: 1) Identifying representative marine areas (candidate sites) within the larger marine region; 2) Selecting a potential NMCA from the candidate sites based on ecological, social and economic considerations; 3) Assessing the feasibility of a NMCA including consultations and support of local communities; 4) Negotiating agreements, which set out the terms and conditions under which the NMCA will be established and managed; and 5) Establishing NMCAs under the Act. Key to this process is the negotiation of an impact and benefits agreements; which provides an opportunity for both Indigenous rights holders and governments to clearly set out management arrangements and benefits.

The *Migratory Birds Convention Act* allows for the creation of regulations to protect migratory birds from being killed, harmed, or harassed during a critical part of their life cycle, and to protect migratory bird eggs and nests. Creation and management of Migratory Bird Sanctuaries (MBSs) follows the *Migratory Bird Sanctuary Regulations* and is housed within the Canadian Wildlife Service under ECCC. The Act is older than others used for designating MPAs; it was first passed in 1917 to implement a convention between Great Britain (on behalf of Canada) and the United States to protect migratory birds and their nests. The Parksville Protocol amended the Act in 1995, when habitat protection provisions and recognition and endorsement of Indigenous traditional harvesting rights were added. MBSs restrict and control certain activities, and the extent of the authority for the control and management of MBSs depends on the conditions of ownership. There are 92 MBSs across Canada including nine in Nunavut, but no new MBS has been created since 1998. One of ECCC's strategic goals has been to convert Crown-owned Migratory Bird Sanctuaries to National Wildlife Areas to offer more comprehensive year-round habitat protection (Environment Canada 2005).

National Parks created under the *Canada National Parks Act* are established to protect and represent natural and unique landscapes within Canada's identified 39 natural regions under the National Parks System Plan, and also to provide the public with access by promoting education and tourism. National Parks are managed so that visitors can understand, appreciate, and enjoy them in a way that does not compromise their ecological integrity. National parks are not a typical designation for marine protection, especially as Parks Canada has a specific designation for marine areas (NMCAs). However, national parks can have marine and coastal components, which are part of

Canada's marine protected areas network and count towards marine protection. Similarly, provinces and territories have the authority to establish parks on land that can offer some coastal protections (in Québec, parks created under provincial jurisdiction are named *parc nationale*). Land claims agreements relevant to the Greater Hudson Bay Marine Region, such as the Nunavut Land Claims Agreement and the Nunavik Inuit Land Claims Agreement, have provisions relating to the establishment of parks and Inuit participation in their development.

### 2.3. Other effective means of protection: marine refuges

Canada's MPA definition allows areas to count towards the national MPA network that are recognized and managed through legal means or through "other effective means." DFO recently released policy guidance for the term 'other effective means' and to recognize managed marine areas that can count towards Canada's 2020 marine conservation targets (DFO 2017). Other Effective Area-Based Conservation Measures or OEABCMs are not legal designations; this is a category that recognizes enhanced protection through non-regulatory mechanisms, such as stewardship plans and agreements by private land owners (e.g., Indigenous groups, non-profit environmental organizations that may own conservation lands) or long-term fisheries closures. DFO has termed OEABCMs 'marine refuges'; as of December 2017, 34 marine refuges comprising 275,000 km<sup>2</sup> have been recognized, contributing 4.78% of protected marine territory to the achievement of Canada's marine conservation targets (DFO 2018).

### 2.4. Protections under land use plans

Land use plans for Nunavut, the Eeyou Marine Region, and the Nunavik Marine Region are in various stages of development. Under the respective land claims for these regions, land use planning commissions have been established as Institutions of Public Government. The commissions have the authority and responsibility to develop land use plans for the respective settlement areas under their jurisdiction, including large marine areas. The general process is that land use plans are developed in extensive public consultation with communities and other regional authorities. Final draft plans are completed and submitted for approval to the responsible government ministers; once approved, governments are required to follow the plans. The land use plans for land claim settlement areas within the Greater Hudson Bay Marine Region will identify land use designations and a set of conditions or restrictions on types of use for that designation, and then classify areas by land use designation. They will also identify elements of the environment with ecological, biological, economic, social, or cultural significance; these valued components will then need to be



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considered during regulatory reviews of any development projects. In addition to providing protections through land designations, land use plans can also identify areas as candidates for formal protection under legislation.

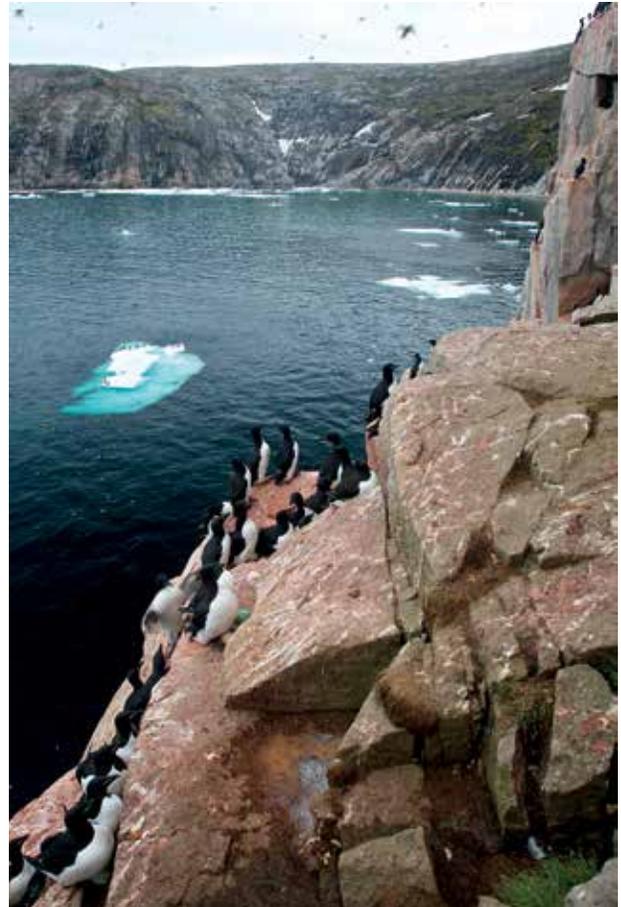
## 2.5. Indigenous protected areas

Indigenous Protected Areas (IPA) or Indigenous Protected and Conserved Areas (IPCA) are not currently available as a protected area designation in Canada, but are a topic of significant discussion. This dialogue has been spurred on by the Government of Canada's commitments to implement the *United Nations Declaration on the Rights of Indigenous Peoples* and to advance reconciliation with Indigenous peoples on a Nation-to-Nation and Inuit-Crown basis. Further, the Ministerial Representative for Arctic Leadership, Mary Simon, submitted a report to Indigenous and Northern Affairs Canada that included recommendations on Indigenous Protected Areas, including that Canada:

- *Continue progress toward becoming the first country in the world to have a legal mechanism to recognize Indigenous Protected Areas*
- *Work with Arctic governments and Indigenous organizations to conceive a new federal policy directive that sets out a process for the identification, funding and management of IPAs* (Simon 2017: 33)

IPA/IPCAs are viewed as a potential platform for developing culturally-appropriate conservation initiatives and programs, increasing Indigenous employment in environmental and wildlife monitoring, improving vessel management and monitoring, improving emergency preparedness and response, and developing tourism in ways that are compatible with local uses of the environment. IPA/IPCA development is also in line with the Aichi targets, which included objectives around full integration of respect for Indigenous knowledge and the customary and sustainable use of biodiversity by Indigenous peoples, as well as full and effective participation of Indigenous peoples in United Nations Convention on Biological Diversity implementation (CBD 2010). IPA/IPCA development also aligns with Canada's 2020 Biodiversity Goals and Targets (Canada 2016).

The federal government has established the Indigenous Circle of Experts to "consider how a spectrum of Indigenous Protected and Conserved Areas (IPCAs) could be realized in Canada and contribute toward achieving Canada Target 1 in the spirit and practice of reconciliation" (Indigenous Circle of Experts n.d.). The federal government has also established a National Advisory Panel on Marine Protected Area Standards that has been tasked with providing recommendations based on the best available science and traditional knowledge



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regarding categories and associated protection standards for federal MPAs, using IUCN guidance as a baseline. The Panel has been specifically tasked with providing advice on IPAs, drawing on relevant recommendations of the Indigenous Circle of Experts. The Panel is also exploring use of the "other effective means" definition to recognize existing Indigenous protection and management of territories as a contribution to protected area targets. The Panel's report, released in 2018, can inform decisions on how Canada can achieve its land and freshwater conservation targets by 2020.

In early 2017 the Prime Minister of Canada and the Inuit of the four land claims regions, along with Inuit Tapiriit Kanatami, signed the Inuit Nunangat Declaration on Inuit-Crown Partnership to "collaboratively identify and take action on shared priorities and monitor progress going forward." This agreement led to the creation of a formal, high-level, Inuit-Crown Partnership Committee (ICPC) that developed work plans around a set of shared priorities. The structure and work of the ICPC reflects a new federal whole-of-government approach that recognizes and works to operationalize the Inuit

Nunangat policy space—that is, an approach that recognizes Inuit as one people despite diverse arrangements for governance, and that ensures the federal policies and programs are equally available to all Inuit. This is being operationalized through cooperation among key federal departments, commitments to implementation targets and increased accountability. The ICPC has led to progress in key areas such as housing, advancing language rights and early-childhood education. At the April 2018 meeting of the ICPC, the Prime Minister, key cabinet ministers and Inuit leaders agreed to include a new priority focusing on IPA/IPCAs, including the Indigenous Guardians Program. Mary Simon’s report and the work of the ICPC are just two of many Inuit contributions to forwarding the dialogue on IPA/IPCAs and the development of a formal designation.

### 3. Existing protected areas in the Greater Hudson Bay Marine Region

There are a number of land-based protected areas that border on the marine waters of the Greater Hudson Bay Marine Region and thus offer coastal protection (Figures 1 and 2). Currently, there are two national parks in the region, Ukkusiksalik National Park (see Box 1) and Wapusk National Park. In the coastal areas of the Greater Hudson Bay Marine Region there are six provincial parks in Quebec, Ontario and Manitoba and three territorial parks in Nunavut. In addition, there are three National Historic Sites and many bird sanctuaries. Table 3 gives details about the existing parks and historic sites and Table 4 lists the bird sanctuaries.

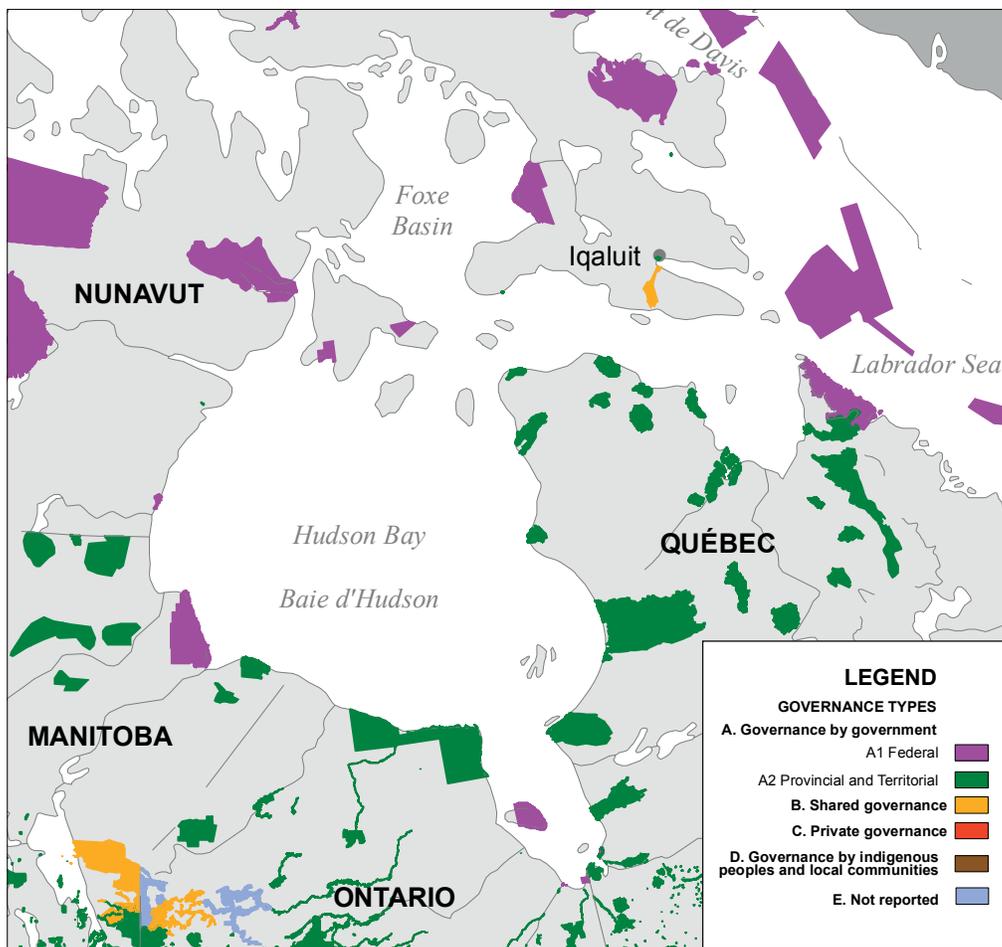
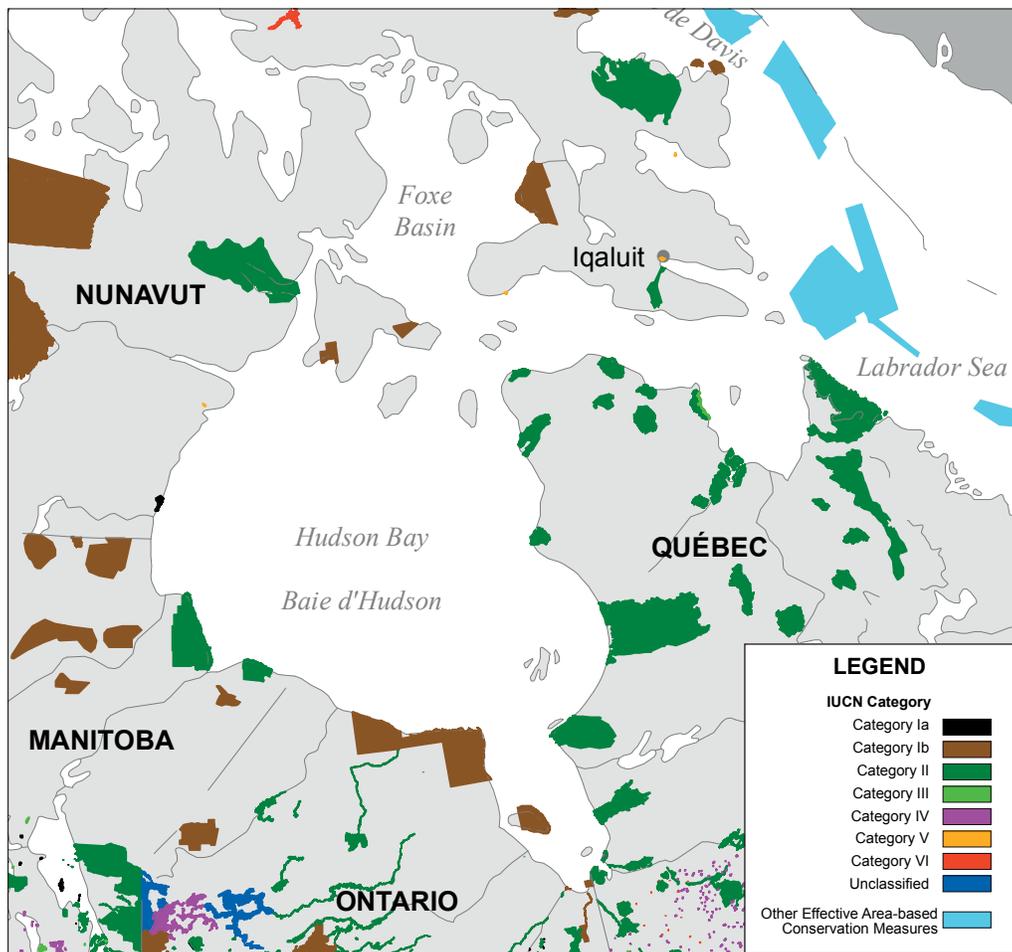


FIGURE 1. Map of the protected area network around the Greater Hudson Bay Marine Region by governance type, adapted from the Canadian Council of Ecological Areas (2017a).



TRAVEL MANITOBA



**FIGURE 2.** Map of the protected area network around the Greater Hudson Bay Marine Region by IUCN category, adapted from the Canadian Council of Ecological Areas (2017b).

TABLE 3. Highlights of parks and historic sites that border on the Greater Hudson Bay Marine Region

Type	Location	Name	Notable Information
National Park	Nunavut	Ukkusiksalik National Park	“Ukkusiksalik”, an Inuktitut term, means “place where there is stone to carve pots and oil lamps”. The park was first proposed as a protected area in 1978; it was established in 2014 following the negotiation and signature of the Nunavut Agreement and the Inuit Impact and Benefit Agreement for Ukkusiksalik National Park of Canada (IIBA) in 2003 (Parks Canada 2018a). The park is jointly managed by Inuit and Parks Canada as required by the Nunavut Agreement and the park’s IIBA.
National Park	Manitoba	Wapusk National Park	Wapusk is the Cree word for “white bear” and this 4430 km <sup>2</sup> park protects one of the world’s largest known polar bear maternity denning areas. Wapusk National Park was established in 1996. In 2016, the State of the Park Assessment noted the need for the inclusion of Indigenous Peoples’ participation in the park management. The key strategies for the ten-year management plan published in 2017 incorporated this recommendation (Parks Canada 2017a).
Provincial Park	Ontario	Polar Bear Provincial Park	The Polar Bear Provincial Park is located along the southwestern shore of Hudson Bay, just north of James Bay. It is the largest Provincial Park in Ontario (23 552 km <sup>2</sup> ) and was established in 1970 as a means of protecting the fragile wildlife habitat of many local terrestrial and marine mammals including the polar bear.
Provincial Park	Ontario	Tidewater Provincial Park	Tidewater Provincial Park is managed by the province of Ontario under partnered agreement with the Moose Cree First Nation. The park was established in 1970 and consists of five islands in the Moose River estuary close to Moose Factory and Moosonee. The surrounding river system (i.e., Moose River) and estuary off the shore of Tidewater Provincial Park is home to Northern Pike, Walleye, and Whitefish. This area is also a haven for many species of bird, including warblers, eagles, herons, and many types of shorebirds, who take advantage of the tidal flats and pools.
Provincial Park	Ontario	Winisk River Provincial Park	The Winisk River Provincial Park is situated solely within terrestrial borders, however the Winisk River is directly connected to the Hudson Bay marine system. Most of the length of the river and its banks from Winisk Lake to the Polar Bear Provincial Park has been designated as a provincial waterway. It is categorized as a non-operating park meaning that there are no visitor facilities or services available.
Provincial Park	Manitoba	Caribou River Park Reserve	The Caribou River Park Reserve was established in 1995, and is located in the northeast portion of Manitoba along the Manitoba/Nunavut border. The park landscape is a transition between the boreal forest and tundra regions with eskers and glacial raised beach ridges that dominate the landscape. Although it is not a coastal Hudson Bay park, the Caribou River Park falls within 50 kms of the coastal edge.
Provincial Park	Québec	Parc National Tursujuq	The Parc national Tursujuq covers an area of 26 107 km <sup>2</sup> making it the largest park in Québec. The primary objective for the creation of this park was to provide protection to representative examples of the Hudson Cuestas and the Hudson Plateau. It also includes the mouth of the Petite rivière de la Baleine and is intended to provide additional protection to unique biodiversity, in particular summer habitat for beluga whales.
Provincial Park	Québec	Parc National Kuururjuaq	The Parc national Kuururjuaq was created in May 2009 and covers 4,460 km <sup>2</sup> between Ungava Bay to Mount D’Iberville at the northern tip of the Québec-Labrador Peninsula. Like all of Nunavik’s parks, it is operated by the Kativik Regional Government (KRG). The park’s focus is the spectacular Koroc River, which flows from the Tornqat Mountains across the George River Plateau to Ungava Bay.

Type	Location	Name	Notable Information
Territorial Park	Nunavut	Katannilik Territorial Park	Katannilik Territorial Park is situated on the Meta Incognita Peninsula of southern Baffin Island. The Park stretches north from the top of Pleasant Inlet near the village of Kimmirut and follows the Soper Valley and Itijjagiq Trail all the way to the south shore of Frobisher Bay. The Itijjagiq Trail is a 120-kilometre traditional overland trail from Iqaluit to Kimmirut along the Soper River designated a Canadian Heritage River in 1992 and remains a culturally significant place for Inuit.
Territorial Park	Nunavut	Mallikjuaq Territorial Park	Mallikjuaq, “big wave” in Inuktitut, is a territorial park situated on Mallik Island, northwest of Cape Dorset. The park consists of rounded rocky hills and low tundra valleys, and has been home to Inuit hunting camps for millennia as seen by the many archaeological sites and stone features scattered along the shorelines. Tundra nesting birds are common in summer, including the Lapland longspur, snow bunting, and horned lark. Caribou and arctic hares are only occasionally found in this park, while marine mammals such as ringed seals and beluga whales can often be seen just off the coast.
Territorial Park	Nunavut	Inuujaarvik Territorial Park – Baker Lake	The Inuujaarvik Territorial Park is a small park just south of the community of Baker Lake community. It is designated as a campground for visitors and used by canoeists traveling from the Thelon and Kazan Heritage Rivers.
National Historic Site	Manitoba	Prince of Wales Fort National Historic Site	Built between 1731 and 1771 by the Hudson’s Bay Company, the National Historic Site includes nearby Cape Merry Battery and the winter harbour of Sloop Cove. Parks Canada’s management plan lists the protection of commemorative integrity; facilitation of meaningful visitor experiences; and fostering public appreciation and understanding of Parks Canada’s heritage places (Parks Canada 2011).
National Historic Site	Manitoba	York Factory National Historic Site	York Factory National Historic Site sits on the shore of the Hayes River. Operating between 1684 and 1957, York Factory was one of the oldest and most important fur trade establishments of the Hudson’s Bay Company and a large, vibrant community, known as Kihci-wâskâhikan in the Cree language. York Factory, a national historic site administered by Parks Canada, includes a management plan that involved the exchange of information and ideas among Parks Canada staff from a number of research and management functions, First Nations communities associated with York Factory, tour operators and outfitters, professional engineers and scientists outside of Parks Canada, and interested public (Parks Canada 2018b).
National Historic Site	Nunavut	Arvia’Juaq and Qikiqtaarjuk National Historic Site	This historic site is comprised of two portions: Arvia’Juaq and Qikiqtaarjuk. Arvia’Juaq is a traditional summer camp of the Paallirmiut Inuit located on Sentry Island. The area is a 5 km long island joined in the middle by a thin isthmus, and is located 8 km off the coast from the Hamlet of Arviat on the western shore of Hudson Bay. Situated in an area rich in marine wildlife resources, the island contains many ritual and spiritual sites. Qikiqtaarjuk is a point of land projecting into Hudson Bay from the mainland immediately opposite Arvia’Juaq. These historic sites were recognized in 1995 by the Government of Canada through the Historic Sites and Monuments Act (R.S.C., 1985, c. H-4) (Parks Canada 2019). Arvia’Juaq and Qikiqtaarjuk National Historic Site is not administered by Parks Canada.
National Historic Site	Nunavut	Inuksuk National Historic Site of Canada	Inuksuk National Historic Site of Canada is situated on the Foxe Peninsula, approximately 88.5 km from Cape Dorset on Baffin Island, Nunavut. Two groups of Inuksuit exist on this site, approximately 100 of which remain standing. The Inuksuit consist of carefully piled stones placed to form cairns. The grouping of cairns may have been built as long as two thousand years ago. Inuksuk National Historic Site is not administered by Parks Canada.

TABLE 4. Bird sanctuaries in the Greater Hudson Bay Marine Region

Location	Name	Notable Information
Ontario	Moose River Migratory Bird Sanctuary	The Moose River Migratory Bird Sanctuary comprises two separate landmasses situated at the mouth of the Moose River on the southwest side of James Bay. These include Ship Sands Island - located along the west side of the Moose River - and a section of mainland on the east side of the river. Tidal creeks cut into the sanctuary, while freshwater creeks flow through the sanctuary and into James Bay. The sanctuary provides a large, undisturbed feeding and resting area for migrating geese.
Ontario	Hannah Bay Bird Sanctuary	The Hannah Bay Bird sanctuary is managed by the Province of Ontario, and like other coastal parks in the Hudson Bay region, areas below the hide-tide mark are managed by the Government of Nunavut. This sanctuary was established in 1958, and is situated along the southernmost coast of James Bay, and its eastern edge borders the Province of Québec. Its southerly location along the funnel-shaped Hudson and James bays results in migrating birds from across the Arctic to concentrate here each fall. This sanctuary's extensive tidal flats and marshes attract both the Lesser Snow Geese and Canada Geese, along with thousands of shorebirds. The coastal portion of the sanctuary is important as a moulting area for Canada Geese.
Nunavut	Harry Gibbons Bird Sanctuary	The Harry Gibbons Migratory Bird Sanctuary is located within the Kivalliq region of Nunavut on Southampton Island. It is within the drainage basin of the lower Boas River and includes the delta and estuary. It was established in 1959 to protect the main nesting areas of Lesser Snow Geese.
Nunavut	East Bay Migratory Bird Sanctuary	This sanctuary is also located on Southampton Island in the Kivalliq region of Nunavut. It includes the marine waters of East Bay and most of the lowland terrestrial area west of the Bell Peninsula between East Bay and Native Bay. It supports important nesting habitat for Lesser Snow Geese.
Nunavut	Dewey Soper Migratory Bird Sanctuary	Established in 1957, this was the first Arctic bird sanctuary. It was created to protect the Lesser Snow Geese and their nesting and feeding habitat. It is estimated that up to 1 million geese nest in the sanctuary and adjacent areas. It supports the largest known Lesser Snow Geese colony in the world.
Nunavut	Bowman Bay Wildlife Sanctuary	Bowman Bay is a wildlife sanctuary located within the Great Plain of the Koukdjuak River on western Baffin Island near Foxe Basin. This sanctuary protects the nesting grounds of the Blue goose.
Nunavut	Akimiski Island Bird Sanctuary	The Akimiski Island Bird sanctuary is situated in mid-western James Bay, near the mouth of the Attawapiskat River. The closest community is Attawapiskat in Ontario however the island is within the Qikiqtaaluk region of Nunavut. Akimiski Island is a critical stopover for migratory geese, ducks and shorebirds, including tens of thousands of snow geese. In addition to its importance for migratory birds, Akimiski Island is a maternity den area for polar bears.
Nunavut	McConnell River Migratory Bird Sanctuary	The McConnell River Migratory Bird Sanctuary is located in the Kivalliq Region of Nunavut on the west coast of Hudson Bay just south of the community of Arviat. The sanctuary protects important breeding grounds for a variety of geese. It is also home to four species of special concerns listed under the species at Risk Act: Polar Bear, Rusty blackbird, Short-eared Owl and Peregrine Falcon.
Québec	Boatswain Bay Migratory Bird Sanctuary	The Boatswain Bay Migratory Bird Sanctuary was established in 1941 and is located in south eastern James Bay 35 km north of the Cree community of Waskaganish. The 162.9 km <sup>2</sup> area is in the natural province of the Abitibi and James Bay Lowlands. It is an important nesting and staging area for numerous waterfowl and shorebirds during the spring and fall migrations. Species include Canada Geese, Lesser Snow Geese, Brant and Black ducks. Twenty six species of shore birds are known to frequent the area. It also provides habitat for Yellow Rails, Short-eared owls, Nelson's Sparrows and Sandhill Cranes.



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#### 4. Overview of ecological and biological protection needs

The Greater Hudson Bay Marine Region is comprised of four distinct marine regions—James Bay, Hudson Bay, Foxe Basin and Hudson Strait—each with common and distinct ecological and environmental characteristics (see Introductory Chapter for a description of the physical and ecological characteristics of the Marine Region and its sub-regions). DFO (2011) identified Ecologically and Biologically Significant Areas (EBSAs) in the Canadian Arctic, including in the Greater Hudson Bay Marine Region, based on the criteria of uniqueness, aggregation, fitness consequences, and presence of rare or endangered species (Figure 3). The large majority of the coastline of the Greater Hudson Bay Marine Region falls within EBSAs.

Sponges and deep sea coral beds are considered important for providing structural complexity to marine habitats; they support benthic communities and host many associated species (DFO 2010) manage, and exploit fish stocks in a sustainable manner, as well as to manage the impacts of fishing on sensitive benthic areas and vulnerable marine ecosystems. In support of these commitments and initiatives, and in response to requests for advice from various sectors within DFO, a national science advisory process was held (March 9-12, 2010; Ottawa. In a DFO study of benthic EBSAs, areas of Hudson Strait were shown to have relatively high concentrations of soft corals and sponges compared to other areas within the Greater Hudson Bay Marine Region (Kenchington et al. 2011). The density of coral and sponge beds in Hudson Strait and Ungava Bay are key factors contributing to numerous benthic EBSAs in this area.

**Box 1. Ukkusiksalik National Park marine ecosystem**

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**Ukkusiksalik (oo-koo-sik-salik) National Park** is located approximately 150 km south of the community of Naujaat (Figure 1), protecting 20,880 km<sup>2</sup> of tundra and marine ecosystems. The park represents the geology, physiography, vegetation, and wildlife of the Central Tundra Natural Region (Parks Canada 1997); it is also located within the Foxe Basin marine region (Parks Canada 1995). Ukkusiksalik National Park was first proposed as a protected area in 1978 and it was established following the negotiation and signature of the *Nunavut Agreement* (1993) and the *Inuit Impact and Benefit Agreement for Ukkusiksalik National Park of Canada* (IIBA) in 2003. The park has been administered as a national park since 2005 and was fully established under the *Canada National Parks Act* in 2014 (Government of Canada, 2014). Inuit and Parks Canada jointly manage the park. Naujaat, Coral Harbour, Chesterfield Inlet, Baker Lake and Rankin Inlet are identified in the IIBA as the communities that have a special relationship with the park. Most members of the Joint Inuit-Government Ukkusiksalik Park Management Committee (UPMC) have come from these communities.

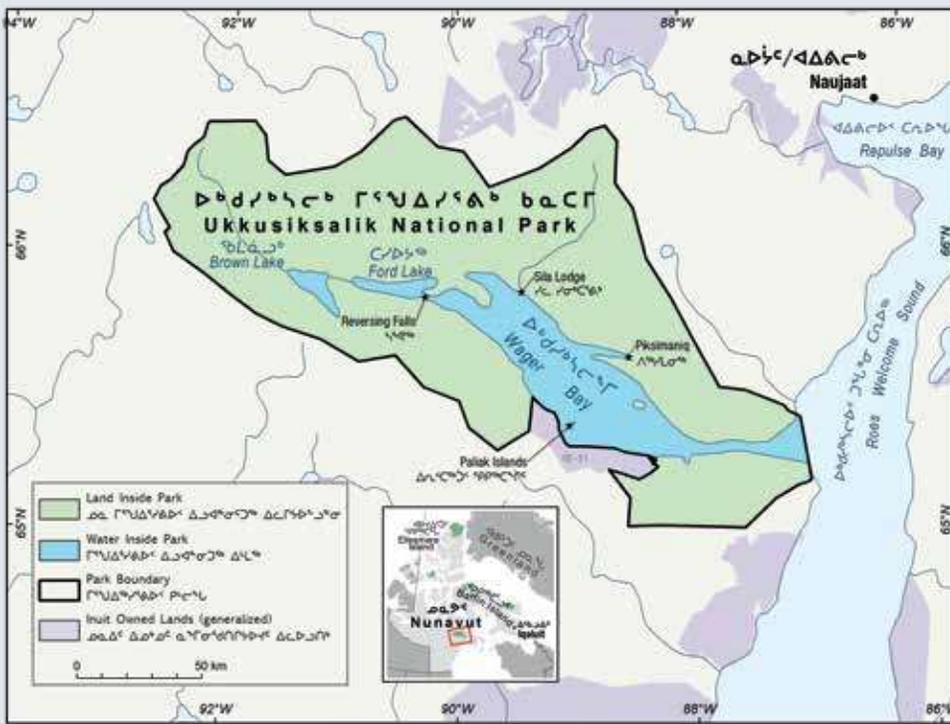
The park includes Wager Bay, a large (approximately 3,000 km<sup>2</sup>) and inlet with strong tidal currents, particularly through the narrow channel that connects Wager Bay to Roes Welcome Sound and Hudson Bay. During flood tide, saltwater flows into Tasiujaq (Ford) Lake through the so-called Reversing Falls (Sarvaq), creating saline bottom waters in the Lake (Wedel, 1997). The inclusion of a large marine component like Wager Bay within a Canadian National Park reflects the ecological and cultural importance of Wager Bay to Inuit of the Kivalliq region of Nunavut, who continue to maintain a strong connection to the land and the Bay.

**Wager Bay (Ukkusiksalik National Park) marine baseline study – 2016**

Few research efforts have taken place in the marine environment of Wager Bay (Parks Canada 1977; Dredge and McMartin 2005; Jefferson et al.; Ukkusiksalik Inuit Knowledge Working Group; Mouland and Manseau 2013). As a result, a basic understanding of the ecosystem function, habitat, and oceanographic setting of Wager Bay and what role this large inlet has in the greater Hudson Bay marine region is not well known. In fact, prior to 2016, Wager Bay was completely uncharted with

the exception of a single bathymetric track through the Narrows (Canada 1977). Although mining activity is not permitted within the park boundaries, there is the potential that future mines outside the Park could ship ore through Wager Bay. The project aimed at helping prepare for an increase in tourism and to plan for future assessments of the environmental effects of neighbouring mining and other activities.

To prepare for possible ship traffic in addition to developing plans for resource management, tourism, and research priorities for this young park, the Parks Canada Agency in collaboration with the Government of Nunavut, Department of Environment’s Fisheries and Sealing Division initiated and supported a multi-disciplinary marine baseline study of Wager Bay (Ukkusiksalik National Park) in 2016. The study



**FIGURE 1.** Map of Ukkusiksalik National Park as well as the major rivers, lakes, and islands (map created and provided by the Parks Canada Agency) (Note: Sila Lodge is not currently within the park boundary.)

included a Western science and an Inuit knowledge component. The study priorities and locations of interest within Wager Bay for the scientific component of the project were based on a preliminary assessment by Parks Canada of areas that are likely to see the most boat activity in the near future, and was discussed with the Ukkusiksalik Park Management Committee.

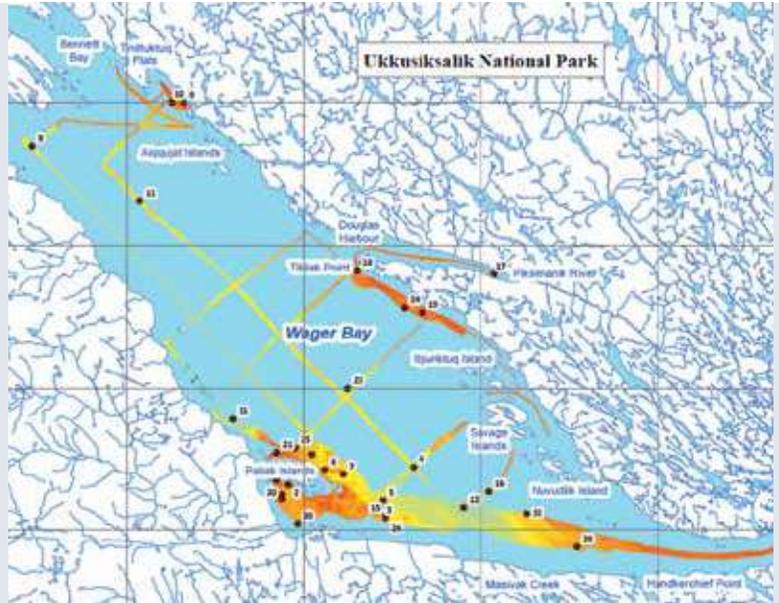
The Inuit knowledge component of the marine baseline study was initiated in 2015. The park's Inuit Knowledge Working Group (IKWG) provided advice to Parks Canada on collecting Inuit knowledge of the marine ecosystem of the park. Workshops between Parks Canada and Inuit who have lived or worked in the park were held in 2016 and 2017. A report on the Inuit Knowledge shared during these workshops was in progress at the time this IRIS report was being produced.

The Western science component of the baseline study was conducted from the *FRV Nuliajuk* and a smaller Parks Canada boat and involved researchers from the University of Manitoba, the Université du Québec à Rimouski (that research team is now at Laval University), Memorial University of Newfoundland, the Canadian Hydrographic Service, and Department of Fisheries and Oceans. Data was collected on tides, bathymetry, water chemistry, plankton, historical contaminants recorded in sediments, benthic species diversity and abundance and seabed habitat. This data was collected from three priority marine areas within Wager Bay: at the mouth of Sila River, Paliak Islands, and Douglas Harbour.

Many of the results from this marine baseline study were not yet published in peer-reviewed literature at the time of this publication. However, the multibeam bathymetric survey (see Figure 2) and preliminary observations from the field campaign (presented at conferences, for example) have already significantly improved understanding of the system and, in addition to other data collected, will be indispensable in guiding future research in Wager Bay. For example, the reconnaissance multibeam survey showed some interesting geomorphological features in the seafloor including surprising shallow shoals along the north side of the bay and a very deep (>300 m) channel along the southern shoreline west of the Paliak Islands. A report compiling the results of the Western science and Inuit Knowledge components of the project will be available through Parks Canada.

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**FIGURE 2.** A preliminary map of the first multi-beam bathymetric survey of Wager Bay (Ukkusiksalik National Park) conducted in 2016 from *FRV Nuliajuk*. The colours represent the depth of Wager Bay with dark blue being depths of > 350 m and red being shallow depths of near 0 m. The numbered black points are where a sound velocity cast was performed. The preliminary map was prepared by Kirk Regular from the Fisheries and Marine Institute of Memorial University of Newfoundland.

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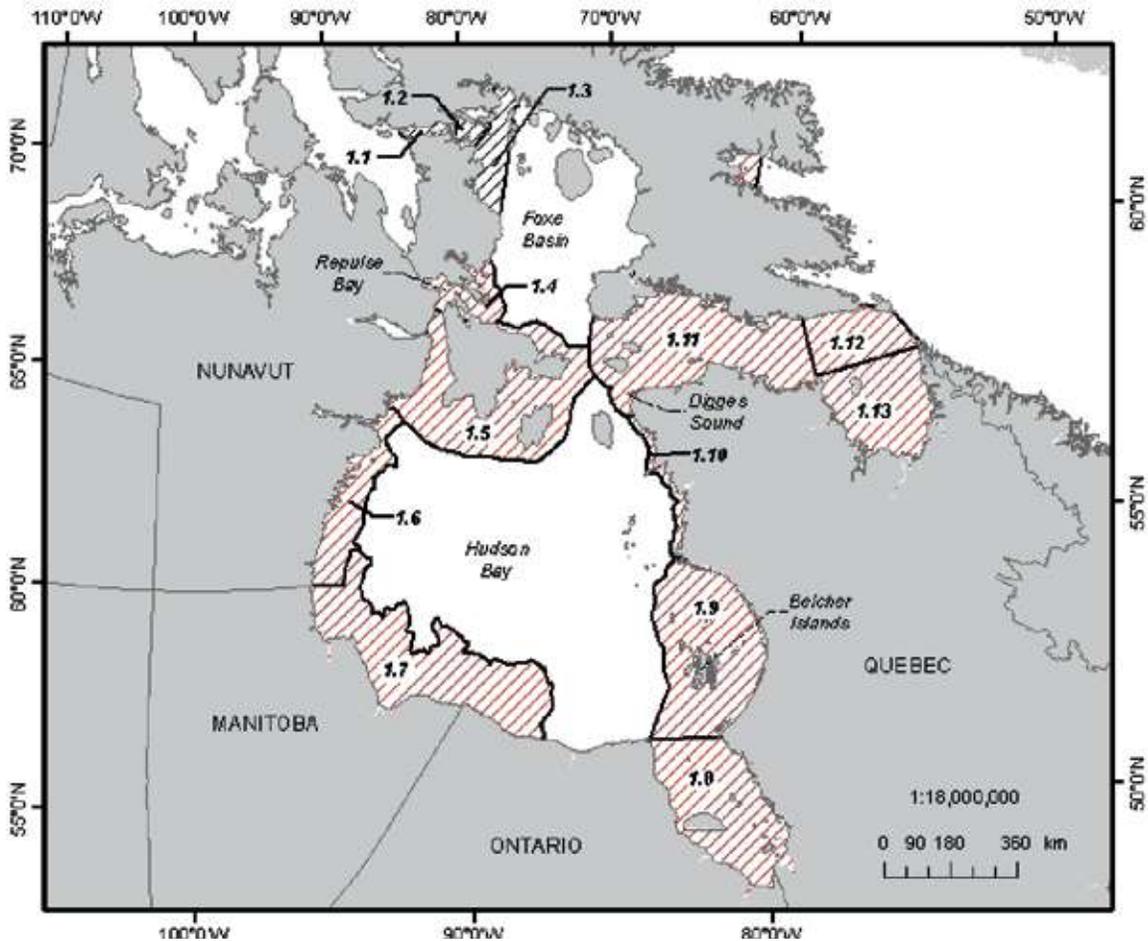
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**FIGURE 3.** Ecologically and biologically significant areas (EBSAs) within the Greater Hudson Bay Marine Region (DFO 2011).

Syntheses by Mallory and Fontaine (2004) and these areas support tremendous numbers of marine birds. At the start of the 21st century, the Canadian marine zone is the subject of much concern as a result of a variety of anthropogenic threats. The Canadian Wildlife Service (CWS and Latour et al. (2008) identify marine and terrestrial sites of importance to migratory birds in the Arctic, including numerous sites in the Greater Hudson Bay Marine Region. BirdLife International has developed internationally-recognized criteria for identifying Important Bird Areas that support threatened birds, large groups of birds, and birds restricted by range or habitat. The Marine Region hosts numerous Important Bird Areas along its coasts as shown in Figure 4. Table 4 (in section 3 above) lists the bird sanctuaries associated with many of these Important Bird Areas.

There are several species of conservation concern that reside or use the Marine Region. Under COSEWIC, the Eastern Canada-West Greenland bowhead population, Atlantic walrus,

and narwhal are all listed as special concern, while the Eastern Hudson Bay and Ungava Bay beluga whale populations are listed as endangered (COSEWIC 2004a; 2004b; 2009; 2017). Polar bear is listed as special concern under COSEWIC and the *Species at Risk Act* (SARA) (COSEWIC 2008)000 years to occupy the niche of hunting seals from a sea-ice platform. Many of the physical traits of polar bears can be viewed as adaptations to hunting arctic seals. Distribution Polar bears are a circumpolar species that occur in Canada from Yukon to Newfoundland and Labrador, and from northern Ellesmere Island south to James Bay. The population is distributed among 13 subpopulations with some evidence for genetic separation between them. The length and frequency of seasonal movements undertaken by bears within subpopulations varies with the size of the geographic area occupied, the annual pattern of freezing and break-up of sea ice, and availability of features such as land masses, multi-year ice, and polynyas. Distinctions between subpopulations or larger-scale divisions based on ecoregions



FIGURE 4. Important Bird Areas in the Greater Hudson Bay Marine Region (BirdLife International 2018).



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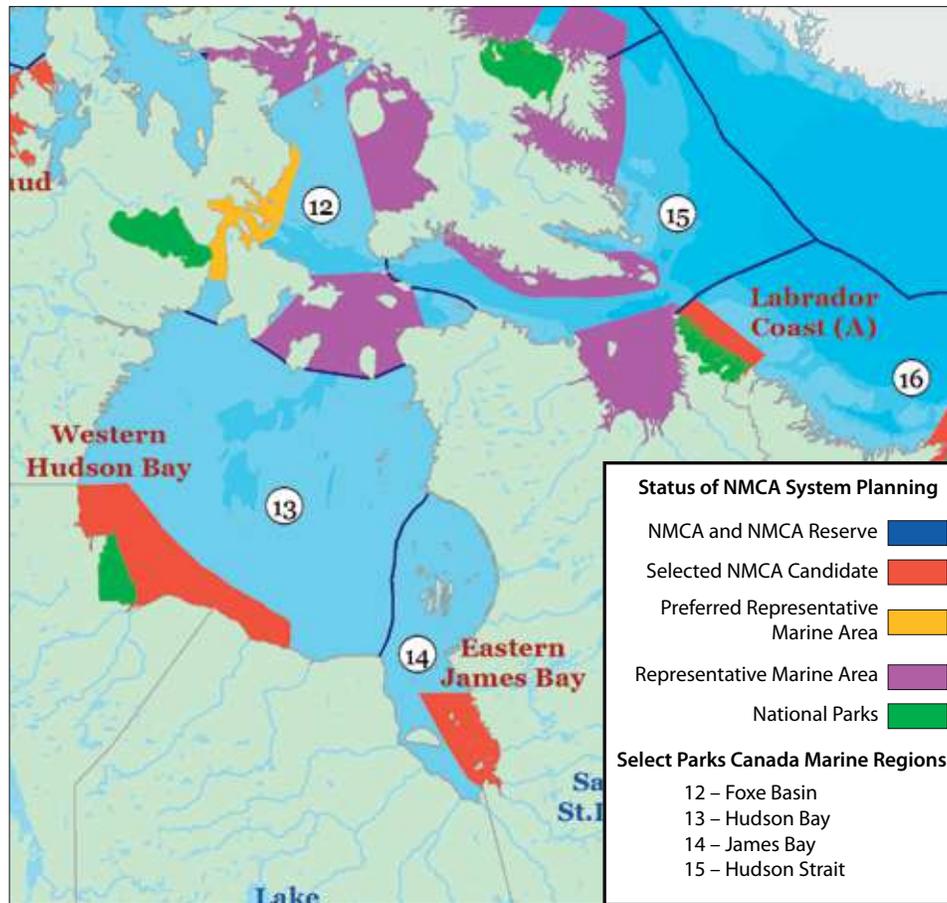
are insufficient for status to be assigned to designatable units below the species level. Habitat The productivity of polar bear habitat is closely linked to the physical attributes of sea ice (type and distribution).

When discussing climate change and associated impacts, the conversation must include not only focus on biophysical impacts but also social and cultural impacts. Inuit and Cree continue to depend heavily on the marine environment for food security, cultural well-being and identities. Climate change and development have had significant measurable impacts on their lives. The predicted change in temperatures, the changes to the sea ice regime and precipitation may well lead to significant, permanent changes in the overall marine and coastal environment. Add to this the effects of hydro development and new transportation corridors to support industry and community supply, it becomes clear that within this region there is the need for increased research, monitoring and conservation. It is imperative that Indigenous peoples and their knowledge lead these initiatives.

## 5. Marine protection challenges and opportunities

The Greater Hudson Bay Marine Region is governed by a complex and sometimes confounding mix of provincial and territorial authorities, self-government agreements, land claims agreements, and pending land claims, all of which need to be harmonized. This can create political, policy and legal roadblocks to the establishment of protected areas. At the same time, the regimes set out in land claims agreement can accelerate the process. A full discussion of the governance in the Greater Hudson Bay Marine region is included in the introductory chapter.

A good portion of eastern James Bay, eastern Hudson Bay and Hudson Strait is covered by land claims agreements, notably the Eeyou Marine Region Land Claims Agreement, the Nunavik Inuit Land Claims Agreement and the Nunavut Land Claims Agreement. These agreements also create overlap areas and provide for the rights of each group within the overlap areas.



**FIGURE 5.** Status of NMCA System Planning relevant to the Greater Hudson Bay Marine Region. Adapted from a map provided by Parks Canada, 2018 (pers. communication).

There is also a mix of federal and territorial jurisdiction. North of the 60<sup>th</sup> parallel, the water is under the jurisdiction of the Government of Nunavut. South of the 60<sup>th</sup> parallel, the Federal government has jurisdiction over waters. Islands in Hudson Bay, James Bay and Ungava Bay south of the 60<sup>th</sup> parallel remain under the jurisdiction of the Government of Nunavut. Also relevant to this discussion is the lack of certainty regarding the coastal boundaries of Quebec.

Québec deems marine areas between two points of land (bays) within its jurisdiction; this conflicts with federal interpretation and thus with the Eeyou Marine Region Land Claims Agreement and the Nunavik Inuit Land Claims Agreement, as Québec was not a signatory to these agreements. This issue complicates matters related to MPA development (e.g., development of an MPA with a coastal component, development of an MPA that requires federal title) and may prove to be a roadblock in the future. MPA development in the Estuary and Gulf of St. Lawrence is driving the creation of a federal-Québec

agreement to resolve this issue for the explicit purpose of MPA development.

Even with all the jurisdictional challenges, there are currently two areas that have been selected as NMCA candidates within the Marine Region (Figure 5). Parks Canada and the Cree Nation Government are completing the negotiation of a memorandum of understanding regarding an NMCA in eastern James Bay. The other candidate area is along western Hudson Bay, a migration destination for moulting, calving, and feeding for over one-quarter of the global beluga whale population. The candidate area also borders on Wapusk National Park. DFO is about to publish an ecological and biophysical overview of the proposed 'Area of Interest' for the Southampton Island Ecologically and Biologically Significant Area (SI EBSA). Sanikiluaq (NU) is hosting meetings in 2019 to further their exploration of marine protection options relevant to eider ducks and other wildlife that rely on ice-covered coastal habitats including polynyas. There are several other areas within the

Greater Hudson Bay Marine Region that are in various stages of exploring the available options for protected area designations. Some are still in the consultation stage while others are near finalization with the expected designation to be announced in the near future.

## 6. Conclusions

Protected areas have an important role to play in the national and global response to climate change and industrialization. Currently, the networks of protected areas have been designed to protect specific natural features, species and communities (Lemieux et al. 2010). Future protected areas need to take into account the major shifts in ecosystems that are currently happening, and look at protecting areas that are changing and areas that may be important refuges for adapting species (Lemieux et al. 2010).

Protected areas also play a role in mitigation and adaptation and help Indigenous peoples and communities increase resilience and reduce vulnerability to the impacts of climate change by providing a range of ecosystem services such as continuing access to wildlife for food and protection of cultural spaces. Recently, involvement of Indigenous peoples in conservation planning that meets their needs is seen by the Federal government as an avenue for advancing reconciliation. Science and Indigenous knowledge both have an important role to play in determining where and how conservation efforts are directed.

The overview of protected areas in the Greater Hudson Bay Marine Region reveals that while there has been good progress on the establishment of a variety of land-based protected areas with coastal and marine components, there are no Ocean Act MPAs and the region remains unrepresented in the NMCA system plan. At the same time, the region is relatively undisturbed and untouched by industrial development. At present, the main concern lies with managing marine transportation for community supply, Port of Churchill activities, and mining. The relative absence of immediate threats aside from climate change and other large-scale environmental changes provides a good opportunity for partners to engage in integrated land use and conservation planning. Of note is the recent initiative between Parks Canada and the Cree Nation Government to develop a Memorandum of Understanding to conduct a feasibility assessment for a national marine conservation area in the Eeyou Marine Region.

Designation of an area as a National Marine Conservation Area (NMCA) allows for a range of activities and ecologically sustainable uses, while ensuring protection of ecosystems, special and representative features and sensitive elements of

the area. While all NMCAs prohibit exploration and exploitation of hydrocarbons and minerals, and strict restrictions on ocean dumping, the range of specific activities and uses that may occur in an NMCA may vary, depending on the particular circumstances of the NMCA.

Planning, from the perspective of Indigenous peoples, is not simply a technical exercise. Rather it is a process through which their interests can also advance. It must be supported by investments in research, science and working with local knowledge holders. Governments for their part must be more flexible and open to adjusting policy and regulatory frameworks to support partnership and new outcomes. Recent Federal initiatives through the Inuit-Crown Partnership Committee and work on the development of a new Arctic Policy Framework are providing opportunities for positive steps forward.

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### III. iv.

# Tourism in the Greater Hudson Bay Region

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## Summary

The Arctic and Subarctic are no longer the exclusive realm of adventurous and affluent travellers. Within the Greater Hudson Bay Marine Region most of the tourism is associated with marine mammal viewing (beluga whales, polar bears and walrus), aurora viewing and hunting and fishing. Like all issues in the Region there is controversy in regards to tourism. There are costs and benefits to the activity. Small communities can be easily overwhelmed by large numbers of tourist disembarking from cruise ships. Some people feel there is a tension between the pursuit of science, conservation and tourism that has an enormous per capita carbon footprint. On the other hand, sustainable arctic tourism suggests collaboration between tourism and local community members as well as conservation and research organizations, which could create economic growth.

## Key Messages

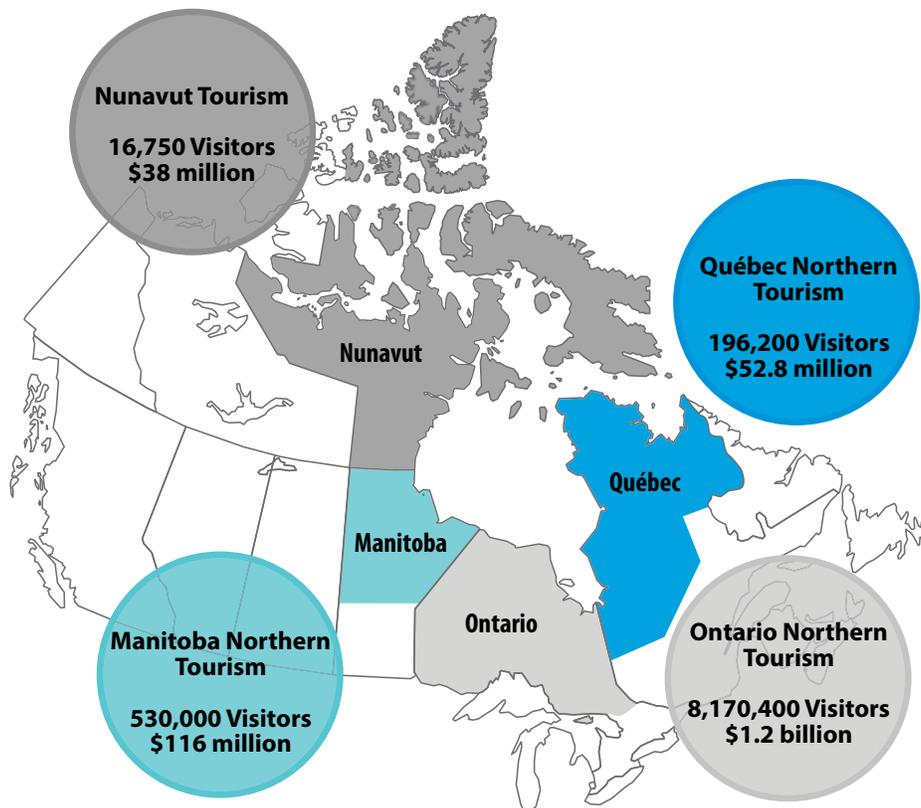
- **Tourism is related to the global economy and the sort of tourism available in the region. Examples include marine mammal viewing, aurora viewing, and fishing.**
- **Sea ice retreat has increased marine tourism throughout the Arctic, with the 'last chance' tourism mentality. Examples include edge floe tourism and polar bear viewing.**
- **The growth of tourism is dependent on the accessibility of the region, the promotion of the region and the infrastructure to receive tourists. Within most communities of the Greater Hudson Bay Marine Region there is a lack of infrastructure to receive a large number of tourists. In order to sustainably promote tourism in the region there will be costs and challenges associated with building or improving the infrastructure.**
- **Increases in tourism may come with an increase in emergency response and search and rescue needs.**

## 1. Introduction

The beauty and rich, diverse habitat of the Greater Hudson Bay Marine Region and the surrounding terrestrial habitat has long drawn travellers and visitors to the region in search of resources, understanding and inspiration. The harsh sub-arctic and arctic climates and the remarkable vistas present challenges for visitors, but the rich rewards have continued to bring visitors to the North to experience the environment for themselves. The success of tourism in the Hudson Bay region depends largely on the wildlife viewing opportunities that exist and the facilities that are in place (e.g., lodge, hotel, boats, off-road vehicles, air support) that offer visitors enjoyable and unique experiences. Another element is the Inuit Art aspect of communities such as Cape Dorset in Hudson Strait. There is also an increasing interest in participating in one-on-one integrated experiences with northern community members. All of these types of tourism bring economic benefits to the region.

Tourism in the region has flourished in recent years, particularly with land-based tourism opportunities developing offerings that have welcomed numerous visitors (see

Figure 1). The tourism industry has traditionally focused on polar bear viewing with the recent additions of summer time beluga whale watching and winter-based northern lights viewing. Backcountry lodges and outfitters also continue to offer excellent hunting and fishing opportunities in the region. The industry is particularly well developed in Manitoba and Ontario, where communities are accessible by rail, with tourism in Quebec increasing due to the road access to Cree communities in Eastern James Bay. As a whole, the province of Manitoba recorded just over 11 million person visits in 2014 that yielded approximately \$1.6 billion in total visitor spending (Travel Manitoba 2017). The entirety of the Northern tourism region in Manitoba captured around 5% of these visitors (530,000) and \$116 million in total visitor spending. In 2015, the province of Ontario recorded nearly 142 million person visits and approximately \$25.4 billion in visitor spending. As a whole, the three sub-regions that comprise Ontario's Northern tourism region accounted for about 6% (8,170,400) of total visits and approximately \$1.2 billion in total visitor spending. In 2015, Tourism Nunavut estimated that 16,750 people visited Nunavut and were responsible for a total of \$38 million in visitor spending



**FIGURE 1.** A map showing the number of visitors to the northern regions of Manitoba, Ontario and Québec as well as Nunavut and the estimated economic benefits.



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(Nunavut Visitor Exit Survey 2015). In 2016, Tourisme Québec reported that 32.7 million visitors for all of Québec with a total spending of \$8.8 billion. Of this 0.6% were reported to visit James Bay, Duplessis, Eeyou Istchee and Nunavik or approximately 196,200 visitors spending \$52.8 million.

With limited transportation access to the Greater Hudson Bay Marine Region, the continued visits by government and military personnel and researchers enhances the economic development of the region and will provide information and resources that may be used by present and future tourism offerings. Remote access to these habitats throughout Hudson and James Bay are also used widely by technology users who virtually visit the sites. While opportunities for cruise tourism exist in the region, there only a few ships and routes that include a visit to Hudson Bay in their itineraries.

## 2. Polar tourism

Throughout history, Indigenous people have expressed their belief in an interconnected world where nature is seen as a closely woven community of living beings with a strong spiritual

presence (Brandson 2011) and many travelled widely on the land for the resources and experiences. While travel for strictly tourism purposes can be traced back to the late 1800s in the Arctic, the modern era of polar tourism is commonly regarded to have commenced in the 1960s when communities in the Arctic began to embrace the development opportunities and potential of nature-based, cultural and business tourism (Stewart et al. 2017). Polar tourism research continues to develop and has established itself as a field that creates and expands the understanding of polar tourism phenomena, with many of the researchers participating in this field having worked in the Churchill region (e.g., Stewart, Dawson, Lemelin, Groulx). The increasing interest in polar tourism research by policy makers (e.g., The Arctic Council Arctic Marine Tourism Project in 2015) has shown the strategic importance and benefits of polar tourism and the related research field (Stewart et al. 2017).

The Arctic and Subarctic have joined the list of places that were once the exclusive realm of adventurous and affluent travellers. While the costs of travelling to the region are still high the meaningful benefits like local economic development and environmental education (Dawson et al. 2010) make travel more attractive to a wider demographic. This group also includes



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the traveller who may visit an area on last chance tourism (LCT), a phenomenon where tourists seek out disappearing landscapes and/or natural and social features to visit (Groulx et al. 2016). This distinct travel motivation may draw visitors to parks and protected areas, set aside to protect species and/or undisturbed habitat for the future. The desire to collect travel experiences before they are gone happens in many places, but in the polar regions the reaction to the perceived irreversible impacts of climate change presents new opportunities for LCT (e.g., polar bears on melting chunks of sea ice) (Dawson et al. 2010). In a case study in Churchill, MB, Groulx et al. (2014) found that while LCT played a role in tourists' motivation to visit, the desire to share a connection to nature with similar individuals, and to become part of the local story was also important. The visitors' sense of place identity and natural relatedness also contribute significantly to their motivation (Groulx et al. 2014).

### 3. Indigenous tourism

Indigenous tourism can be defined as a tourism activity in which Indigenous people are directly involved either through control and/or by having their culture serve as the essence of the attraction. Throughout the Hudson Bay region there are many examples of Indigenous operated tourism that are widely promoted including dogsledding, guided hunting expeditions, and wildlife viewing safaris (Lemelin et al. 2015). There are also many Indigenous operated art galleries and cultural sites in the region such as the Matchbox Gallery in Rankin Inlet, the Itsanitaq Museum in Churchill and the Chisasibi Cultural Museum. In addition to Indigenous tourism, tourists who visit a site may experience cultural tourism by looking at an oil lamp and learning about the historical and modern-day significance of snow shelters to the local people. The interpretation provided with the opportunity is a key aspect to ensuring the tourist has made the connection to the local culture.

### 4. Other land-based tourism opportunities

There is a wide range of other land-based tourism activities that are occurring in the Hudson Bay region. Many of these opportunities also involve wildlife viewing (e.g., Churchill Wild and Arctic Kingdom). Along the northwestern shores of Hudson Bay, the communities of the Kivalliq Region offer opportunities to venture out on the land on cross-country skis, by dog sled, snowmobile or ATV as a great way to enjoy the natural serenity of the coastal region. Many communities in Nunavut, Nunavik, Ontario, Quebec and Manitoba offer exhilarating dogsledding



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runs/tours for visitors. At various times of the year in local communities there are snowmobile races, igloo building competitions and music festivals that celebrate the culture and musical heritage of local regions (e.g., the Inuumariit Music Festival in Arviat). Local fishing is popular in communities across the region of Hudson Bay and James Bay. Many outfitters and backcountry lodges offer opportunities in more remote locations away from communities for fishing and hunting packages for non-residents (e.g., Nunavik Tourism Association).

Arctic tourism has seen major shifts in the last decade as global events and local developments have affected the industry, this is particularly true in communities in Nunavik. Recent events in Kuujuaq included the controlled caribou sports hunt in 2010–11 and the transition (in 2010) from the regionally owned Cruise North Expeditions to a joint venture between Cruise North and Adventure Canada (Lemelin et al. 2012). In many communities, tourism diversification strategies include encouraging local entrepreneurs and associations to establish home grown programs like the Aqpik Jam Festival, Hudson Bay Quest sled-dog races and the development of other specialized cultural tours.

## 5. Cruise tourism

Longer periods of open water in arctic sea ice have created the potential for an increase in ship-based tourism in other areas of the Canadian Arctic. Cruise lines travelling in this region are dominated by exploration/soft adventure cruise brands that operate relatively small vessels (120 to 300 passengers) and do not require extensive marine terminal type infrastructure. Some of the limits to cruise tourism include the lack of maritime infrastructure in the North to support the operations (Stewart et al. 2013), the lack of search and rescue operations (Stewart et al. 2011) and the additional strain these arctic rescue missions put on local arctic communities (Stewart et al. 2015). The complexity of regulations in the Arctic also present some challenges for cruise tourism (Dawson et al. 2017). For more information see the Transportation Chapter (Theme III. Chapter ii).

Cruise tourism tends to focus on the journey through the historically important Northwest passage (e.g., Crystal Serenity cruise in 2016 with 1,000 passengers on board) with fewer ships making their way into Hudson Bay. Between 2006, 2008 and 2009, Stewart et al. 2010 reported an overall decline

in cruise tourism in Hudson Bay. The decline was linked to the shortening duration of sea ice conditions that decreases the opportunity for prime arctic marine wildlife viewing opportunities (e.g., polar bear, walrus) that are often associated with expedition cruising. In western Hudson Bay, Churchill is the main community destination for cruise tourism (Stewart et al. 2010) but visits by cruise ships are often short (day visits) that offer limited opportunity for cultural, commercial and nature-based tourism experiences in comparison to the larger land-based tourism opportunities. Other Nunavut communities like Arviat, Rankin Inlet and Chesterfield Inlet have also been sporadically visited by cruise ships, commonly Silversea Cruises. In 2019, Churchill Cruises has a 14-day offering departing from Churchill and continuing to Rankin Inlet, Coats Island and north to Cape Dorset before continuing on to Baffin Bay and Greenland. In eastern Hudson Bay, Inukjuak welcomed four cruises in 2006 but few ships have visited since, likely reflecting the lack of demand for cruises on the eastern shores of Hudson Bay. In the north part of Hudson Bay the most common shore location visits are to Digges and Mangel Islands where polar bear and walrus are often found (Luk et al. 2010).

## 6. Tourism through research facilities and remote users

Other visitors include the scientists, government and military personnel. With increasing interest in the Arctic from international nations, there will likely be sustained demand for

in these activities. The first European scientists to winter in Hudson Bay were with the Royal Society; William Wales and his assistant Joseph Dymond. In 1768-1769, they overwintered at the Churchill Hudson Bay Company post to conduct measurements during the transit of Venus across the sun in 1769 (Brandson 2011). Today, researchers collaborate with local communities to develop a deeper understanding of the local environment driven by knowledge sharing and technology advances. There are a number of active terrestrial field stations and training school programs in communities around Hudson Bay, including the Churchill Northern Studies Centre, Centre d'études Nordiques and Nunavik Arctic Survival Training Center. These three examples illustrate the diverse network of research facilities and training centres that continue to promote activity beyond tourism throughout Hudson Bay. In addition, Box 1 Learning Vacations shows how many travellers are actually attracted by the knowledge developed by these facilities.

Many visitors who 'visit' the Hudson Bay area may not actually set foot on the ground but are using technology to virtually visit the area. The remote users are using the variety of live web cameras and satellite images (e.g., NASA Worldview) that are available to access real time (or very close to real time) viewing. A large portion of the visitors to Wapusk National Park are using the live Explore.org Cape Churchill polar bear camera to access the site and this may provide the only interaction with the environment. As in other studies around remote visitors to museums (Garandi and Chalmers 2013), there exists a series of social interactions between remote visitors and on-the-ground tourists through live web chat functions and live webstream



C. PAETKAU

### Box 1. Learning Vacations: An Educational Tourism Experience

Tourism is usually associated with sightseeing and tours, but a learning vacation can provide a enriched experience. Experts in their field can teach new skills or provide a deeper understanding unique to the region and topic. The idea of a learning vacation can be found around the world, with experiences such as Space Camp in the USA, Yoga Teacher Training in India or Flower Arranging in Japan. The Churchill Northern Studies Centre has brought the concept of a Learning Vacation to the Greater Hudson Bay Marine Region.

The Churchill Northern Studies Centre ([www.churchillscience.ca](http://www.churchillscience.ca)) is an independent, non-profit research and education facility located 23 km east of the town of Churchill, Manitoba, Canada. The Centre provides accommodations, meals, equipment rentals, and logistical support to researchers working on topics as diverse as tourism to hydrology to ecology. In addition to research, the Centre facilitates a wide range of educational programming ranging from university credit courses for students to learning vacation experiences for travellers.

The Churchill Northern Studies Centre offers a unique experience for tourists to help bridge the gap between tourism and science and to give the tourist a more in-depth understanding of the region they are visiting. The learning vacations are an opportunity for members of the general public to experience 5-7 day programs led by a scientist or an expert guide. Each participant has the opportunity to develop a deeper understanding and appreciation of the environment, culture and history of the Churchill area through daily interaction with visiting scientists and fellow travellers. There are no tests or grades, but these guided tours accommodated in an active field research station open new doors to learning for even the most seasoned travellers.

Using a series of evening lectures, tours and interactions with local community members and locations, the instructors and guides share information about research that focus on the topic of study and invites participants to contribute to citizen science projects that are on-going at the Centre. The programs also provide opportunities to view wildlife or the natural environment up close with the instructor close at hand to help participants delve deeper into the topic at hand. In addition, some of the courses teach new skills such as how to build a traditional igloo or quinzhee, or how to photograph the aurora borealis.



A. DYER

The Churchill Northern Studies Centre

The educational travel experiences like those offered through the Churchill Northern Studies Centre can have unexpected benefits. In an immersion situation, the daily exposure to a different set of values or ideas can lead to dramatic changes in a participant's perceptions and attitudes (Bodger 1998; Conceicao and Skibba 2008). Educational travel in the Greater Hudson Bay Marine Region can allow for a unique connection with not only the research in the region but with the local culture and the people who live there. Educational travel can help promote sustainable tourism, conservation and a deeper understanding of the region.

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events (e.g., Polar Bears International Tundra Connections program). The number of remote visitors to these sites is impossible to quantify but provides an opportunity for connection to the land and protected areas when other options are not economically or physically possible.

## 7. Churchill: an example of tourism in Hudson Bay

Tourism in Manitoba is a \$1.6 billion industry, representing 2.8% of the province's GDP, and some 11 million visitors to Manitoba (2014 from Travel Manitoba). Tourism in northern Manitoba represents about 5% of the overall tourism in Manitoba including an estimated 10,000 tourist/year that visit Churchill, Manitoba with the larger portion visiting during the polar bear migration period of mid October – late November (Dawson et al. 2010). Over the last several decades a tourism industry has grown, with oversight by the Manitoba government, to

take advantage of these conditions and visitor demands to see polar bears in subarctic habitats. Tourism peaks in the late fall as polar bears congregate close to the shoreline waiting for ice to form on Hudson Bay. In recent years, the tourist numbers have remained relatively steady during the polar viewing season with visitor numbers increasing in other seasons as the tourist offerings have diversified for the summer (e.g., beluga whale watching with Sea North Tours or Lazy Bear Expeditions) and the winter seasons (e.g., northern lights viewing with Natural Habitat Adventures).

Churchill has a population of 899 people and is located on the west coast of Hudson Bay in Manitoba (Statistics Canada 2017). The town of Churchill grew from a gathering point (circa 4000 B.P.) to a remote outpost of the Hudson Bay Company on the west side of the Churchill River to a bustling seaport with the construction of the Hudson Bay Railroad and Port of Churchill on the east side of the river in the late 1920s. Through much of the 1950s and 1960s, the town was a thriving military community servicing Fort Churchill and the Churchill Research



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Range. Churchill's economy today is based on four main pillars: tourism, transportation, health and research. With the decline of the rail service and the reduction in shipping through the Port of Churchill in 2016 and 2017, the town has relied on tourism and research activities to boost the economic activity.

The community also possesses a rich cultural history with the intersection of three aboriginal peoples (the Caribou Inuit, the Sayisi-Dene and the Maskêkô-winniwak or Swampy Cree) and, following the establishment of a Hudson Bay trading post, become home to a significant Métis population (Brandson 2011). European settlers, the Canadian and US military, and currently a temporary labour force with ties stretching to Australia and Southeast Asia round out the population of Churchill. The connection with the land and the confluence of the marine, tundra and boreal biomes is strong in the region and has long attracted travellers. The physical environment and the wildlife viewing opportunities continue to capture people's attention and bring them to visit the place (Groulx et al. 2016).

While polar bears are an iconic species for the province of Manitoba and particularly the town of Churchill, it is only since the 1970s that the polar bear tourism industry has been in operation (Struzik 2014). Polar bears congregate along the shores of the Hudson Bay for approximately six weeks during the fall, where they decrease their metabolic rates and subsist on stored fat reserves, thereby allowing them to conserve

energy while they await the formation of sea ice on Hudson Bay (Derocher et al. 1993). Tourism operators have capitalized on this unique congregation of bears during the "waiting period" when the bears are relatively inactive and highly visible, thus providing visitors with an opportunity to easily view them in their natural habitat. Most tourism activities occur within the Churchill Wildlife Management Area (CWMA), a provincially managed landscape starting about 15 km east of Churchill (Nelitz et al. 2015). Polar bear tourism in the CWMA has evolved into an adventure experience that is offered by two main operators; Frontiers North Adventures and Great White Bear Tours. In addition, there are tour operators/outfitters that provide a wide variety of tours on the built-up roads within the CWMA.

The relationship between polar bears and humans in the community of Churchill has also been conflicted. The Polar Bear Alert Program of the Manitoba Government is preventative in nature by minimizing the possibilities of unsafe or unexpected interactions between people and polar bears. To accomplish this, a control zone was established in which polar bears are not allowed. Conservation staff respond to requests made by the public to areas outside of the zone if a polar bear is considered to be a threat. Data from the Polar Bear Alert program shows that the number of bear occurrences around Churchill has steadily been increasing over the last several decades, with supplemental evidence suggesting that this trend is likely

due to a combination of human interventions (e.g., shift in the focus of the Alert Program from destruction to prevention) and changing environmental conditions (e.g., changes in the timing of sea ice formation) (Nelitz et al. 2015). The Polar Bear Alert program restricts (probably wisely so) where tourists are able to navigate in and around the town of Churchill. The heightened sense of ‘danger’ the program promotes is also valued by visitors who are interested in connecting with the Churchill story and retelling these stories as part of their experience (Groulx et al. 2016).

A recent tourism strategy for Manitoba’s northern region (Northern Manitoba Tourism Strategy 2017-2022) has brought forward a recommendation to grow tourism in Northern Manitoba from \$116 million to \$152-150 million annually by March 2020 with specific focus on Churchill. This document presents that path forward although no specifics are discussed on how to increase revenue. Marketing efforts by local operators and Travel Manitoba have steadily increased and focused on the North American and international markets.

## 8. The future of tourism in the Greater Hudson Bay Marine Region

Like all issues in the region there is controversy in regards to tourism. There are costs and benefits to the activity. Small communities can be easily overwhelmed by large numbers of tourist disembarking from cruise ships. Some people feel there is a tension between the pursuit of science and conservation and tourism that has an enormous per capita carbon footprint. There are also concerns that the increased marketing of tourism in the region may lead to over-tourism. On the other hand,

sustainable arctic tourism suggests collaboration between tourism and local community members as well as conservation and research organizations and studies could create economic growth.

Although tourism can have a large economic benefit to communities in the Greater Hudson Bay Region, an increase in tourism in the region may have adverse impacts on small communities and wildlife. Particularly for cruise ship tourism, which can potentially impact the whole marine region in the event of a spill or the introduction of invasive species. While many aspects of the future of tourism in the Greater Hudson Bay Marine Region remain uncertain, a sustainable future for arctic tourism involves the consideration of these issues taking an inter-jurisdictional and interdisciplinary view.

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## Conclusion

# Perspectives on the Future of Research in the Greater Hudson Bay Marine Region

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## 1. Introduction

This IRIS assessment report represents a major outcome of the ArcticNet research program, bringing together 15 years of new knowledge about the Greater Hudson Bay Marine Region. During this time, significant progress has been made towards gathering information relevant to understanding the impacts of climate change, industrialization and development in this region. There have also been significant improvements in *how* research is carried out. The old way of doing research ‘on’ Indigenous peoples’ lands and waters has been thoroughly and rightfully challenged, and is being increasingly replaced by research approaches that centre Indigenous knowledge and Indigenous peoples in the decision-making process.

By reporting on knowledge gained in the last decade and a half, the earlier chapters present what has been done and what we know now—but what about the future? A positive outcome of a knowledge assessment, such as this one, is to identify gaps. It is a sincere desire of those involved in the Hudson Bay IRIS process that the knowledge gaps and key priorities detailed in the Science-to-Policy Synthesis, at the front of this report, will inform policy changes, generate new initiatives, and spur on other changes necessary to address concerns. In some cases, we already see changes in progress. Like any quest for knowledge, scientific research is never ending—the answer to one question usually creates new ones, and as some research and monitoring programs come to an end, they set the groundwork for new ones to be launched. All of this leads to the questions: What will the research landscape in this region look like in the next decade? And what *should* it look like?

This concluding chapter looks forward. We present major trends and initiatives that are likely to make a significant mark on the research landscape in the Greater Hudson Bay Marine Region into the future. We also highlight where changes are needed in the process and focus on research efforts to advance the needs and aspirations of Inuit and Cree communities around the Greater Hudson Bay Marine Region.

## 2. Advancement of Indigenous research agendas

There have been progressive changes in Arctic research approaches over the last several decades, from the 'old' extractive model to a 'new' participatory model, where research is more applicable to local contexts and concerns, communities are involved in co-directing research with academic partners, and Indigenous knowledge is respected. However, there are still significant steps needed to achieve a vision of research that is led and implemented by Indigenous peoples, and where the majority of the beneficial impacts of research directly reach Arctic communities and regions (Brunet et al. 2014). Inuit Tapiriit Kanatami (ITK), the national voice of Inuit, developed a National Inuit Strategy on Research (2018), and the Inuit Circumpolar Council (ICC) is developing a complementary International Inuit Research Strategy. These strategies will lay out a path for what needs to change within research to ensure that it is conducted in a way that reflects and forwards Indigenous self-determination.



Johnny Kudluarok from Sanikiluaq deploys a water sampling instrument as part of the Community-Driven Research Network.

Two of the three major research councils in Canada have also recently taken significant steps to support and promote research by and with Indigenous people. The Social Sciences and Humanities Research Council of Canada (SSHRC) developed guiding principles for Aboriginal research (SSHRC 2015), and created a new policy on merit review of Aboriginal research that aims to help ensure that social science research on Indigenous topics is respectful and relevant (SSHRC 2016). The Canadian Institutes of Health Research (CIHR) has

developed an action plan to strengthen Indigenous health research in Canada; it includes actions such as advocating to the federal government to include Indigenous representation on that agency's governing body and Indigenous mentorship program renewal (CIHR 2016a; 2017). CIHR has also been improving processes to ensure appropriate review of Indigenous health research (CIHR 2016b). Even at the university level, the last decade has seen expressions of commitment to ensuring that First Nations, Métis and Inuit knowledge, cultures and traditions are embraced and reflected in the pursuit of university missions of education and research.

While advocacy by Indigenous peoples for changes in Indigenous research has been long-standing, the context in which this advocacy is taking place has been changing. The Canadian government recently adopted and committed to implement the *United Nations Declaration on the Rights of Indigenous Peoples* and Truth and Reconciliation Commission's 94 Calls to Action. In 2017, the Canadian government and elected Inuit representatives signed the *Inuit Nunangat Declaration*—a commitment to renew the Inuit-Crown relationship. Government commitments to reconciliation between Indigenous and non-Indigenous peoples reflect a national desire for a fundamental shift from business-as-usual to truly respectful Nation-to-Nation and Inuit-Crown relationships. While these commitments cannot be implemented overnight, they are creating new and critically needed possibilities for change over the medium to long term. Thus, over the next decade, positive shifts in the role of Indigenous peoples in research will continue and accelerate. Further, it is important for all individuals and institutions involved in research in this region, and in the Arctic more generally, to respect Indigenous self-determination.

## 3. Massive large-scale research projects: BaySys and Sentinel North

The IRIS report has summarized the research findings from studies dating back to the 1980s through to the present, with a focus on the past 15 years. Although the accumulation of knowledge over this time period is impressive, there are still many unanswered questions and information that needs to be updated, particularly in view of the rapid rate of change within the system. Two massive research projects recently got underway that are expected to make significant research advances in the Greater Hudson Bay Marine Region in the coming decade.

First, the Hudson Bay System Study—known as the BaySys Project—is a five-year, \$15 million project that focuses on the role of freshwater in the marine system and developing a

A. EASTWOOD

better understanding of how climate change and regulation are affecting the freshwater-saltwater interactions in the marine environment. The BaySys Project began in 2015; initial results of modelling and fieldwork are included in parts of the preceding ocean, sea ice and freshwater-marine coupling chapters. In June 2018, the project brought the CCGS *Amundsen* research icebreaker into Hudson Bay. This was the first time that scientists conducted a bay-wide survey with detailed observation of freshwater-marine interactions during the critical 'spring bloom' period. Further analysis and reports from this program will help address gaps in knowledge of the physical environment and ecosystems. The BaySys Project is funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Manitoba Hydro. The project is co-led by the University of Manitoba and Manitoba Hydro. Six other universities are also involved: University of Northern British Columbia, Université de Québec à Rimouski, University of Alberta, University of Calgary, Université Laval, and Trent University.

Second, Sentinel North is the result of a \$98 million grant to the Université Laval from the federal government's Canada First Research Excellence Fund. Sentinel North is a transdisciplinary research program that focuses on three broad themes: 1) understanding complex systems and interactions, from microscopic (microbiomes) to large-scale (infrastructure, permafrost, ecosystems), 2) investigating light and its influences, from developing new technologies to assess and treat chronic diseases, to improving ice and water remote sensing, to researching solar energy technology for northern applications, and 3) understanding interactions between microbiomes and human health. Use of new and innovative technologies is a common thread throughout Sentinel North's themes and projects. A major emphasis of Sentinel North is training of young scientists through scholarships, research grants, and an international PhD school.

In the future there will always be a need for these kinds of massive research projects that involve many research teams and universities and address questions in various disciplines on large spatial scales. The Greater Hudson Bay Marine Region is large, complex and has historically been understudied. Vessels like the CCGS *Amundsen* that can be mobilized for these large projects provide a means of surveying this large marine system in a semi-synoptic manner. Furthermore, projects like BaySys have the potential to offer profound insight into the whole marine ecosystem and can provide new discoveries and updated information relevant for communities, decision makers and all levels of government. However, with such a large-scale emphasis, this type of project is limited in the extent to which it can address local issues and concerns. Large vessels suitable for bay-wide scientific cruises are generally unable to work in shallow coastal waters and thus there is less



L. DALMAN

**Two research scientists working on sea ice in Hudson Bay as part of the BaySys project.**

opportunity for engagement with communities during field surveys. Thus, these massive projects are an essential part of the research horizon for the Greater Hudson Bay Marine Region but not sufficient by themselves for developing the baseline data needed at this time of rapid environmental change. It should also be noted that despite their large geographic focus, these sorts of fixed-term university-led research programs do not replace the need for long-term monitoring programs in the region.

#### 4. Research support

Within the Greater Hudson Bay Marine Region there has been recent investment in new research centres, observatories and other research infrastructure, as well as increased provision of research support by community organizations. The enhanced support for field research through new and existing facilities has the potential to significantly increase coastal and marine research in this area in the future.

In Manitoba, the Churchill Northern Studies Centre has been facilitating research in the Churchill region since 1976. Recently, government, universities and private partners have dedicated \$32 million to establish the Churchill Marine Observatory (CMO), a new research facility to be constructed in Churchill, Manitoba that will focus on studying oil spills and other environmental impacts in the arctic marine environment. Creation of the CMO represents a significant and long-term



M. FORTIER/ARCTICNET

The research station and community centre of the Centre d'études nordiques (CEN) in Kuujuarapik-Whapmagoostui, Nunavik.

investment in marine research infrastructure in the Greater Hudson Bay Marine Region. This facility will be associated with the University of Manitoba and involves numerous other partners, including the Churchill Northern Studies Centre, Indigenous organizations, the private sector, and various levels of government. The CMO will include two saltwater sub-pools where various contained experiments may be conducted; an environmental observing system located in the Churchill estuary and along the main shipping channel across Hudson Bay and Hudson Strait; and a logistics base to support the research activities.

In Nunavik, the Nunavik Research Centre—located in Kuujuaq, Nunavik and operated under Makivik Corporation—has been carrying out studies related to wildlife populations, the coastal marine environment, and numerous other environmental issues since 1978. The Centre d'études Nordiques (CEN) conducts research into environmental change and adaptation in the North, and operates six research stations on or near the eastern coast of Hudson Bay, specifically: the Radisson Ecological Research Station; the Whapmagoostui-Kuujuarapik Research Complex and the Whapmagoostui-Kuujuarapik Community Science Centre; the Umiujaq Research Station; the Clearwater Lake Station; the Boniface River Field Station; and the Salluit Research Station. CEN is run by three academic institutions: the Université Laval, the Université du Québec à Rimouski, and the Centre Eau, Terre et Environnement of the Institut national de la recherche scientifique.

In Eeyou Itschee, a new research institute was established in 2017 in Chisasibi – the Chisasibi Eeyou Resource and Research Institute (CERRI). CERRI is well positioned to contribute Cree Knowledge to research programs related to eelgrass, geese and coastal habitat. In west James Bay, the Mushkegowuk Council has hosted several Climate Summits

that bring together researchers, scientists, and Elders who share expertise on the health, conservation, and enhancement of the Hudson and James Bay wetlands. The Summits have focused on determining wetland research gaps and priorities in order to create research opportunities as well as help policy makers make better decisions on climate change. The Moose Cree also conduct regular research and monitoring efforts along the Moose River and at several other locations near river mouths and the coast.

For research in offshore waters of Hudson Bay, Hudson Strait, and Foxe Basin, it is critical to have the support of larger and ice-strengthened research vessels. During the last 15 years, the CCGS *Amundsen* research icebreaker was a critical catalyst for Arctic science, spending approximately 40% of the year in the Arctic and sub-Arctic supporting research. In the Greater Hudson Bay Marine Region, the CCGS *Amundsen* completed three four-week or longer oceanographic surveys and was used for the *Qanuilirpitaa? 2017* health survey of all 14 Nunavik communities, led by the Nunavik Board of Health and Social Services. The Government of Nunavut has commissioned two research vessels, the Research Vessels (RV) *Nuliajuk* and the *Papiruaq*. These vessels support coastal and marine projects related to conservation and sustainable development of Nunavut fisheries and also provide research training and employment opportunities for Nunavummiut. The RV *Nuliajuk* supported Ukkusiksalik/Wager Bay marine baseline studies for Parks Canada Agency in 2016 and both vessels have supported fish stock assessment activities in parts of Hudson Strait. The most recent addition to the fleet of vessels supporting research in the region is the RV *William Kennedy*, which completed its first research cruise in summer 2018 in support of the University of Manitoba "Southampton Island Marine Ecosystem Project" (SIMEP). The RV *William Kennedy* is a retrofit of a 65-foot fishing trawler operated by the Arctic Research Foundation in partnership with the University of Manitoba. It will remain part of the logistics base associated with the new CMO facility in Churchill.



The RV *Nuliajuk* in front of Chesterfield Inlet as part of the Ukkusiksalik/Wager Bay marine baseline study in 2016.



L. CANDLISH

The CCGS *Amundsen* supports many research projects and programs including ArcticNet, BaySys, Sentinel North, *Qanuilirpitaa?* 2017 health survey and GenIce.

While there have been recent large investments in research infrastructure in the region, there is still a need for additional resources. The distribution of research infrastructure is far from even, with comparatively little infrastructure in James Bay, the Kivalliq, Foxe Basin and northern Hudson Strait. Many communities are very interested in being engaged in research and it is challenging for municipal governments and organizations such as Hunters and Trappers Organizations to coordinate this engagement in addition to their mandated work. There is a need to increase communication and collaboration among the research centres in the region but the uneven distribution of resources and capacity presents a barrier. In some cases, it may be appropriate to coordinate and standardize collection practices, meta-data management, and reporting. Given that there are several distinct marine bioregions in the Greater Hudson Bay Marine Region, there is a need for several well-distributed research and monitoring support facilities.

## 5. Regional and community-based research and monitoring efforts

To respond to concerns about wildlife, changing sea ice and weather conditions and impacts on travel safety, a number of communities and regions have been initiating and developing research and monitoring programs. As changes in environmental conditions continue to accelerate, these programs are expected to become even more important at the community level.

For example, the Kativik Regional Government (KRG) in Nunavik has been engaged in community-based ice monitoring since 2004 in response to community concerns. In the latest iteration of this program, the KRG has been leading community-based ice monitoring around Deception Bay in the Hudson Strait, which addresses dual issues of climate change and shipping impacts on ice conditions.

The Eeyou Istchee Comprehensive Coastal Habitat Research Program, overseen by the Niskamoon Corporation, began in 2016 and is planned as a three-year program. The



M. KAMULA

Near Chesterfield Inlet, Augustine Mimialik takes part in a POLAR and ArcticNet funded project “Community-Driven Sea Ice and Ocean Research in the Contrasting Coastal Domains of Hudson Bay”.

goal of the program is to develop a better understanding of the oceanography and ecology of the coastal region of Eeyou Istchee, with a focus on eelgrass (*Zostera marina*) and links with wildlife, particularly waterfowl, which are an integral part of Cree culture and subsistence living. Cree Traditional Ecological Knowledge will be incorporated into the research program together with scientific research techniques. The program has a broad-based steering committee made up of representatives from coastal Cree communities, the Cree Nation Government, Hydro-Québec and the Canadian Wildlife Service. Several universities are involved in various aspects of the research including the University of Manitoba, University of New Hampshire, Université du Québec à Rimouski, and Université du Québec à Montréal.

In 2014, a Community-Driven Research Network was established by the Arctic Eider Society with Sanikiluaq, Inukjuak, Umiujaq, Kuujjuaraapik and Chisasibi. An initial focus of the network was addressing data gaps and local priorities quantifying large scale changes to oceanographic and sea ice conditions. This has been facilitated by collaboration with the University of Manitoba, and a parallel Inuit knowledge study of cumulative impacts has been underway since 2017

in partnership with Carleton University and the University of Toronto. Funding from POLAR Knowledge Canada is helping expand oceanographic programs to the coastal region of northwestern Hudson Bay near Chesterfield Inlet and Naujaat.

Building on a prototype used by the Community-Driven Research Network, the SIKU Indigenous Knowledge Wiki & Social Mapping Platform project, led by the Arctic Eider Society in partnership with the Nunavut community of Sanikiluaq in southern Hudson Bay, won the 2017 Google.org Impact Challenge in Canada. The SIKU project is making tools and services available to communities across the north to facilitate self-determination in research including the ability of communities and regional organizations to maintain intellectual property rights over their data and programs. In combination with a mobile app and online platform designed with and for Inuit, the platform allows documenting land use activities, tagging entities like wildlife species and Inuktitut terminology for sea ice, providing access to satellite imagery and other services to create new ways to document and mobilize Inuit knowledge for community benefit, including travel safety. It also implements near-real time sharing of scientific observations and is providing a unique approach for communities and researchers to work together.

Other community monitoring programs are in development. For example, an Eeyou Istchee initiative called the James-Bay Community-Based Coastal Climate Monitoring Program has been proposed to the federal government for funding. It seeks to gather baseline environmental change data to develop a long-term community-based monitoring network based on Cree knowledge and Western scientific data. In eastern James Bay, a long-term monitoring program is being developed by the Moose Cree First Nation in partnership with Ontario Power Generation Corporation related to aquatic, terrestrial, social, and physical impacts of the Lower Mattagami Hydroelectric Complex (about 200 km south of Moose Factory). The monitoring program is currently in the planning phase, with Moose Cree community members expressing a desire for the program to monitor changing estuary and coastal ice conditions.

Community-based monitoring programs and regional projects are valuable on multiple levels—they provide information of relevance to local and regional decision-makers and residents, create local research training and employment opportunities, and gather long-term environmental data of relevance to both local decision makers and science communities. All areas around the Greater Hudson Bay Marine Region can benefit from community-based monitoring programs and regional projects. However, additional resources and supports are needed to continue to foster community-based monitoring networks in communities.



J. HEATH/ARCTIC EIDER SOCIETY

Peter Kattuk and Daniel Qavvik on the lookout for belugas trapped in a polynya near Sanikiluaq, as a part of the Arctic Eider Society's Community-Driven Research Network with the Nunavut General Monitoring Plan.

It should also be noted that community and regional programs do not replace the need for federally funded long-term monitoring programs in the region. Change cannot be accurately assessed without a thorough understanding of baseline conditions and the natural temporal and spatial variability in properties within a system. Thus, effective long-term monitoring requires repeated systematic surveys, which often are beyond the scope of university or community-led research programs. There are a few examples of successful long-term monitoring efforts in the region that should be maintained, including the coastal habitat and migratory bird research program led by the American Museum of Natural History and the Ontario Ministry of Natural Resources that has continued at La Perouse Bay for more than 30 years. Monitoring of seabird colonies in northern Hudson Bay by the Canadian Wildlife

Service has similarly continued for more than 30 years. To our knowledge, similar examples of long-term data sets generated by monitoring programs do not exist for ice or ocean properties or any aspects of fish or marine mammal habitat.

## 6. Growth in education, training, and science outreach initiatives

Science education and training for northerners and outreach that focuses on scientific and Indigenous knowledge exchange is a huge component of most local and regional community-based research and education initiatives. It has also been an important part of the ArcticNet research program. There are numerous successful programs at local and regional levels that are expected to continue and expand. We note several here, but these only provide a small sampling of the diverse range of programs being developed and offered in communities around the Greater Hudson Bay Marine Region.

The Kivalliq Science Educators' Community has been hosting a Science Cultural Camp for high school student in the Kivalliq region of Nunavut. The camp, for which students can receive high school credits, combines a western understanding of science along with traditional Inuit knowledge. Inuit Elders are involved and students spend time on the land to learn about topics such as rocks and minerals, traditional transportation (qajaqing), archaeology, aquatics and fish, and comparative anatomy.

The Qajaq Program, based in Chesterfield Inlet, engages knowledge keepers and Elders to teach the youth how to build and paddle their own traditional qajaqs. Students can earn high school credits for their participation. The program builds up



G. BROCKLEBANK

Youth participants in the Qajaq Program.



L. BARBER

**The Expedition Churchill e-book.**

youth skills as well as confidence, and was awarded \$140,000 in 2018 by the Arctic Inspiration Prize to continue and expand.

The Nunavut Community Aquatic Monitoring Program (N-CAMP) is a program that is currently being developed to train Nunavummiut in basic fisheries and aquatic monitoring techniques. The certified training modules are based on other Canadian aquatic monitoring protocols, but adapted for Arctic conditions, and incorporating *Inuit Qaujimagatuqangit* principles into the content and delivery methods.

Expedition Churchill: A Gateway to Arctic Research is a creative public education and outreach campaign intended to highlight major University of Manitoba research programs and partnered projects operating within the geographic scope of Churchill and Hudson Bay. The project is a partnership with University of Manitoba, Centre for Earth Observation Science, VIA Rail Canada, Town of Churchill, Churchill Northern Studies Centre, Assiniboine Park Zoo - Journey to Churchill, and Travel Manitoba. Unique features of the project include: the use of the VIA Rail train from Winnipeg to Churchill as a platform for educating the public about the breadth of research activities being conducted in Churchill and Hudson Bay; interactive kiosks at public venues in Churchill and Winnipeg; and a stunning visual multi-media and interactive e-book available for free download at the App Store, Google Play, and [expeditionchurchill.ca](http://expeditionchurchill.ca).

The Arctic Eider Society in partnership with Kativik Ilisarniliriniq (the Nunavik School Board) has been developing a series of 27 lesson plans that will form part of the core curriculum for the Nunavik school system with plans to expand to other regions in the future as a part of the Arctic Sea Ice Educational Package project ([www.arcticseaice.com](http://www.arcticseaice.com)). Lesson plans link together results of community-driven research programs to teach STEM (Science, Technology, Engineering and Math) outcomes in an Inuit cultural context that closely

links science and Inuit knowledge using hands on activities and interactive content. Lesson plans cover a wide range of topics centered around sea ice, including physical characteristics of the Arctic, wildlife ecology and culture. The SIKU.org provides the platform for interactive sequences and activities where students can explore concepts using data collected by Inuit community researchers, explore polynyas and floe edges using Street View technology and other dynamic features.

The future research landscape needs to have initiatives for education, training and outreach embedded into it; there needs to be dedicated support for science communication and outreach. To build capacity in the North there needs to be a program for inspiring and mentoring northern youth and facilitating their future engagement in Arctic climate change research. Increasing youth engagement in science is a priority in both Cree and Inuit communities. The development of a national Northern training program should be coordinated with Northern Colleges and the HTOs with support from universities and governments.



SCHOOLS ON BOARD

**A high school student learning how to analyze benthic samples as part of the 2006 ArcticNet field program.**

## 7. Concluding comments

An assessment like the Hudson Bay IRIS can help pave the way for future work to be more progressive in terms of supporting Inuit and Cree efforts to assert rights to self-determination. As climate change and industrial resource development in this complex marine region move onward, there is a need for new research and monitoring efforts to be more inclusive and address societal and Indigenous demands for a greater say in how knowledge generation is conducted and managed. Another issue, looking ahead, is to improve the flow of new knowledge so that it better supports inter-jurisdictional communication, cooperation and coordination, and improved environmental stewardship and resource management. The Hudson Bay Consortium launched at the Hudson Bay Summit in Montreal in February 2018 provides one example of efforts to improve inter-jurisdictional coordination around environmental stewardship and sustainable development in the Region. The following recommendations emerged from the IRIS process:

- Indigenous peoples' ownership of their traditional and living Indigenous knowledge should be recognized. Inuit and Cree should be included early in research processes, and specifically in the identification of knowledge gaps and research priorities. Processes for appropriate inclusion of Indigenous knowledge must be determined in partnership with communities.
- Funding agencies and sponsors of research and monitoring programs should provide better support to community-researcher partnerships to improve capacity for community involvement in research and help sustain community-driven programs.
- Data management, maintenance and accessibility should be a priority when developing any research or monitoring programs. Through a living data management plan, data ownership and data licenses should be discussed and clearly laid out during research partnerships. This needs to include strategies to ensure data and information is preserved and is made readily available.
- Plans for communication of research results and outreach initiatives should be developed with local and regional guidance.
- Knowledge mobilization efforts such as those undertaken by ArcticNet need to be maintained over the long term and adapted to respond quickly and efficiently to the evolving needs of decision makers and end-users of the research.

The recommendations from the IRIS Steering Committee provide a clear path forward for successful future research in the Greater Hudson Bay Marine Region.

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