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THE HUDSON BAY, JAMES BAY AND FOXE BASIN MARINE ECOSYSTEM:
A Review

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Prepared for Oceans North

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The Hudson Bay, James Bay and Foxe Basin Marine Ecosystem: A Review

Prepared for Oceans North by Polynya Consulting Group

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1 INTRODUCTION

1.1 PURPOSE

In the center of Canada is a large inland sea created by the waters from Hudson Bay, James Bay and Foxe Basin, which together forms the homeland for thousands of Inuit and Cree that live in communities along its coastline. Although the waters are not known for their productivity, these shallow waters are the summering area for Canada's largest population of belugas. Its southern end supports the migration of thousands of geese, ducks and shorebirds while narwhals and bowhead whales migrate through its northern end. In the winter months polar bears from three subpopulations roam the sea ice in search of ringed seals. It is also an area that has experienced major anthropogenic changes, notably the damming of La Grande Rivière, which affected the entire marine region. There is uncertainty about what these anthropogenic driven changes may mean for ice, marine food webs, the wild food resources that local Indigenous communities depend on for sustenance and livelihoods.

Oceans North aims to foster science- and community-based conservation in the Arctic marine regions of Canada and Greenland, within the framework of Inuit knowledge, rights and consultation. To inform priorities for decision-making regarding research, education and other activities in Hudson Bay, James Bay and Foxe Basin, Oceans North has commissioned a report that synthesizes knowledge about this important Arctic marine region. Throughout this report, the marine area of Hudson Bay, James Bay and Foxe Basin will be collectively referred to as the Hudson Bay Marine Ecosystem or HBME (Figure 1.1).

1.2 APPROACH

To review and synthesize knowledge about the HBME, peer-review and grey literature was gathered on topics identified with Oceans North. For section 2.1 (ecological boundaries), all of chapter 4 (marine and coastal habitat), all of chapter 5 (implications of climate forcing) and section 6.1 (cumulative impacts), a systematic keyword search was performed in 2019 in the following databases: Google Scholar, Arctic Science and Technology Information System (ASTIS), the Fisheries and Oceans (DFO) library and Google.

Keywords used are listed in Table 7.1. Keywords were selected based on the geographic extent of the study area and prior knowledge of key words of relevance to each subtopic identified by Oceans North. Based on previous work contributing to the Integrated Regional Impact Study for the Greater Hudson Bay Marine Region (Kuzyk and Candlish 2019) and other research projects, lead authors of this review were aware that there is an uneven distribution of research on some topics and regions of relevance, and this uneven distribution was taken into consideration in

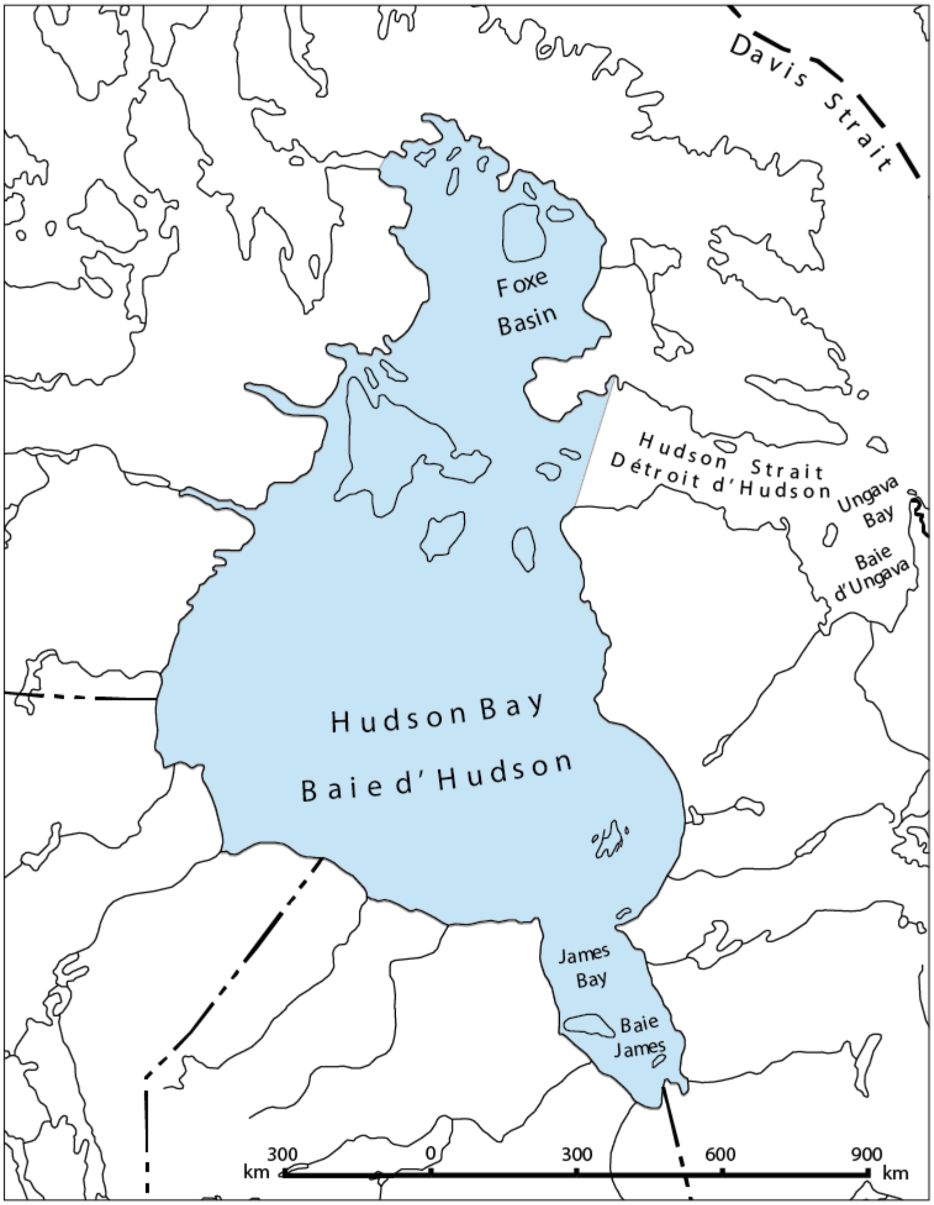


Figure 1.1 Extent of the Hudson Bay Marine Ecosystem (HBME) (boundaries defined by Oceans North). Adapted from Natural Resources Canada 2007.

developing keywords to ensure a balance between thoroughness and efficiency in literature gathering. ArcticNet, a Network of Centres of Excellence of Canada, is a major research body that has facilitated the study of impacts of climate change and modernization in Canada's North since 2004. Throughout the first four phases of the ArcticNet program (2004–2019), projects were required to contribute to four Integrated Regional Impact Studies (IRISes) that, when taken together, roughly correspond to the area of Inuit Nunangat. The exception was the marine-based Integrated Regional Impact Study for the Greater Hudson Bay Marine Region, which extended to James Bay and southern Hudson Bay, including Cree traditional homelands that are outside of Inuit Nunangat. As a result, while research on climate change and its impacts in the Canadian

Arctic has increased substantially in the last two decades, much of it has been focused on Inuit homelands. It should be noted that the 2019–2022 phase of ArcticNet has extended the geographic scope to include a new fifth continental IRIS region that includes the Yukon, continental NWT and interior of the Kivalliq region of Nunavut. Considering this context, the keywords for geographic scope included one or all of Hudson Bay, James Bay, and Foxe Basin for sections 2.1, 4, 5, and 6.1, and some additionally included the terms Nunavut and marine, and Nunavik and marine. Selective/purposeful searching was employed additionally to address any knowledge or topic gaps as needed, for example, for the Eeyou Marine Region. As the settlement of the *Eeyou Marine Region Land Claim Agreement* only came into effect in 2012, the Eeyou Marine Region is relatively new and research that uses this term is only just beginning to appear in the literature.

Search results (number of items retrieved), number of items reviewed, and number of articles found were all documented. In Google Scholar, approximately 16,500 search results were reviewed, 22,000 search results were reviewed in ASTIS, approximately 12,000 search results were reviewed in the DFO library, and 6,000 search results were reviewed in Google. In total, approximately 550 articles were retrieved using systematic keyword searching. Retrieved articles were documented in an Excel spreadsheet and imported into Mendeley, a citation manager. For each article retrieved, relevance to Hudson Bay, James Bay, Foxe Basin and Hudson Strait (direct, indirect, or none) was identified, as was the years that the data was based on, along with other descriptive information (e.g. author, publication date, publication title).

For section 2.2 (management boundaries), chapter 3 (human context), and sections 6.2 to 6.6 (predictive trends and discussion), it was determined that a systematic keyword search may not yield the most relevant results and that building on existing knowledge of chapter authors would be preferable. As a result, for these sections, selective/purposeful searching was conducted using Google and Google Scholar, and utilizing existing libraries of chapter authors. Approximately 400 additional sources were identified using these methods and imported into Mendeley.

For chapter writing, lead authors for each chapter reviewed articles that had been gathered, and summarized key findings. Given the volume of articles found, not all articles are cited—the most relevant, recent, or comprehensive articles were focused on.

While both literature employing Western scientific methods and literature that documents Traditional Ecological Knowledge (TEK) (or Indigenous Knowledge) were gathered through the systematic and purposeful searches, as evidenced in the Supplemental Information where a full reference list is presented, Western scientific literature is, on the whole, more heavily utilized in this report. There are two main reasons for this. First, the significant quantity of literature gathered meant that literature with a regional or sub-regional level focus, which tended to be based in Western scientific methods, was generally favoured over literature with a local focus. Second, the report is structured by specific sub-topics. The topically specialized nature of Western scientific literature meant that this literature tended to accord more easily with the report subtopics and was more often used and cited, compared to the more holistic literature documenting TEK. TEK is focused upon in chapter 3, as well as highlighted throughout chapter 4 and chapter 5. It should be noted that only a limited fraction of Cree and Inuit knowledge of the HBME has been documented in TEK literature, and thus Cree and Inuit knowledge of the HBME extends far beyond what is documented in this report.

Some research trends are reported in the body of this report. In general, trends were found to vary by topic. For example, in section 5.9, it is described how, in general, there was more literature identified on human dimensions of climate change relating to Inuit communities and regions around the HBME as compared with Cree communities and regions. Specifically, there was relatively less literature on interactions between environmental change and subsistence harvesting for First Nations along Ontario's Hudson Bay coastline (Lemelin et al. 2010; Robus 2012) and the western coast of James Bay (Hori et al. 2012; Tam et al. 2013; Khalafzai et al. 2019) compared to other reaches of the HBME. In particular, there was a relatively higher concentration of research on human dimensions of climate change related to the community of Igloolik (Ford et al. 2006; Ford et al. 2008; Ford et al. 2009; Ford 2009; Laidler et al. 2009; Karpala 2010) (see Figure 1.2). Also, the growing volume of research on climate heating impacts on wildlife in the HBME is distributed unevenly among species and food web interactions, with more studies on marine mammals than other wildlife groups (see section 5.6). Among these, most studies relate to polar bears and ringed seals.

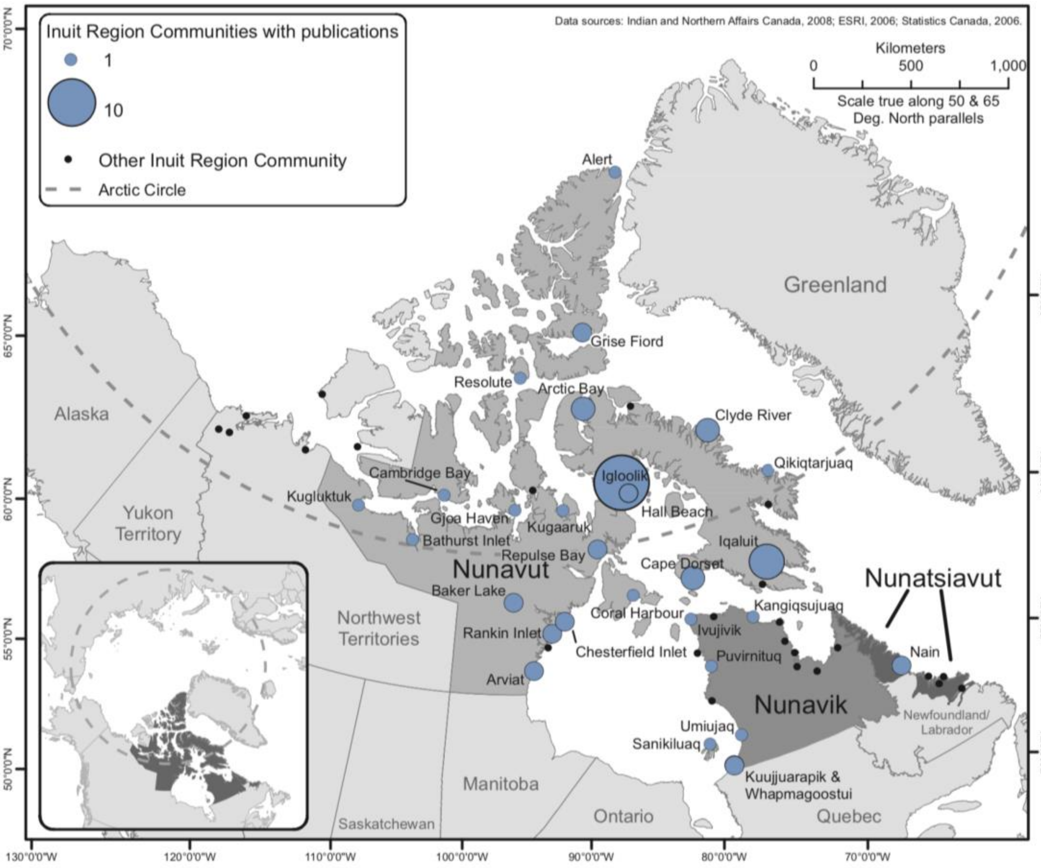


Figure 1.2 Communities that are a focus of human-dimensions of climate change research, as identified by a systematic review by Ford et al. (Ford et al. 2012, p. 294)

1.3 REFERENCES

Ford JD (2009) Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. Regional Environmental Change 9:83–100. doi: 10.1007/s10113-008-0060-x

Ford JD, Bolton KC, Shirley J, et al. (2012) Research on the human dimensions of climate change in Nunavut, Nunavik, and Nunatsiavut: A literature review and gap analysis. Arctic 65:289–304. doi: 10.2307/41758936

Ford JD, Gough WA, Laidler GJ, et al. (2009) Sea ice, climate change, and community vulnerability in northern Foxe Basin, Canada. Climate Research 38:137–154. doi: 10.3354/cr00777

Ford JD, Pearce T, Gilligan J, et al. (2008) Climate change and hazards associated with ice use in Northern Canada. Arctic, Antarctic, and Alpine Research 40:647–659. doi: 10.1657/1523-0430(07-040)[FORD]2.0.CO;2

Ford JD, Smit B, Wandel J, MacDonald J (2006) Vulnerability to climate change in Igloolik, Nunavut: what we can learn from the past and present. Polar Record 42:127–138.

Hori Y, Tam B, Gough WA, et al. (2012) Use of traditional environmental knowledge to assess the impact of climate change on subsistence fishing in the James Bay Region of Northern Ontario, Canada. Rural and Remote Health 12:1–16.

Karpala KSE (2010) Adapting to a World of Change: Inuit Perspectives of Environmental Changes in Igloolik, Nunavut. Carelton University

Khalafzai MAK, McGee TK, Parlee B (2019) Flooding in the James Bay region of Northern Ontario, Canada: Learning from traditional knowledge of Kashechewan First Nation. International Journal of Disaster Risk Reduction 36:101100. doi: 10.1016/j.ijdrr.2019.101100

Kuzyk ZZ, Candlish L (2019) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. Quebec City

Laidler GJ, Ford JD, Gough WA, et al. (2009) Travelling and hunting in a changing Arctic: Assessing Inuit vulnerability to sea ice change in Igloolik, Nunavut. Climatic Change 94:363–397.

Lemelin H, Matthews D, Mattina C, et al. (2010) Climate change, wellbeing and resilience in the Weenusk First Nation at Peawanuck: the Moccasin Telegraph goes global. Rural and Remote Health 10:1333.

Natural Resources Canada (2007) Lakes, rivers and names of Canada. https://www.nrcan.gc.ca/maps-tools-publications/tools/geodetic-reference-systems/reference-maps/16846#canada

Robus J (2012) Linking two ways of knowing to understand climate change impacts on geese and First Nations in the Hudson Bay Lowland. Trent University

Tam BY, Gough WA, Edwards V, Tsuji LJS (2013) The impact of climate change on the well-being and lifestyle of a First Nation community in the western James Bay region. The Canadian Geographer / Le Géographe canadien 57:441–456. doi: 10.1111/j.1541-0064.2013.12033.x

2 GEOGRAPHICAL BOUNDARIES

2.1 ECOLOGICAL BOUNDARIES

The Hudson Bay Marine Ecosystem (HBME), the geographic focus of this report, comprises of Hudson Bay, Foxe Basin and James Bay. The boundaries of Hudson Bay were standardized by the International Hydrographic Organization based largely on bathymetry and for the purposes of navigation; its northern boundary goes from Nuvuk Point, Nunavik (62"21' N, 78"06' W) to the southwestern extreme of Southampton Island, along the western shore of the Island and crosses to mainland Nunavut (66"03' N, 86"06' W) (International Hydrographic Organization 1953). To understand its ecology, this enormous inland sea cannot be considered separate from the other bodies of water to which it is connected, as they form an integrated habitat that a myriad of wildlife species utilizes and moves through.

To understand and communicate the types and characteristics of systems and units within Hudson Bay and adjoining waters, as well as marine areas in general, multiple scientific approaches have been used. This section reviews major ecosystem classifications that are relevant to the HBME and provides insight into ecological areas that the HBME is a part of as well as ecological areas that it is comprised of. Detailed descriptions of the climate, ecosystem function and processes as well as ecosystem structure and composition of the HBME, which complement the information presented here on ecological boundaries, can be found in Niemi et al. (2010), Stewart and Barber (2010), Stewart and Lockhart (2005a), and Wiken et al. (1996).

2.1.1 Biogeochemical Provinces of the Ocean: Boreal Polar Province

Longhurst (2007) developed and applied a classification for the world’s oceans termed Biogeochemical Provinces of the Ocean (BGCP), a system that aims to characterize the oceanographic processes that define an ecosystem’s productivity. BGCP is based on the premise that ecosystems are characterized by the oceanographic mixing processes that provide nutrients to the lower tropic levels of the food chain (i.e. phytoplankton). As a result, BGCP are regions with similar physical and biological characteristics. There is recognition of flux within oceans in this classification, so regions are emphasized, and boundaries are deemphasized. Hudson Bay, James Bay and Foxe Basin are a small part of the Boreal Polar Province, which generally describes Arctic circumpolar waters and underscores the Bay’s connectivity to a much larger system (Longhurst 2007).

2.1.2 Large Marine Ecosystem: Hudson Bay Complex

In the early 1980s, the Large Marine Ecosystem (LME) approach to the assessment and management of marine resources and their environments was introduced by the National Oceanic and Atmospheric Administration (NOAA) (Sherman and Hempel 2008). LMEs focus on coastal and shelf areas, and their boundaries are based solely on four interconnected ecological criteria:

- Bathymetry
- Hydrography
- Productivity
- Trophic relationships

Sherman and Hempel (2008) described how the bathymetry (bottom topography) greatly influences the water column structure and flow. Hydrography determines to a large extent the levels of productivity, which are a determinant of zooplankton biomass and diversity, which in turn is the foundation for the rest of the marine food web. Based on these four criteria, 64 LMEs were identified around the world, one of which was Hudson Bay (including James Bay, and excluding Foxe Basin). This was updated, and now the whole Hudson Bay Complex (inclusive of Hudson Bay, James Bay, Ungava Bay, Foxe Basin and Hudson Strait) is designated as an LME (United Nations Development Program et al.) (Figure 2.1). The Marine Regions Gazetteer is a marine regions database that includes boundaries of relevance to the HBME and relevant sources (Flanders Marine Institute (VLIZ)).

The Arctic Council's Protection of the Arctic Marine Environment Working Group (PAME) developed LMEs specific to the Arctic (PAME 2013). One of the 17 Arctic LMEs is the Hudson Bay Complex, with boundaries that align with those now recognized globally.

The Canadian Science Advisory Secretariat (CSAS) recommended biogeographic classification system for Canada's marine regions based on LME and other sources (DFO 2009). As with LMEs, the classification is based on ecological criteria, including consideration for benthic and pelagic environments, species composition, influences of ecological structures in defining habitats and their arrays of species. Twelve marine regions were identified by the CSAS, one of which is the Hudson Bay Complex. The Hudson Bay Complex was also recognized as an ecoregion within the Marine Ecosystem of the World (MEOW) classification, which was initiated by The Nature Conservancy and World Wildlife Fund to help identify the full range of diversity of coastal environments for the purposes of informing their management (O'Boyle 2010).

While no ecological classifications currently identify sub-regions in the Hudson Bay Complex, Siron et al. (2008) note that based on assemblages of seabirds and marine mammals, Hudson Bay, Foxe Basin and Hudson Strait are three natural sub-ecoregions, and that they may eventually be considered for planning and management purposes.

Figure 2.1 Area of Hudson Bay Complex (United Nations Development Program et al.)

2.1.3 Marine Ecoregions of North America: Hudson Bay/Boothian Arctic

The Commission for Environmental Cooperation developed a classification of marine ecoregions of North America (Wilkinson et al. 2009). The boundaries used to define the ecoregions are the region’s oceanographic or physiographic conditions that influence species distribution and are also a practical substitute for incomplete biological data. As a result, the marine ecoregions of North America classification system is based on the alignment of selected characteristics at each level, with attention to areas that may benefit from similar types of management and conservation. Level II regions describe the area between the near-shore and oceanic areas and is determined by large-scale features such as ocean trenches and continental slope, whereas Level III describes localized differences along the continental shelf and is finer resolution than Level II (Wilkinson et al. 2009). The Hudson Bay/Boothian Arctic is one of 24 North American ecoregions, with Level II seafloor geomorphological regions including Hudson Boothian Shelf and Hudson/Boothian Slope. Level III coastal regions include Coronation/Queen Maud Gulf, Peel/Boothian Neritic, Foxe Basin, Central Hudson Bay, and Southern Hudson/James Bay (Figure 2.2).

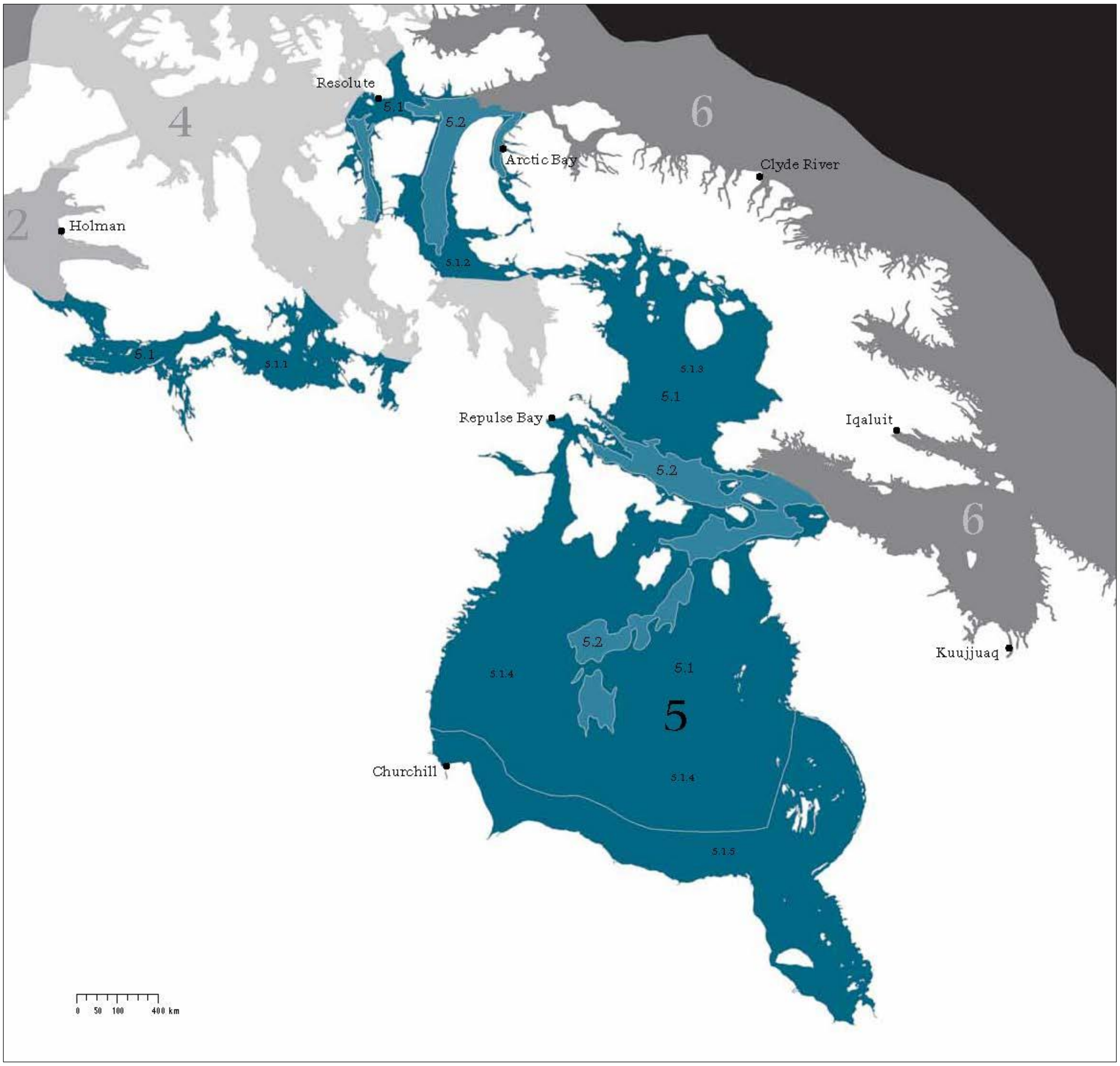


Figure 2.1 Hudson Bay/Boothian Arctic marine bioregion (Wilkinson et al. 2009, p. 32). Level II seafloor geomorphological regions: 5.1 Hudson/Boothian Shelf; 5.2 Hudson/Boothian Slope. Level III coastal regions include: 5.1.1 Coronation/Queen Maud Gulf; 5.1.2 Peel/Boothian Neritic; 5.1.3 Foxe Basin; 5.1.4 Central Hudson Bay; 5.1.5 Southern Hudson/James Bay.

2.1.4 Coastal Ecozones: Northern Arctic, Southern Arctic, Taiga Shield, Hudson Plains

Canadian terrestrial ecozones were classified in the 1980s, and then continued to be refined. The Canadian Ecological Framework was developed in a joint initiative between Environment Canada, Agriculture and Agri-Food Canada and the Canadian Council on Ecological Areas in the 1990s (Wiken et al. 1996). The ecozone classification that these organizations developed used a national approach to defining ecological area types based on the integration of biophysical characteristics, including air, water, land, and biota components (e.g. elevation, land cover, land and water area, permafrost, landform, soil, climate) (Wang et al. 2018). In 2014, ecozones were updated using geographic and climatic data interpreted into a national soil map, the Soil Landscapes of Canada (Figure 2.3). The authors note that this framework replaces the previous 1995 ecological framework, as well as the temporary Ecozone+ framework used for the Ecosystem Status and Trends Report (see Niemi et al. 2010). Figure 2.3 shows ecozones for coastal areas around Hudson Bay—from north to south, these are Northern Arctic, Southern Arctic, Taiga Shield, and Hudson Plains (see Table 2.1). The 2014 ecozone map also integrates marine ecozones with terrestrial ecozones on one map. Further subdivisions include ecoprovinces (53) and ecodistricts (1021).

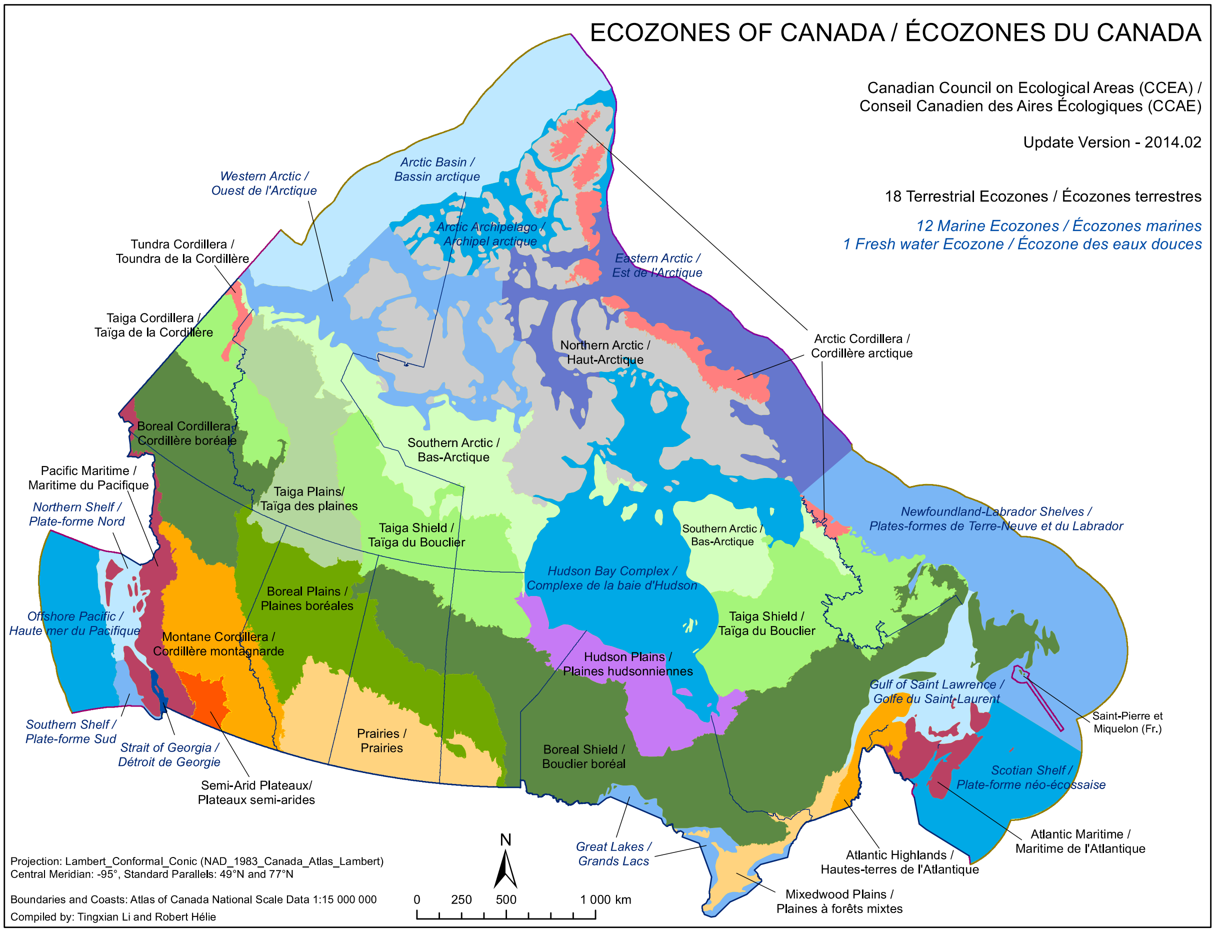


Figure 2.3 Terrestrial and marine ecozones of Canada (Canadian Council on Ecological Areas 2014)

Table 2.1. Biophysical characteristics of terrestrial ecozones surrounding the HBME (after Wiken et al. 1996, p. 4)

Ecozone	Landforms	Surface materials/soils	Climate/oceanographic characteristics	Vegetation/productivity
Northern Arctic	Plains, hills	Moraine, rock, marine/Cryosols	Very cold, dry, continuous permafrost	Herb-lichen tundra
Southern Arctic	Plains, hills	Moraine, rock, marine/Cryosols	Cold, dry, continuous permafrost	Shrub-herb tundra
Taiga Shield	Plains, some hills	Canadian Shield rock, moraine/Cryosols, Brunisols	Cold, moist to semi-arid, discontinuous permafrost	Open evergreen-deciduous trees, some lichen-shrub tundra
Hudson Plains	Plains	Organic, marine/Cryosols	Cold to mild, semi-arid, discontinuous permafrost	Wetland; some herb moss-lichen tundra, evergreen forest

2.2 MANAGEMENT AUTHORITIES AND BOUNDARIES

This section aims to provide a brief overview of key authorities of relevance to the HBME, their powers, and the geographic extent of their management authority. This content is drawn from materials previously prepared for the introductory chapter of the Integrated Regional Impact Study for the Greater Hudson Bay Marine Region (IRIS-3), with permission (Kuzyk and Barber 2019). The content of this section is largely derived from Daoust et al. (2010), Wilson et al. (2015), Rodon (2014), and Benoit (2011), as well as relevant land claims agreements.

Governance in the HBME is multifaceted, with a combination of federal, provincial, territorial, and municipal authorities; Cree Nation bands; Cree and Inuit rights-holding bodies; regional governments; and Institutions of Public Government created as a result of land claims agreements (co-management boards) (Figure 2.4). Further, while the federal and Ontario governments exercise 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 HBME today is a significant improvement over the regime just over four decades ago, before the settlement of modern treaties region began with the *James Bay and Northern Québec Agreement* of 1975. Current levels of local and regional autonomy are a proud achievement and ongoing focus for Indigenous populations around the HBME.

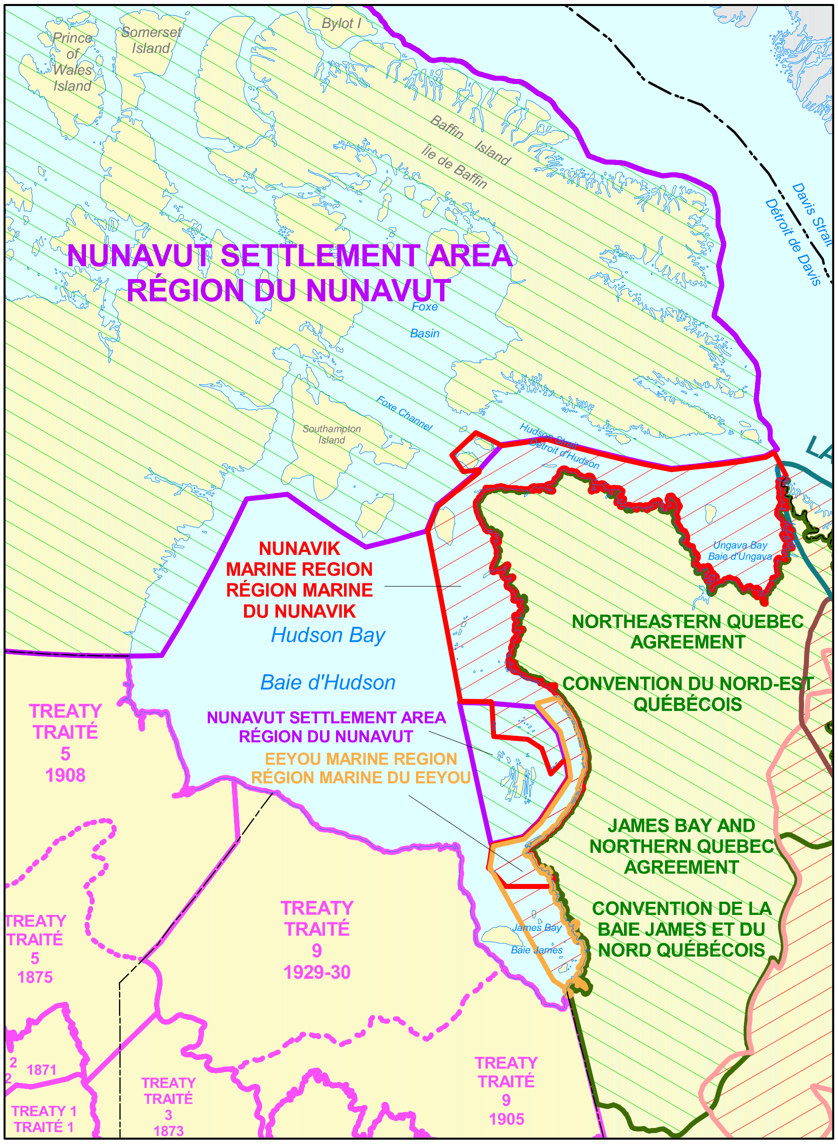


Figure 2.3 Treaties and comprehensive land claims in the HBME (Natural Resources Canada 2004)

2.2.1 Nunavut

As one of the first modern land claims agreement in the region, the *Nunavut Land Claims Agreement* (*Nunavut Agreement*) (1993) and the subsequent establishment of the Government of Nunavut has had overarching significance in the region. A significant portion of the HBME is located within the Nunavut Settlement Area (NSA), including northern Hudson Bay, Foxe Basin and the Belcher Islands and surrounding islands and waters.

The *Nunavut Agreement* protects the traditional rights of the Inuit throughout the NSA and provides direction for Inuit involvement in its management and governance. The *Nunavut*

Agreement 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 or public safety). Nunavut Tunngavik Inc. (NTI) represents Inuit beneficiaries of the *Nunavut Agreement* 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 HBME: 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 on the Belcher Islands. Each Nunavut community also has a Hunters and Trappers Organization or Association (HTO or HTA) that manages harvesting activities among beneficiaries in the community, including the allocation of tags in accordance with a Total Allowable Harvest (TAH) and setting of harvest seasons. Within each Nunavut region, HTOs and HTAs are represented by a Regional Wildlife Organization (RWO) that allocates the TAH among communities, and distributes accumulated harvest credits for accidental, defense or illegal kills of polar bears.

The *Nunavut Agreement* also established five Institutions of Public Government (IPG) that function as co-management boards, four of which have responsibilities related to marine planning and management: the Nunavut Wildlife Management Board (NWMB), Nunavut Planning Commission (NPC), Nunavut Impact Review Board (NIRB), and Nunavut Water Board (NWB) (the fifth is the Nunavut Surface Rights Tribunal). These IPGs have federal, territorial (Government of Nunavut), and Inuit representation, and subject to the ultimate authority of the relevant Minister, they have authority to make decisions on topics relevant to their mandates.

The NWMB is the main instrument of wildlife management and the main regulator of access to wildlife in the NSA. In addition, the NWMB has an advisory role with respect to marine management which occurs in Zones I and II and adjacent marine areas. Zone I refers to those waters that are north of 61 degrees latitude and subject to Canada's jurisdiction seaward of the territorial sea boundary but are not part of the NSA or another land claim settlement area. Zone II refers to the waters of James Bay, Hudson Bay and Hudson Strait that are not part of the NSA or another land claim settlement area (Nunavut Wildlife Management Board).

The NIRB is responsible for identifying and monitoring the ecosystem and socio-economic impacts of development projects and recommends terms and conditions for authorizations. Under the *Nunavut Agreement*, NIRB's jurisdiction applies to both the land and marine areas within the NSA and to the Outer Land Fast Ice Zone, off Qikiqtaaluk. With federal agreement, the NIRB may also review a project proposal located outside of the NSA which may have significant adverse impacts or socio-economic effects on the NSA.

The NPC is responsible for land use planning (including water, wildlife, and offshore areas) and to determine whether project proposals conform with the land use plans. The NWB has responsibilities and powers over the use, management and regulation of inland (freshwater) use in Nunavut, and it exercises this authority by licensing uses of water and deposits of waste.

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 NMC has authority under the NLCA, the federal government must consider its advice and recommendations in making decisions that affect the NSA.

Currently, the ultimate authority for 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 the territory gaining greater powers related to its marine areas (NTI 2007).

2.2.2 Nunavik

Nunavik covers much of the Québec territory above the 55th parallel, an area of 660,000 km^2. It was created with the signing by Inuit of the *James Bay and Northern Québec Agreement* (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. 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. Whereas KRG is the governing and administrative body for Nunavik (onshore), 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.

The rights of Nunavik Inuit to the offshore were excluded from the JBNQA. The *Nunavik Inuit Land Claims Agreement* (NILCA) (2006) addresses these rights, by establishing the Nunavik Inuit Settlement Area, comprising of 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, totalling 5,300 km^2. It also established three IPGs: the Nunavik Marine Region Wildlife Board (NMRWB), the Nunavik Marine Region Planning Commission (NMRPC), and the Nunavik Marine Region Impact Review Board (NMRIRB). As with Nunavut IPGs, these co-management boards have jurisdiction to make decisions related to their mandates that are then subject to the ultimate approval of the respective federal or territorial Minister. The NMRWB 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 NMRPC is responsible for co-developing planning policies and objectives and developing land use plans for the NMR. The NMRIRB carries out screening and review of projects and makes recommendations regarding project approvals and conditions.

Each community in Nunavik elects a Local Nunavimmi Umajulivijiit Katujiqatigininga (LNUK or Anguviaapik) that is responsible for regulating harvesting practices and techniques among their members, including the use of non-quota limitations. The Regional Nunavimmi Umajulivijiit Katujiqatigininga (RNUK), the regional hunting authority, is responsible for the regulation and monitoring of harvesting practices and techniques among the LNUKs, including non-quota limitations, and the allocation and enforcement of basic needs levels. LNUKs are consultative bodies to the RNUK and the RNUK is a consultative body to the NMRWB, representing the interests of NILCA beneficiaries with respect to wildlife management in the NMR.

2.2.3 Eeyou Istchee

The Cree homeland in Northwestern Québec is referred to as Eeyou Istchee. Today, 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 traditional territory of the Cree extends beyond the territory over which Cree have recognized jurisdiction in legislation and agreements, overlapping the Nunavik territory north of the 55th parallel and extending into lands which the Cree historically occupied in what is now Ontario.

The JBNQA was a product of litigation arising from hydroelectric development, but it also serves as the first modern land claim settlement, and it contributes to the definition of Cree government structures in this region. The JBNQA and its successor agreements also define the political and institutional framework for industrial development in this region, with the focus on hydroelectric development and forestry.

There are currently 11 Cree First Nation communities within Eeyou Istchee, and nine have an allocation of lands under the JBNQA. The tenth and eleventh communities to be recognized by the Cree Nation Government as part of Eeyou Istchee are Washaw Sibi and MoCreebec, and though they also have representation on the Cree Nation Government, their status has not been formally confirmed in legislation or through agreement with government. The Cree Nation Government exercises governmental and administrative functions on behalf of the Cree Nation, while the Ground Council of the Crees (Eeyou Istchee) represents Cree rights and interests. In practice, the Cree Nation Government and Grand Council of the Crees have identical memberships and board members, and are operated as one.

Cree offshore interests were excluded from the JBNQA, and have now been recognized and addressed in the *Eeyou Marine Region Land Claims Agreement* (EMRLCA) (2012). 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 NILCA. Within the EMR, most of the islands are owned by the Cree Nation Government—either outright or jointly with Nunavik Inuit. The islands in the EMR are subject to Nunavut territorial jurisdiction. As with the NILCA, and following the model of the *Nunavut Agreement*, the EMRLCA established three IPGs: the Eeyou Marine Region Wildlife Board (EMRWB), Eeyou Marine Region Impact Review Board (EMRIRB), and Eeyou Marine Region Planning Commission (EMRPC), with authority that corresponds to the NILCA IPGs as described above.

2.2.4 Omushkego Cree and Swampy Cree

Ontario borders on the HBME, extending along the 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 are connected by water taxi. 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. MoCreebec does not have a reserve but was recently recognized as part of Eeyou Istchee by the Cree Nation Government and now has representation on the Board/Council. While Moosonee is a town and not a First Nation reserve, its population is about 85% Cree. Kaschechewan and Fort Albany First Nation, while being separate communities, are both located on one reserve on the banks of the Albany River. 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 northern Ontario lie with 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). Federal and provincial interpretations of Treaty 9 differ from First Nation understandings of the agreement (RCAP 1996), and based on federal and provincial interpretations, the 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*, 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).

There are several regional First Nations organizations along the HBME's southwestern coast. The Mushkegowuk Council is the senior representative for seven Omushkego First Nations in western James Bay. Also in Ontario, the members of MoCreebec (the Moose Factory Cree of Quebec) trace their ancestry back to eastern James Bay but have been living in the Moose Factory – Moosonee area for generations and hundreds of years. MoCreebec families were not signatories to Treaty no. 9 in Ontario. The Nishnawbe Aski Nation (NAN) is a political organization for First Nations territory encompassing James Bay Treaty No. 9 and the Ontario portion of Treaty No. 5, and consists of 49 member communities. The Keewatin Tribal Council provides advisory services to 11 member First Nations located in northern Manitoba and their region covers the length of the Manitoba coastline along Hudson Bay.

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: York Factory First Nation, relocated from their homeland along the Hudson Bay coast to Kawechiwasik or York Landing), Shamattawa First Nation and Fox Lake Cree Nation, which are within 200 km of the HBME coast; and Fox Lake Cree Nation, War Lake First Nation and Tataskweyak First Nation.

Treaty 5 (1875, 1908, adhesions in 1908, 1909, 1910) covers all of northern Manitoba with the exception of the northeastern corner, which falls within Treaty 9. No comprehensive land claims 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, none have recognized jurisdiction adjacent to the HBME. 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^2 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.

2.2.5 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, at the time of report publication, 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^2 (21% of the 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 report publication, none of the First Nations on the Hudson Bay's Ontario coastline has a draft or approved community land use plan under the Act (Government of Ontario 2019). The Ontario government announced in 2019 that it would repeal the Act based on economic rationale for the Ring of Fire mining development, but as of report publication it is still in place.

Manitoba's current northern development strategy, while not packed under a single initiative, continues a half-century of hydroelectric development. 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 the sections describing Nunavik and Eeyou Istchee. There is also a lack of certainty regarding the coastal boundaries of Québec. Québec deems marine areas between two points of land (bays) within its jurisdiction; this conflicts with federal interpretation and thus with the EMRLCA and the NILCA, to which Québec was not a signatory.

2.2.6 Federal authority

The federal government has jurisdiction over fisheries, shipping, and navigation, even within provincial or territorial boundaries; it has ultimate jurisdiction over aquatic species (including marine mammals), migratory birds, and species at risk and it is responsible for regulating water resources in Nunavut (Fisheries and Oceans Canada 2009). Legislation that relates to federal environmental management of waters and resources in the Marine Region includes the *Oceans Act*, *Fisheries Act*, *Impact Assessment Act*, *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*, *Fishing and Recreational Harbours Act*, *Coastal Fisheries Protection Act*, *National Marine Conservation Areas Act (NMCAA)*. Another relevant piece of legislation is the *Indian Act*, administered by Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC) and Indigenous Services Canada.

Fisheries and Oceans Canada (DFO) is the lead federal government agency with regard to marine planning and management and is responsible for developing and implementing policies and programs in support of Canada's economic, ecological and scientific interests in oceans and internal marine waters, including conservation and sustainable use of fisheries resources. In 1997, the adoption of the *Oceans Act* gave the DFO the mandate to lead integrated management for all marine, coastal and estuary activities including in the HBME. Environment and Climate Change Canada (ECCC) has a mandate to preserve and enhance the quality of the natural environment and conserve Canada's renewable resources and biological diversity. The department supports DFO by undertaking marine-related initiatives within the context of its mandate. In Nunavut, ECCC is responsible for protection of migratory birds through the implementation of the *Migratory Birds Convention Act*, the *Migratory Birds Regulations* and the *Migratory Birds Sanctuary Regulations*. Parks Canada establishes and co-manages National Parks with marine components and National Marine Conservation Areas as part of its mandate to protect and promote education about the natural and cultural heritage of Canada's special places. Transport Canada regulates marine transportation, including through Canada's oceans. CIRNAC is the Government of Canada's lead for the North and is responsible for nation-to-nation and Inuit-Crown relationships between the federal government and First Nations, Inuit and Métis. The department is also responsible for managing oil and gas resources in Nunavut and the Arctic offshore, administering non-shipping offshore activities (e.g. pollution prevention), and developing and coordinating policies and programs related to northern environment and conservation, among other responsibilities. More details and the roles of other federal departments with respect to Canada's oceans can be found in a report by DFO about the role of the Canadian government in the oceans sector (Fisheries and Oceans Canada 2009).

2.3 COLLABORATION AND COORDINATION

Given the jurisdictional complexities in this region, it is challenging and important to have collaboration and coordination across James Bay and Hudson Bay. To this effect, concerted efforts by communities, organizations and stakeholders resulted in the creation of the Hudson Bay Consortium (HBC) which provides for a forum for this coordination through regional roundtables and a summit (every four years). Although without legal authority, the composition of the HBC steering committee and meeting attendees includes many of the authorities listed above. To date there have been efforts around collaboration and coordination for research and monitoring, protected areas and communications. The vision of the HBC is to facilitate communication and cooperation 'in the pursuit of knowledge and means to protect, improve and steward the greater Hudson Bay/ James Bay ecosystem for the primary benefit of the people, flora and fauna that live there' (Hudson Bay Consortium 2020).

2.4 REFERENCES

Benoit LE (2011) On thin ice: An overview of the governance of Hudson Bay.

Canadian Council on Ecological Areas (2014) Ecozones of Canada. doi: 10.1201/9781420037784.axe

Daoust T, Haider W, Jessen S (2010) Institutional Arrangements Governing Marine Conservation Planning in the Canadian Arctic: The Case of Nunavut, Canada. Environments: a journal of interdisciplinary studies 3:73–93.

DFO (2009) Development of a framework and principles for the biogeographic classification of Canadian marine areas.

Fisheries and Oceans Canada (2009) The role of the Canadian Government in the oceans sector.

Flanders Marine Institute (VLIZ) Marine Gazetteer Place Details: Hudson Bay Complex. https://www.marineregions.org/.

Government of Ontario (2019) Land use planning process in the Far North. https://www.ontario.ca/page/land-use-planning-process-far-north#section-2.

International Hydrographic Organization (1953) Limits of oceans and seas, 3rd ed. International Hydrographic Organization, Monte-Carlo, Imp. Monégasque

Kuzyk ZZ, Barber D (2019) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. Synthesis and Recommendations. Quebec City

Longhurst A (2007) Ecological geography of the sea, 2nd ed. Elsevier, Amsterdam

Natural Resources Canada (2004) Treaties and Comprehensive Land Claims in Canada.

Niemi A, Paulic J, Cobb D (2010) Ecosystem status and trends report: Arctic Marine Ecozones.

Nishnawbe Aski Nation (2017) Ontario's Far North Act. http://www.nan.on.ca/article/ontarios-far-north-act-463.asp. Accessed 7 Dec 2017

NTI (2007) Devolution and marine areas: Discussion paper.

Nunavut Wildlife Management Board Introduction. https://www.nwmb.com.

O'Boyle R (2010) Review of Selected Biogeographic Classification Systems with Relevance to the Canadian Marine Environment. Bedford, Nova Scotia

PAME (2013) Large Marine Ecosystems (LMEs) of the Arctic Area. Revision of the Arctic LME Map, 2nd Ed.

RCAP (1996) Report of the Royal Commission on Aboriginal Peoples. Ottawa, ON

Rodon T (2014) From Nouveau-Québec to Nunavik and Eeyou Istchee: The Political Economy of Northern Quebec. The Northern Review 38:93–112.

Sherman K, Hempel G (2008) The UNEP Large Marine Ecosystems report: A perspective on changing conditions in LMEs of the world's regional seas. Nairobi, Kenya

Siron R, Sherman K, Skjoldal HR, Hiltz E (2008) Ecosystem-Based Management in the Arctic Ocean: A Multi-Level Spatial Approach. Arctic 61:86–102.

Stewart DB, Barber D (2010) The Ocean-Sea Ice-Atmosphere System of the Hudson Bay Complex. A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay. pp 1–38

Stewart DB, Lockhart WL (2005) An overview of the Hudson Bay marine ecosystem.

United Nations Development Program, Global Environment Facility, United Nations Development Programme Hudson Bay Complex. In: Large Marine Ecosystem Hub: A Regional Perpsective on the World's Oceans. http://www.lmehub.net/#hudson-bay.

Wang J, Grenier M, Henry M, Soulard F (2018) Classification of ecosystem types: Experiences and perspectives from Statistics Canada.

Wiken EB, Gauthier D, Marshall I, et al. (1996) A Perspective on Canada's Ecosystems.

Wilkinson T, Wiken E, Creel JB, et al. (2009) Hudson/Boothian Arctic. Marine ecoregions of North America. pp 33–35

Wilson GN, Alcantara C, Rodon T (2015) Multilevel Governance in the Inuit Regions of the Territorial and Provincial North. In: Papillon M, Juneau A (eds) Aboriginal Multilevel Governance. McGill-Queen's University Press, pp 43–64

3 THE HUMAN CONTEXT

3.1 INDIGENOUS COMMUNITIES' USE OF THE HUDSON BAY MARINE ECOSYSTEM

The Hudson Bay Marine Ecosystem (HBME) is geographically, culturally, and ecologically diverse. Indigenous use and occupancy of the HBME trace back thousands of years. Much has changed over the last 100 years that has shaped the relationships Indigenous peoples in this region have with the terrestrial and aquatic environments, including the establishment of permanent settlements, the creation of modern land claims, and significant shifts in traditional lifestyles. Currently, twenty-eight communities are located on or near the shores of the Marine Region (Figure 3.1), of these, fourteen are Inuit communities (nine in Nunavut; five in Nunavik, Québec), twelve are Cree First Nations (five in Eeyou Istchee, Québec; one in Manitoba; six in Ontario), and two are municipalities with significant Indigenous populations (Churchill, Manitoba and Moosonee, Ontario). In the adjacent Hudson Strait, there are a number of Inuit communities that also make use of Hudson Bay and Foxe Basin (three in Nunavik; two in Nunavut).

Over generations, local and regional geography has shaped the marine and coastal ecosystems throughout the HBME. In turn, local food networks and marine-based economies have evolved in relationship with these ecosystems, resulting in both regional similarities across communities as well as unique local systems. While the sub-regions within the HBME can be considered individually, they exist as a whole network, interacting through ocean currents, animal migrations, human use, and family connections. Further, the marine cannot be completely separated from the terrestrial and freshwater:

> *Rivers and lakes contribute a lot to the well-being of people.... The currents and rivers are the veins of Hudson Bay. They start from inside the basin and go out through Hudson Strait. Any part of the currents or rivers are altered in Hudson Bay, the basin will start to slowly die ... and the animals will die with it.*
>
> *–Peter Kattuk, Sanikiluaq (McDonald et al. 1997)*

3.1.1 Nunavut Inuit

Nunavut is home to approximately 38,000 residents distributed over 25 communities, 84% of whom are Inuit (Nunavut Bureau of Statistics, 2016). The population of Nunavut is young and is projected to increase to 48,000 by 2035 (Nunavut Bureau of Statistics, 2014). In the HBME, along the northwest border of Hudson Bay are six communities in the Kivalliq region of Nunavut: Arviat,

Figure 3.1 Communities located on or near the shores of the HBME (adapted from Kuzyk and Candlish 2019a, p. 11)

Whale Cove, Rankin Inlet, Chesterfield Inlet, Coral Harbour, and Naujaat. Igloolik and Hall Beach are the two communities from the Qikiqtani Region that fall within Foxe Basin. Sanikiluaq is located on the southeastern Belcher Islands, while Cape Dorset and Kimmirut are found along the north coast of Hudson Strait (Figure 3.1; Table 3.1).

As in all of Inuit Nunangat, Nunavut's economy is historically based on harvesting traditions. Fast (1996) provides a generalization of traditional seasonal land use in Nunavut. Prior to permanent settlements, movement was a defining component of Inuit land use (Aporta 2010). This harvesting economy and the traditional lifestyle with total reliance on the land and sea necessitates a deep knowledge of weather patterns and animal movements, among other things. Even with the shift to year-round settlements, harvesting wildlife continues to provide food, fur and skin for clothing, and bones for tools and art. The harvesting economy in Nunavut is estimated to be worth approximately $40 million annually (Government of Nunavut 2017). However, according to new research, integrating the nutritional value of traditional foods into the estimate produces a

Table 3.1. Summary of Nunavut Inuit communities in the HBME. Population as of 2016, from Statistics Canada 2019.

Community	Marine Sub-region	Population	Population Identifying as Inuit
Igloolik	Foxe Basin	1,682	93%
Hall Beach	Foxe Basin	848	96%
Arviat	Hudson Bay	2,514	93%
Whale Cove	Hudson Bay	435	95%
Rankin Inlet	Hudson Bay	2,441	82%
Chesterfield Inlet	Hudson Bay	437	90%
Coral Harbour	Hudson Bay	891	96%
Naujaat	Foxe Basin	1,082	95%
Sanikiluaq	Hudson Bay	882	94%
Cape Dorset	Hudson Strait, bordering on Foxe Basin/Hudson Bay	1,441	93%

number that is much higher, on the order of $143 million (Nunatsiaq News 2019). The invaluable contributions to holistic health and wellbeing and cultural continuity are also important considerations and will be discussed further in section 3.2.

Sea ice, in particular, holds a central place in Inuit land use traditionally and currently. Indeed, for some it moves beyond the physical to the spiritual (McDonald et al. 1997). The ice facilitates travel to hunting and fishing sites, it acts as a hunting platform, it is a habitat for many important species in the HBME food web and connects communities in the winter months. This dependence is reflected in the deep and extensive collective Inuit Knowledge or Inuit Qaujimajatuqangit that is held regarding sea ice (McDonald et al. 1997).

Inuit Qaujimajatuqangit (IQ) is often understood as traditional Inuit knowledge, however, this is only one of its aspects (Arnakak 2000). IQ has been passed down orally through generations, providing knowledge of the land by prioritizing learning through observation and doing. Arnakak (2000) of the Nunavut Department of Sustainable Development describes the Inuit family-kinship model as an ideal management model to apply IQ in organizational and program development within Nunavut. In addition, at the community and territorial level, IQ is about accessing the right to self-governance through integral Inuit values and is a guiding principle for the policy and governance of Nunavut.

Interactions with European settlers and eventually southern Canadians signaled major shifts in Inuit land use. Significant changes and milestones in traditional land use are summarized in Fast and Berkes (1994). For Inuit in western Hudson Bay, some of these events include World War II, government relocations, famine, the centralization of social and administrative government services. The authors note, though, that “the trend of diminishing land use which arose during the period of sedentarization in the late 1960s and early 1970s…has not continued" (Fast and Berkes 1994).

In recent decades, the wage economy has become increasingly important and economic opportunities have diversified in the region to include tourism, research and monitoring, shipping and transport, and renewable and non-renewable resource extraction. These activities shape land use, too: directly, as Inuit become active participants in these sectors, and indirectly, as Inuit modify their subsistence activities in response to industries. Of course, many of these opportunities do not trickle down to Inuit, while the environmental burden is ultimately shouldered by those whose livelihoods are still tied to the land (McDonald et al. 1997)

Fast and Berkes (1994) summarized land use studies in western Hudson Bay up to the early 1990s. At the time, Nunavut had yet to be established and the land fell under the jurisdiction of the Northwest Territories. These studies, from pre-1925 to 1987, were intended to document Indigenous use and land claims, eventually leading to the creation of Nunavut. More recently, the Nunavut Planning Commission has been developing a territorial land use plan that will play a major role in how Inuit interact with the land and sea moving forward. A draft was released in 2016, focusing on key conservation areas, environmental protection, healthy communities, and economic development (Nunavut Planning Commission 2016), but the draft plan was met with mixed reviews and has yet to be finalized. The creation of the draft included use and occupancy studies in the communities between 2004 and 2011. These studies documented a comprehensive suite of traditional land uses. The resulting maps are not publicly available, but community meeting summaries available online illustrate where participants have added further emphasis on areas to be protected, areas that are key to health, and areas that are of interest for sustainable development (Nunavut Planning Commission, 2013).

In response to increased ship traffic throughout northern Canada, the Arctic Corridors Research Project documented current day Inuit land and sea use for a handful of land users in Arviat and Coral Harbour (among other communities outside of the HBME) (Carter et al. 2017; Carter et al. 2019). Mapped use from both communities for the open water season is shown below in figures 3.2 and 3.3 to contrast inland versus coastal/marine use for two western Hudson Bay communities. These land use footprints are inextricably tied to the Indigenous food webs for each community (see section 3.2 below).

As with many land use studies, there are limitations to the inferences that can be drawn from the extent of use documented through the Arctic Corridors and Northern Voices study. These maps show only a snapshot in time from participating individuals, influenced by the scope and intent of the project itself. They do not reflect the entire current footprint, the historical use, or future land use needs.

Land use documentation has largely been driven by land claim preparation and development projects, but extent and nature of use is also captured intentionally and tangentially during wildlife studies. These include Inuit harvesting and wildlife knowledge studies (e.g. Henri et al. 2010; Higdon et al. 2014), health and nutrition studies (i.e. linking harvesting and time on the land to wellbeing (e.g. Wein et al. 1996) and climate change impacts on Inuit land use (Ford et al. 2006; Laidler et al. 2009a).

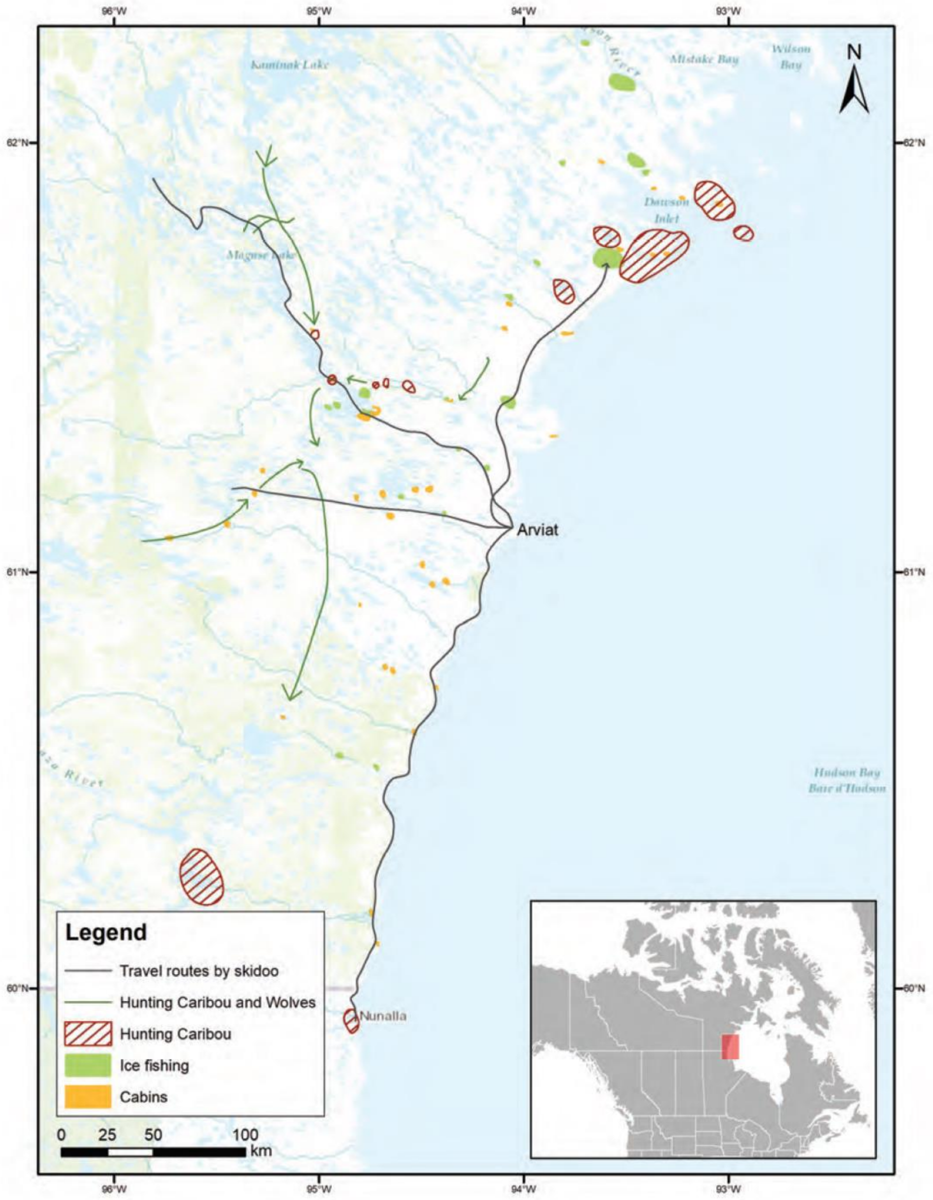


Figure 3.2 Location of Arviat community members' activities during freeze-up and frozen ocean, from the *Arctic Corridors and Northern Voices* study (Carter et al. 2017, p. 16).

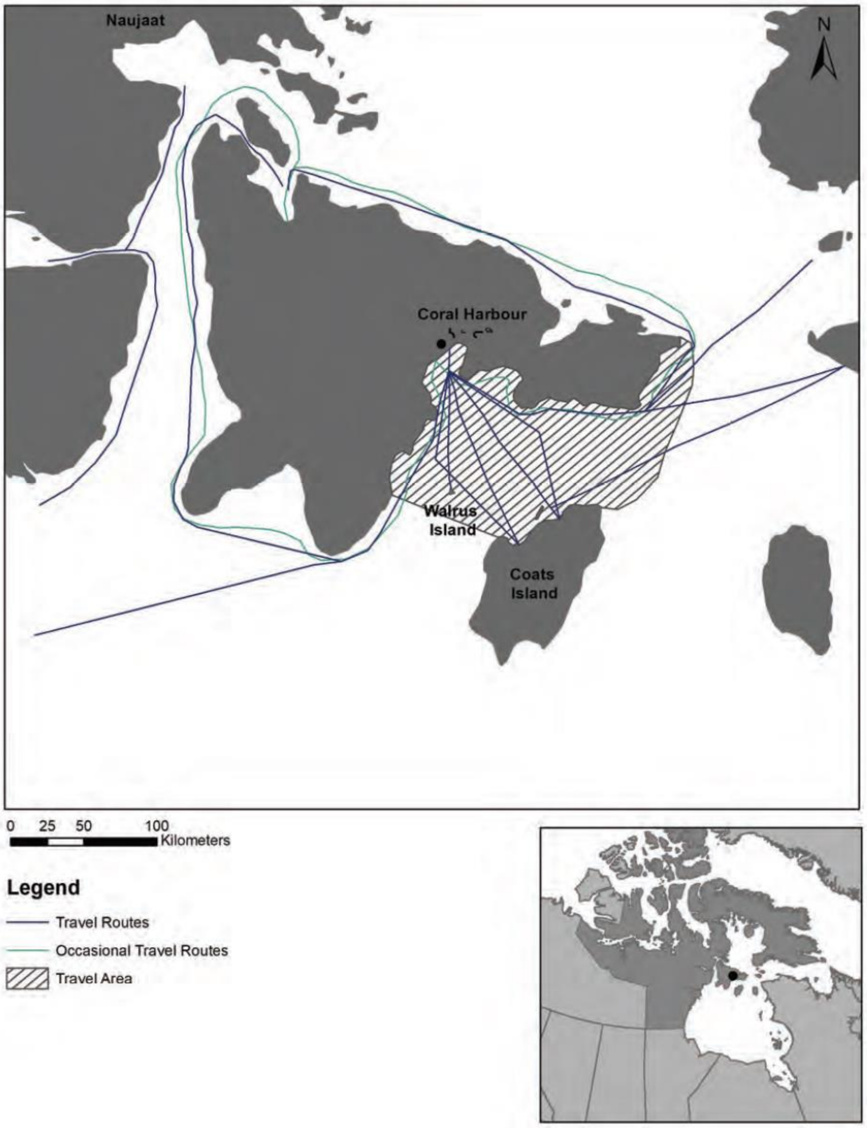


Figure 3.3. Location of Coral Harbour community members' activities during open water, from the *Arctic Corridors and Northern Voices* study (Carter et al. 2019, p. 15).

3.1.2 Nunavik Inuit

The population of Nunavik was about 13,500 in 2016, living in 14 communities along the Hudson Bay, Hudson Strait, and Ungava Bay coasts (Table 3.2; Figure 3.1) (Institut de la statistique du Québec 2017). 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.

Table 3.2. Summary of Nunavik (Québec) Inuit communities in the HBME. Population as of 2016, from Statistics Canada, 2019.

Community	Marine Sub-region	Population	Population Identifying as Inuit
Ivujivik	Hudson Strait, bordering on Hudson Bay	414	95%
Akulivik	Hudson Bay	633	100%
Puvirnituq	Hudson Bay	1,038	94%
Inukjuaq	Hudson Bay	1,312	97%
Umiujaq	Hudson Bay	442	96%
Kuujjuarapik	Hudson Bay	686	74%

Subsistence harvest drove historical land use for Nunavimmiut along the Hudson Bay coast, with much of the activity occurring in the marine environment as opposed to inland (KRG 2007). The presence of Cree groups to the south likely also affected how Inuit traveled and used the area. The arrival of European traders and settlers starting in the 1600s precipitated significant change to the existing land use (KRG 2007). A summary of archeological sites (both pre- and post-contact) was completed in preparation for Tursujuq Provincial Park (KRG 2007), which covers the Hudson Bay coast north and south of Umiujaq as well as much of the inland area to the east. These are extensive and speak to the long history of Inuit (and Cree) land use in the region. Fast and Berkes (1994) have also summarized more recently land use and occupancy studies in eastern Hudson Bay up to the early 1990s. Studies focusing on land use in Inuit communities in northern Québec were conducted from 1973-1980 and were used during land claims negotiations (particularly distance from communities).

By the 1950s, sedentarisation, wage-labour, and increased use of southern technologies were major forces in land use. Although subsistence harvest remained of great importance, the subsistence footprint and how Inuit were interacting with the landscape was shifting. Rifles and motorboats meant hunting could be done in smaller groups and people didn't have to travel as far (KRG 2007). Land use continues to evolve to this day, as technology, community needs, and government policies and initiatives also evolve. Current day use and occupancy throughout Nunavik communities have been documented through the Nunavik Marine Region Planning Commission. Communities along the Hudson Bay coast participated in 2015. These data and summary information are not publicly available.

In recent decades, economic opportunities have diversified to include tourism (park development, outfitting, etc.), research and monitoring, shipping and transport, and renewable and non-renewable resource extraction. These sectors play a role in how land use grounded in subsistence has changed in recent decades. For example, Inuit in Kuujjuaraapik have observed the effect of ship traffic on beluga whales, with the animals arriving later in the season and using areas farther from ship activity (McDonald et al. 1997). These types of changes are important to understand in a land use context, particularly for a culturally important species like the beluga.

Industrial development, including large scale hydroelectric development, has also had a detrimental effect on Nunavik Inuit subsistence activities and relationships to the land. As stated by a contributor to the *Voices from the Bay* study:

> *"Some people have no more drinking water, not to mention the fish which are being destroyed. Also, the ducks and geese have had to change their travel route because of alterations in their feeding habitats. Every part of our environment has been affected by developments, and that includes humans. Our own culture should not be the next to be damaged." Quitsak Tarkiasuk (McDonald et al. 1997)*

While effects of development and economic diversification on land use are often looked at from a traditional use perspective, they are also likely influencing Nunavimmiut land use through their participation in these new sectors (e.g. how does shipping affect movement between communities? Is Indigenous tourism promoting the revival of cultural practices that change how people use the land?). This seems to be a poorly understood, but critical piece in Nunavimmiut determining how they would like to see their communities' relationships with the land and sea evolve.

3.1.3 Eeyou Istchee Cree

There are five Eeyou Istchee Cree communities. Whapmagoostui is along the coast of Hudson Bay, while Chisasibi, Wemindji, Eastmain, and Waskaganish are spread out along the east coast of James Bay (Figure 3.1; Table 3.3). Whapamagoostui and Kuujjaraapik share the same location but have mainly separate services.

Table 3.3. Summary of Eeyou Istchee Cree communities (Québec) in the HBME. Population as of 2016, from Statistics Canada, 2019.

Community	Marine Sub-region	Population	Population Identifying as First Nation	Population Identifying as Inuit
Whapmagoostui	Hudson Bay	984	90%	4%
Chisasibi	James Bay	4,872	93%	1%
Wemindji	James Bay	1,444	95%	-
Eastmain	James Bay	866	97%	-
Waskaganish	James Bay	2,196	96%	-

Bussières (2005) summarized the historical land use of Eeyou Istchee Cree. Similar to other Cree around James and Hudson Bay, land use is strongly tied to subsistence, with archeological evidence of use within a few hundred kilometers off the coast dating back 1500 years. And, like others along the coast, the influx of European settlers from the 1600s onwards significantly altered life in the region. A summary of archeological sites (both pre- and post-contact) was also completed in preparation for Tursujuq Provincial Park (KRG 2007).

Traditionally, Eeyou Istchee Cree used family hunting grounds – a "customary land tenure system." After beaver populations crashed in the early 1900s, the government decided to recognize these areas under the guise of formal traplines (Bussières 2005). Each of these areas has a "tallyman" that monitors harvest and population health, supported by generations of Cree traditional knowledge (Royer and Herrmann 2011). This system is foundational to the long-standing, healthy relationship Eeyou Istchee Cree have with the land and water and continues to this day (Bussières 2005). While current use is centred on the terrestrial, aquatic systems remain important for travel and as habitat for various plants and animals. For example, Paakumshumwaau (Old Factory River) is still considered a highway from the coast to inland harvesting areas by those in Wemindji. The importance of the coast is also evidenced by the concentration of old grave sites in this area (compared to inland along the river) (Bussières 2005).

Fast and Berkes (1994) summarized land use studies in east Hudson Bay and James Bay up to the early 1990s. Studies focusing on Cree communities in northern Québec were conducted from 1974–1979 and were intended to document Indigenous use and land claims. This work focused on Cree wildlife harvest for 32 selected species. Another study based in Chisasibi was conducted between 1972 and 1974. While this work also documented harvest, it also explored family and household composition (e.g. income, subsistence activities). Hunting and wildlife areas around Grande rivière de la Baleine were also documented in 1990 in response to environmental impact assessment requirements for a hydroelectric project. Eeyouch land use is also documented peripherally through climate change research (e.g. Herrmann et al. 2012; Royer et al. 2013; Royer 2016), place-name studies (Denton 2007), wildlife research and monitoring (e.g. Strangway et al. 2016), and health and social studies (Noreen et al. 2018).

In recent decades, the economic landscape in the region has expanded beyond the subsistence economy and commercial trapping to include tourism, research and monitoring, shipping and transport, and renewable and non-renewable resource extraction. These new sectors have implications for Eeyou Istchee Cree land use throughout eastern Hudson Bay and James Bay. Similar to Cree in Manitoba, Eeyou Istchee Cree land use has been drastically shaped by hydroelectric development (Fast and Berkes 1994). In the case of the James Bay hydroelectric project, changes included not just the development activities, but also the negotiation of the JBNQA, which has shaped the face of the region. Fast and Berkes (1994) also summarized many of the major events over the past 100 years that have brought change to the land use of Cree (inclusive of Eeyou Istchee and Mushkegowuk Traditional Territories) in James Bay and southern Hudson Bay. Some of these forces include overhunting of beaver and marten by non-Indigenous trappers, starvation events, increased government involvement in resource management, settlement, relocation, railway development, and non-renewable resource extraction and subsequent environmental degradation/pollution. Incredibly, there remains a strong connection to the land, evidenced by harvesting activities and food preferences (Chan et al. 2019), although in some Eeyou Istchee communities the total amount of "bush activity" may have decreased (Fast and Berkes 1994).

Hydroelectric development has been a defining force for Eeyouch land use in living memory. In Chisasibi, there have been far-reaching socio-economic effects:

> *"[After the river was dammed] the lifestyle change. The health changes. All these new things: civilization, money – lots of it. We could buy anything: food from the store, skidoos to go anywhere you want to go, cars, the pleasures of life – go on holidays. We didn't know what we were doing. We couldn't even go inland on the lakes or rivers like before [the dam]. Everything was motorized. We couldn't walk. We'd walk a few feet and take a rest. We got lazy. Spoiled. That's how it is now. Our health is gone. But we're slowly bringing it back to our kids." Edward Tapiatic (McDonald et al. 1997)*

There have also been tangible effects on specific subsistence activities. For example, Eeyouch fisheries have experienced increased sedimentation following rivers damming that made successful net setting impossible (McDonald et al. 1997). In these instances, fishers either fail to meet their needs or must travel elsewhere to meet those needs, which means changing land use patterns.

Parks and protected areas present a new way for Eeyouch land use to be acknowledged. Along the Hudson Bay coast and extending inland is the Tursujuq Provincial Park, which recognizes the overlapping land use of Cree and Nunavik Inuit (KRG 2007). Off the coast, Cree rights have been established in the Eeyou Marine Region (EMR) and there is now discussion for a new federal marine conservation area in James Bay within the EMR. This tool is being explored in partnership with Cree leadership. While it is still early days, this could be an additional tool in protecting and enhancing Eeyouch land use. In the past, parks and protected areas have curtailed Indigenous land use within their borders, but this is changing. The terrestrial and marine examples above both present opportunities to acknowledge the relationship Cree in Québec have with their land. Importantly, they may define new types of land use as Cree take on roles in research, monitoring, and tourism that are commonly associated with parks.

Evolving land-based programs are also redefining Cree land use. In Chisasibi, a land-based healing program designed to foster the traditional skills, teachings, and connection to place that have faded as a result of a multiple of colonial processes and actions (Radu et al. 2014). These types of programs will help to define what land use looks like for future generations.

3.1.4 Omushkego Cree and Swampy Cree

Ontario borders on the HBME, 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 (Table 3.4; Figure 3.1).

Table 3.4. Summary of Omushkego Cree communities in the HBME. Population as of 2016, from Statistics Canada, 2019.

Community/ Municipality	Marine Sub-region	Population (as of 2016)	Population Identifying as First Nation	Population Identifying as Inuit	Population Identifying as Métis
Fort Severn	Hudson Bay	361	100%	-	-
Peawanuck	Hudson Bay	195	100%	-	-
Moosonee	James Bay	1,481	74%	1%	3%
Attawapiskat	James Bay	1,501	98%	-	-
Kashechewan	James Bay	1,404	100%	-	-
Fort Albany	James Bay	759			
Moose Factory	James Bay	2,232	93%	-	-

Cree land use along the Hudson Bay coast was traditionally driven largely by subsistence harvest – this is very much still the case today. Pilon (2013) described the existing archeological evidence of land use around the Fort Severn region of the coastal Hudson Bay Lowland, while Fast (1996) detailed the historical and contemporary land relationships for York Factory Cree and Omushkego Cree (Moosonee, Moose Factory, Kashechewan, Fort Albany). For both groups, use is centred on the land and freshwater systems, with current day Omushkego Cree hunting grounds covering approximately 250,000km^2. Nonetheless, the marine region, especially the coast, continues to be used to harvest waterfowl and fish (Fast 1996).

For some Cree communities along the Hudson Bay coast, early documented land use is limited to records and journals from Hudson Bay Company employees (Fast 1996). This, of course, introduces a considerable bias. Fast and Berkes (1994) summarized land use studies in southern Hudson Bay and western James Bay up to the early 1990s. In the Mushkegowuk region (western James Bay) a study was conducted from 1989 to 1991 to facilitate regional planning and resource management, wherein distribution and intensity of land use by community, hunter types and species were documented. Over the course of 50 years, starting in 1920, land use by Indigenous peoples in North Central Ontario has been documented to assess environmental impacts of several developments. M'Lot (2002) summarized the modern land use footprint of Cree on the Manitoba coast of Hudson Bay, including the York Factory First Nation, the Fox Lake First Nation, and the Churchill Cree (those that live within the municipality of Churchill, but do not as yet hold official nation status). Land use in this area is still driven by animal migrations and the seasonal round, mirroring ancestors' historical use. Extensive Cree place names throughout coastal Manitoba speak to the land use footprint, but also the Cree relationship with the landscape (M'Lot 2002). Some describe activities, or physical attributes of the land, while others are about how animals and humans use the area or feature. As noted in section 3.1.3, Fast and Berkes (1994) describe the impacts of colonial government policies, as well as other forces and events that have brought changes to Cree land use throughout James Bay and southern Hudson Bay.

More recently, hydroelectric projects in Hudson Bay and James Bay have changed the landscape. Shoreline modifications in James Bay and southwestern Hudson Bay are associated with declines in local walrus sightings (McDonald et al. 1997). Dams have also blocked access to essential habitat for important food species, like seals and anadromous fish. When wildlife change their space use or disappear from an area altogether, there are implications for Cree land use. The plethora of species-specific and environmental changes observed by Cree land users is documented and summarized in *Voices from the Bay* (McDonald et al. 1997). Similarly, Cree land use in Manitoba has been heavily affected by resource development: multiple hydroelectric projects have flooded significant portions of traditional use areas, with limited long-term benefit to local Indigenous peoples (Fast and Berkes 1994).

In the face of development, some Cree communities are aiming for a proactive, community-based approach. The Fort Albany First Nation has identified key land use values that require protection through land use planning. These include food resources, travel routes, water, economic opportunities, traplines, forest resources, land title, and recreation (Minkin 2008). This type of land use plan acts as a formalization of traditional values that have been upheld and implemented for generations.

Unlike development, the relocation of communities often results in the near total transformation in land use. Traditionally, York Factory Cree lived along western Hudson Bay, moving between the coast and the bush following animal movements and seasons. Following the construction of the Hudson Bay trading post at York Factory in 1682, the site became a local hub for Cree and European traders. Despite this development and the influx of new people, Cree families maintained their relationships with the land and continued to be self-sufficient (Fast 1996). By 1957, the fur market had crashed and the decision was made to cease operations at York Factory. The government proceeded to move the York Factory Cree 250 km inland to a boreal landscape of coniferous forest and wetlands – vastly different from their subarctic coastal homeland (Fast 1996). While families were resilient in the face of this extreme change, it had dire consequence. Harvesters had to learn quickly how to hunt, trap, and travel in an entirely new landscape. A settlement at York Landing remains to this day.

3.2 SUBSISTENCE HARVESTING IN THE REGION AND ITS CULTURAL AND SOCIAL SIGNIFICANCE

Subsistence harvesting throughout the HBME continues to play a significant role in the lives of Indigenous residents and in community food networks. For example, the vast majority of adults in Nunavut and Nunavik communities (including those located in the HBME) participate in hunting, fishing, and gathering activities (Duhaime et al. 2015), indicating that subsistence harvesting continues to be a significant social and cultural activity. In Nunavik communities, approximately 12% of daily food consumption is from traditional foods (Duhaime et al. 2002). Further, in Nunavik, 78% of Inuit adults reported that at least half (if not more) of the meat and fish consumed in their households were from traditional food sources. In Nunavut, that figure is similar, at 73% (ITK 2008). First Nations throughout the Hudson Plains and Taiga Shield ecozones, including the Cree communities of the HBME, report similarly high levels of subsistence harvesting

(Berkes et al. 1995; Chan et al. 2019). 76% (Fort Albany, Attawapiskat, Moose Cree, Waskaganish) and 77% (Whapmagoostui) of First Nation households reported some type of traditional food harvesting (hunting, fishing, collecting seafood or plants) (Chan et al. 2019). The amount of subsistence harvesting affects not just the type of calories consumed in the household, but how meals are prepared and shared throughout the seasons. With so many households engaged in preparing and consuming traditional foods, subsistence harvesting shapes the unique socio-cultural fabric of each community.

Subsistence harvesting activities are directly tied to the nature and geography of land (and sea) use. The considerable body of Nunavimmiut knowledge on belugas is an example of this connection. Much of this knowledge focuses on the coastal and estuarine areas of the Nunavik Marine Region. While belugas do travel in deeper waters, the safety and availability of harvest opportunities in shallower areas concentrates Inuit harvest (and thus Inuit knowledge) on these types of habitat (Lewis 2009). In this way, harvesting and other cultural practices determine the footprint of use, the types of knowledge acquired and shared, and has considerable influence on the overall relationship between people and place.

This link between subsistence and land use is reflected in how Inuit and Cree interact with landscapes. 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. This is evidenced by the keystone species in Inuit food supply chains (see section 3.3). The following quotes from knowledge holders, documented in *Voices from the Bay* (McDonald et al. 1997) illustrate the relationship between Inuit of the Hudson Bay Region and the marine environment:

> *The currents are the marine animals' access to [food]. Inuit also need the currents, and we are always watching the currents for hunting. Seals come and go with the currents. There would be no whales if there were no currents." Peter Matte, Akulivik*
>
> *"The currents clean everything, ... If the water stopped moving, the animals in the marine world would stop moving, and Inuit would have nothing to eat. Lucassie Iqaluk, Inukjuak*

For Cree living around Hudson Bay and James Bay (Omushkego 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.

For many that participate in the subsistence economy today, the wage economy is a necessary component to getting out on the land. Boats, snowmobiles, guns, and gas all come at a price. This is referred to as a mixed economy (Wenzel 2009; Wenzel 2019). Despite the evolving role of the relatively new wage-based economy and transfer payments throughout HBME communities, subsistence activities retain a significant role in local and regional economies, in addition to their contributions to health, well-being, community cohesion, and cultural expression (Fast and Berkes 1994). This deep, long-standing connection to place rooted in subsistence activities continues today for all of the Indigenous groups throughout the region. It is evidenced in survival across generations and, more recently, in documented land use and traditional knowledge.

From distributing geese after the annual spring goose hunt in Wemindji to partitioning a bowhead harvest throughout the community of Coral Harbour, sharing has been and remains a central feature of Indigenous culture throughout the HBME (NWMB 2000; Bussières 2005). For Inuit, sharing is a foundational value (Nunavut Wildlife Management Board 2000). The ways and routes through which traditional foods are shared are changing, though. In the past there may have been a more equal distribution of the harvest throughout some Nunavut Inuit communities, whereas harvest sharing is more socially limited in recent time perhaps as a result of new socio-economic dynamics (Armitage 2005).

Over the past few generations, the role and nature of subsistence harvesting within communities may be changing. In Nunavik communities along the Hudson Bay coast, for example, the majority (84%) of households reported accessing community freezers to meet their needs when it comes to traditional food – an increase since this statistic was last recorded in 1994 (Blanchet and Rochette 2008). This shift towards a centralized source of traditional foods within communities may shape the future of subsistence harvesting, which has implications for land use, knowledge sharing, local economies, health and wellbeing, and cultural expression. It may also influence food sharing patterns among community members as well as individual and community values. The existence of community freezers and hunter support programs, which have an economic component, may be seen by some as commodification of shared resources that is out of step with traditional Inuit values of sharing what you have (Gombay 2009).

For most, if not all, of the communities in the HBME subsistence harvesting is already affected by an expanding human footprint, either in the form of adjacent resource development, shipping traffic, climate change, or some combination thereof. Indigenous peoples in this region are noting these changes and their effects on subsistence harvesting, social fabric, and cultural expression (Downing and Cuerrier 2011; Chan et al. 2019). Effects of climate change in the context of the subsistence harvest include reduced availability of traditional foods, decreased access to traditional foods, changes in animal cycles and patterns, changes in the growth rate of traditional foods and shorter hunting seasons (Chan et al. 2019). For Nunavut and Nunavik Inuit in particular, changes in and loss of sea ice are already shaping how communities interact with the land and seascape, as well as how, when, and what people are able to harvest (Ford et al. 2009; Laidler et al. 2009). In Igloolik (Foxe Basin), for example, individuals that depend heavily on traditional foods were found to be among the most vulnerable in the face of a changing climate (Ford 2009). Changes to food systems of the HBME have serious implications for subsistence harvesting and its relationship to community networks and local cultures.

Many of the communities throughout the HBME are also defined by a very young population, indicating that there could be significant population growth and a resulting increase in demand for subsistence harvesting opportunities (Mallory et al. 2010). If the interest in subsistence harvesting continues in coming decades, harvesting and sharing practices may evolve to compensate for an increased need. Whether or not younger generations will desire the same level of subsistence harvesting remains to be seen, however. Already the diet of older Inuit in Nunavik is higher in traditional food than store bought foods compared with younger Inuit, older Inuit more frequently use traditional foods for medicinal purposes compared with younger Inuit, and traditional food consumption in general has declined from 1994 to 2004 (Blanchet et al. 2000). Foods that were once essential and highly valued have been replaced in local diets, too. Decline of bowhead whale harvest and consumption in Nunavut is just one example of how external forces are influencing dietary preferences (NWMB 2000).

Both Inuit and Cree in the HBME have been successfully managing subsistence activities for generations, with harvest management tools that are starkly different from some science-based management approaches (Fast and Berkes 1994). Just as important as the subsistence harvest itself are the teachings, relationships, and controls communities put in place to ensure future generations can care for themselves. In this way, subsistence harvest is much more than just the taking of animals. It informs worldviews by situating the harvester in relation to other humans, animals, and the environment, thus becoming a central feature in each of the cultures of the Region (Fast and Berkes 1994). These management tools and the cultural frameworks in which they exist have come under intense pressure from external colonial processes since contact with European settlers, sparking change in Inuit and Cree communities to varying degrees.

3.3 KEYSTONE SPECIES IN THE INDIGENOUS FOOD WEB

In ecological terms, species are considered to be keystone when their presence or absence has a disproportionately large effect on the rest of the system compared to other species. This definition is nuanced in the context of an Indigenous food supply chain: plants or animals are considered keystone when their presence or absence has a disproportionately large effect on the local food web, which includes Indigenous peoples and their needs and relationships with the system (e.g. harvesting, modifying the landscape, redistributing nutrients, other cultural practices, etc.). Garibaldi and Turner (2004) further refine the definition of a cultural keystone species as “culturally salient species that shape in a major way the cultural identity of a people. Their importance is reflected in the fundamental roles these species play in diet, materials, medicine, and/or spiritual practices” (Garibaldi and Turner 2004, p. 4). Often these cultural keystone species can be grouped into “keystone guilds”– harvesting and other interactions throughout seasons and landscapes can result in two or more species together having a significant impact on a cultural identity (Garibaldi and Turner, 2004).

Changes over time in access to and/or availability of species with high food value can have a dramatic effect on the nature of an Indigenous food web as well as which plants and animals constitute keystone species in that system. Loss of access to a cultural keystone species would likely mean a major shift in the culture itself. This is important to consider in light of a rapidly changing climate at subarctic and Arctic latitudes. The types of harvested species may evolve by necessity to meet food needs (Wenzel, 2016), for example, replacing Arctic char with salmon. However, it is unknown how these kinds of replacements will be adopted at the community level or how other aspects of culture tied to keystone species might shift or disappear. By this definition, there may be many species that are valued (for food, medicine, etc.), but are not considered keystone species.

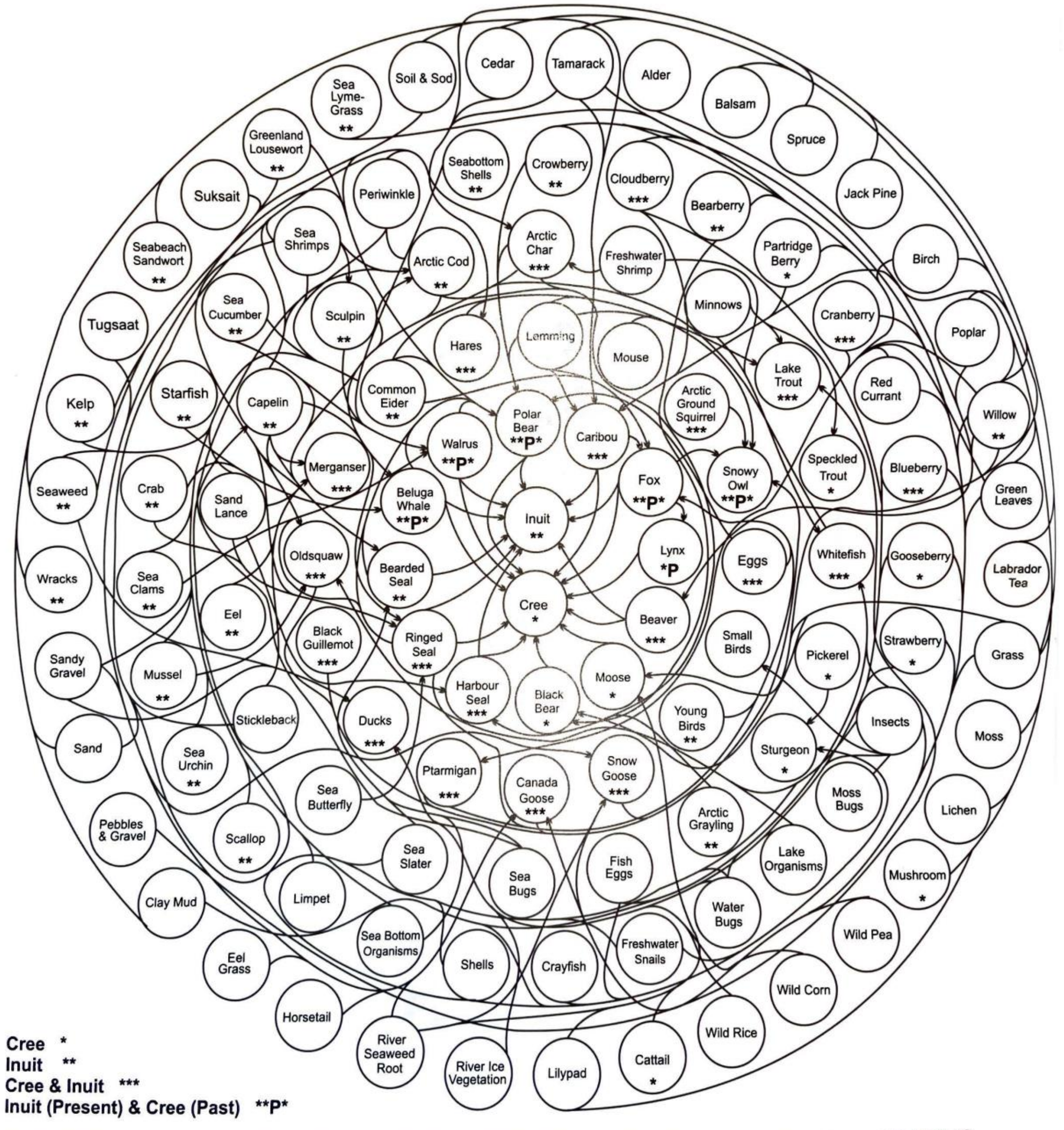
For many communities throughout the HBME, harvest data and food frequency surveys provide the best available insight into keystone species and guilds. In some instances, more knowledge has been documented about particular species that might indicate their importance in the local Indigenous food web. In most cases, however, the lens of cultural keystone species has not been specifically applied to the local system, making identifying these species for this report a speculative exercise. Further, a keystone species may not be heavily harvested or consumed or may not even be harvested at all, but rather support other harvested species or hold significant symbolic value. In these scenarios, ranked harvest data and food frequency surveys fall short and may even be misleading in identifying keystone species. The documentation of traditional knowledge can be driven by external interests as opposed to community priority, e.g. the listing of a species under the federal *Species at Risk* legislation, making this an imperfect measure of species importance as well. Given these limitations, harvest data and food frequency studies are presented as an indicator of likely keystone species (and potentially guilds) and a jumping off point for further investigation in the absence of more specific documented knowledge. Additional insights drawn from traditional knowledge studies are included when available.

In summarizing the types of animals most people in each region or community harvest, there are some species that stand out as key to food systems across the HBME (Figure 3.4). The caribou is one of the most harvested species for both Cree and Inuit communities in the HBME. Over 30% of Inuit households in Nunavut consume caribou daily or almost daily (Meis Mason et al., 2007). After caribou, Cree and Inuit key species begin to diverge, with Inuit relying more heavily on marine species and Cree harvesters turning more to terrestrial and freshwater species.

3.3.1 Nunavut Inuit

Foxe Basin forms part of the largest marine ecozone, the Arctic Archipelago and is home to several Nunavut Inuit communities. 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, Hall Beach, and Naujaat (formerly Repulse Bay) (Table 3.5). The ice forms a hunting platform from which species like the walrus, the ringed seal, the bearded seal, and the polar bear are harvested (Ford et al. 2009). Top aquatic species harvested by Foxe Basin Nunavut Inuit communities are identified in Table 3.5, based on the results of the Nunavut Wildlife Management Board's (NMWB) (2004) Nunavut Wildlife Harvest Study. While the NWMB has been

Figure 5: Hudson Bay Food Web



Source: Hudson Bay Programme, *Traditional Ecological Knowledge of Environmental Changes in Hudson and James Bays, Part I.* (Ottawa: HBP, 1995), 26.

Figure 3.4. Summary of the Hudson Bay Indigenous food web, from *Voices from the Bay* (McDonald et al. 1997), originally published in *Traditional Ecological Knowledge of Environmental Changes in Hudson and James Bays*.

Table 3.5. Top five aquatic food species in each Foxe Basin Nunavut Inuit community, quantified by the number of hunters harvesting each species. Terrestrial species were omitted, as this report focuses on the aquatic environment (Nunavut Wildlife Management Board 2004).

Ranking of wild food species	Community		
	Igloolik	Hall Beach	Naujaat
1	Arctic char	Arctic char	Ringed seal
2	Ringed seal	Lake trout	Lake trout
3	Goose eggs	Ringed seal	Arctic char
4	Walrus	Walrus	Narwhal
5	Snow goose	Bearded seal	Beluga

gathering harvest data since 2012 on a community-by-community basis under its Community-Based Monitoring Network, access to this data is restricted. As a result, Nunavut Wildlife Harvest Study is the only Nunavut-wide harvesting report published by the Board and publicly available.

Hudson Bay, like Foxe Basin, falls within the Arctic Archipelago marine ecozone. Large estuaries throughout Hudson Bay provide vital habitat for anadromous fishes and in some cases beluga whales, which are important food species (Table 3.6). 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). 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. For further discussion on polynyas and other ice features, see section 4.1.6.

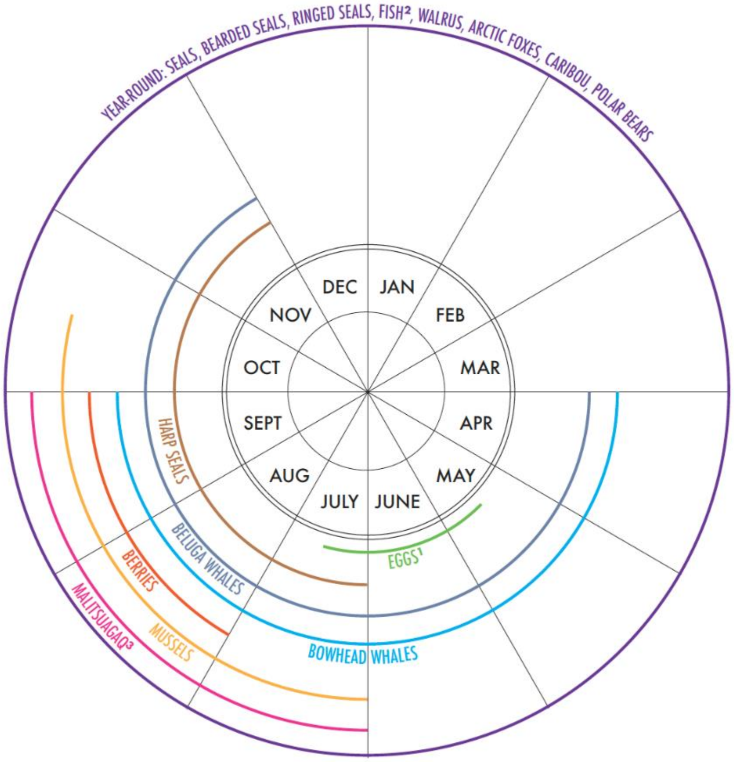
Table 3.6. Top five aquatic food species for each Hudson Bay Nunavut Inuit community, quantified by the number of hunters harvesting each species. Terrestrial species were omitted, as this report focuses on the aquatic environment (Nunavut Wildlife Management Board 2004).

Ranking of wild food species	Community					
	Coral Harbour	Chesterfield Inlet	Rankin Inlet	Whale Cove	Arviat	Sanikiluaq
1	Snow goose	Arctic char	Arctic char	Arctic char	Arctic char	Arctic char
2	Arctic char	Ringed seal	Lake trout	Lake trout	Lake trout	Canada goose
3	Ringed seal	Lake trout	Ringed seal	Ringed seal	Cod	Eider duck
4	Goose eggs	Canada goose	Canada goose	Canada goose	Canada goose	Ringed seal
5	Beluga	Snow goose	Beluga	Beluga	Beluga	Cod

As part of the Arctic Corridors Research Project (Carter et al. 2017; Carter et al. 2019), subsistence harvest was documented in a seasonal round for Coral Harbour (Figure 3.5) and Arviat (Figure 3.6).

While seals and fish are important to both Coral Harbour and Arviat all year round, there are some marked differences that mirror the dissimilarities in land use described above. Coral Harbour is more heavily focused on marine species throughout the year, while Arviat harvesters rely more on wildlife using freshwater and terrestrial harvesting, in comparison.

Inuit Qaujimajatuqangit (IQ) of polar bears can be found throughout various studies as well as in the recently release Nunavut Polar Bear Co-Management Plan (e.g. MacDonald et al. 1997; Wong and Murphy 2016; Government of Nunavut 2019). However, Nunavut remains the only Inuit region in Canada without a comprehensive Inuit Knowledge study of polar bears. As is the case for Nunavik Inuit, the polar bear is likely a cultural keystone species for Nunavut Inuit. Assembling IQ about polar bears would be useful in confirming the role of the species culturally and ecologically, while documenting and supporting the protection of the critical relationship that exists between Nunavummiut and polar bears.



[1] EGGS: Snow Goose, Ross' Goose, Crane, Tundra Swan, Canada Goose (locally called Honkers), Cackling Goose (locally called Canada), Common and King Eider Duck, Gull, Thick-billed Murre

[2] FISH: Cod, Arctic Char, Lake Trout, Land-locked Char

[3] MALITSUAGAQ: Also known as Seabeach sandwort and *Honckenya peptides*.

Figure 3.5. Seasonal cycle of harvesting activities near Coral Harbour, Nunavut, from the *Arctic Corridors and Northern Voices* study (Carter et al. 2019, p. 10)

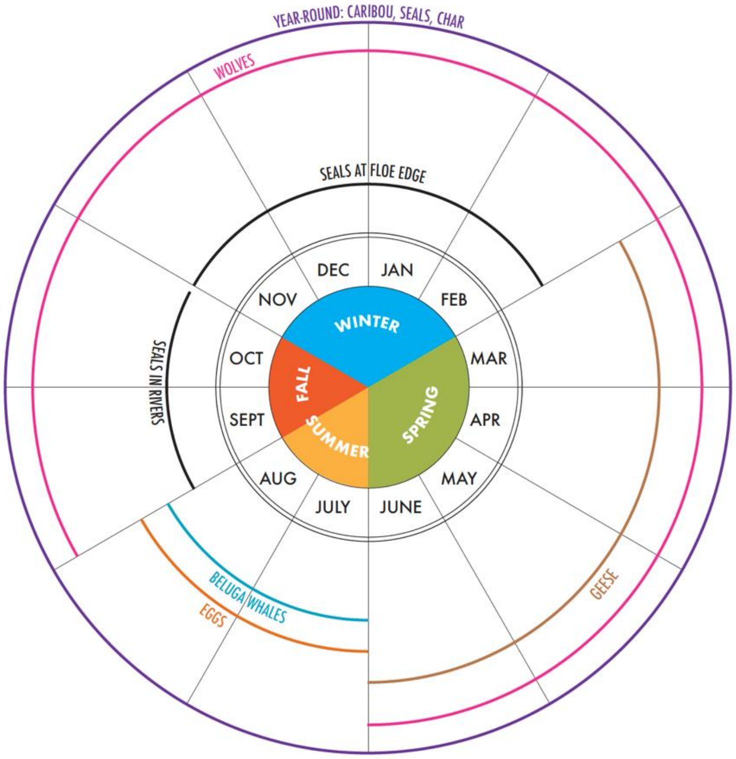


Figure 3.6. Seasonal cycle of harvesting activities near Arviat, Nunavut, from the *Arctic Corridors and Northern Voices* study (Carter et al. 2017, p. 10)

Seals, particularly ringed seals, but also bearded and harbour seals, are central to the Nunavummiut diet and culture throughout Hudson Bay and Foxe Basin (Table 3.5; Table 3.6). However, documented Inuit knowledge of seal species in this region is limited. There is some IQ gathered tangentially in climate change and sea ice studies. This research illustrates the relationship between the ice and these key species as well as the vulnerability of that relationship to change (Laidler et al. 2009; Ford et al. 2008). Language for and understanding of sea ice is also tied to seal ecology (Laidler 2008; Krupnik et al. 2010). Studies of other species, like orca, also capture IQ of seals (Ferguson et al. 2012). Documented traditional knowledge regarding other species or issues can provide tangential insight into the life history and importance of seals, but a more focused understanding of seals, especially ringed seals, appears to be a knowledge gap. In 2019, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated ringed seals as Special Concern, citing their importance to Inuit and polar bear and the threat of disappearing sea ice, a key habitat feature (Brown 2019). A federal listing under the *Species at Risk Act* could follow. It will be important to have Inuit Knowledge and concerns considered alongside the existing scientific knowledge during management discussions for this key species.

The narwhal does not top the list of harvested species, but there is some documented Traditional Knowledge (White 2012) and they are very much a valued species (Hoover et al. 2013). Orcas are not harvested at all, but there is a fair amount of Inuit Knowledge documented for this species (Ferguson et al. 2012; Westdal et al. 2013; Higdon and Ferguson 2014). The focus on knowledge of orca is mainly due in part to external interest and that orca may impact the population health of other species of value to Inuit.

For Inuit in Sanikiluaq, ringed seals, bearded seals, common eiders, 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). In fact, the diet of Sanikiluaq residents is heavily influenced by the fact that the community is on an island surrounded by salt water (Wein et al. 1996). Eider ducks are of particular importance and are likely a cultural keystone species for Inuit in Sanikiluaq. Not only are they harvested by many residents as a food source (Table 3.6), the skin and feathers are a source material for clothing that has helped Inuit in the Belcher Islands area survive in the challenging conditions (Oakes 1991). Their harvest is an important cultural practice.

In some communities, species that were once keystone no longer hold the same role in the Inuit food web. For example, the importance of bowhead whales for Nunavut Inuit communities has significantly decreased following the end of commercial whaling (Nunavut Wildlife Management Board 2000; Hidgon and Ferguson 2010). Historically, a bowhead harvest meant no one would go hungry that year, as one whale was a significant amount of meat and blubber. The whales also provided oil for heating and light, as well as food for dog teams, fuelling the main means of transportation. Nothing was wasted as even the baleen and bones were used as fishing tools and in sled construction, among other uses (NWMB 2000). Since the 1990s, though, there has been a revival of the subsistence harvest of bowhead whales throughout Nunavut, at first unsanctioned and eventually under federal quotas. Several decades without this practice has resulted in challenges in knowledge sharing and changes in food preferences (Kishigami 2015), but a wealth of knowledge, stories, and legends have been documented throughout Nunavut (NWMB 2000).

Caribou are terrestrial, and therefore excluded from the ranking of top aquatic food species (Table 3.6), but their cultural and nutritional importance to the Inuit communities in the HBME is worth noting. The high number of caribou harvesters and the considerable amount of food these animals provide to the communities means that fluctuations in availability of caribou has implications for the rest of the Indigenous food web, e.g. an increased dependence on one or several marine mammal species to meet food needs.

Hudson Strait connects Hudson Bay to the Atlantic Ocean and has a considerable effect on the physical systems, ecology, and communities of Hudson Bay. In addition to the six communities in Hudson Strait, some communities in Hudson Bay have a connection to the region as well, through both proximity and family, making the region an important component of the larger system that warrants consideration in the context of Indigenous food webs.

Hudson Strait is seasonally 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 harvesting efforts are focused along the floe edge and at polynyas, as well as at tidal cracks (Laidler et al. 2011).

Along with a range of deep-water fish species not found in other parts of the HBME, Hudson Strait also provides habitat for marine mammals such as whales, seals, walruses and polar bears, as well as numerous waterfowl. Larger marine species move through or use the Strait on their way to or from Hudson Bay, making it an important component of the larger food web, e.g. beluga (Breton-Honeyman et al. 2016; Colbeck et al. 2013). In general, key aquatic species for Inuit communities on Hudson Strait mirror those in Hudson Bay (Table 3.6): walrus, narwhal, beluga, seals, geese, ducks, Arctic char, salmon, mussels, and clams (Brooke 1992; Furgal et al. 2002). Harvest of some of these key species are well documented, while others are less so, perhaps due to the opportunistic nature of the harvest or local/regional reporting requirements. For example, 15,536 clams were harvested by the community of Cape Dorset in 1997, representing a large source of food for the community (Hurtubise 2016). Likely, clams and mussels represent important species across years, but documented harvest may not reflect that reality. The flow of nutrients within the Arctic marine mammal food web and the Arctic fishes food web, representative of food webs within the HBME, are simplified in Figures 3.7 and 3.8.

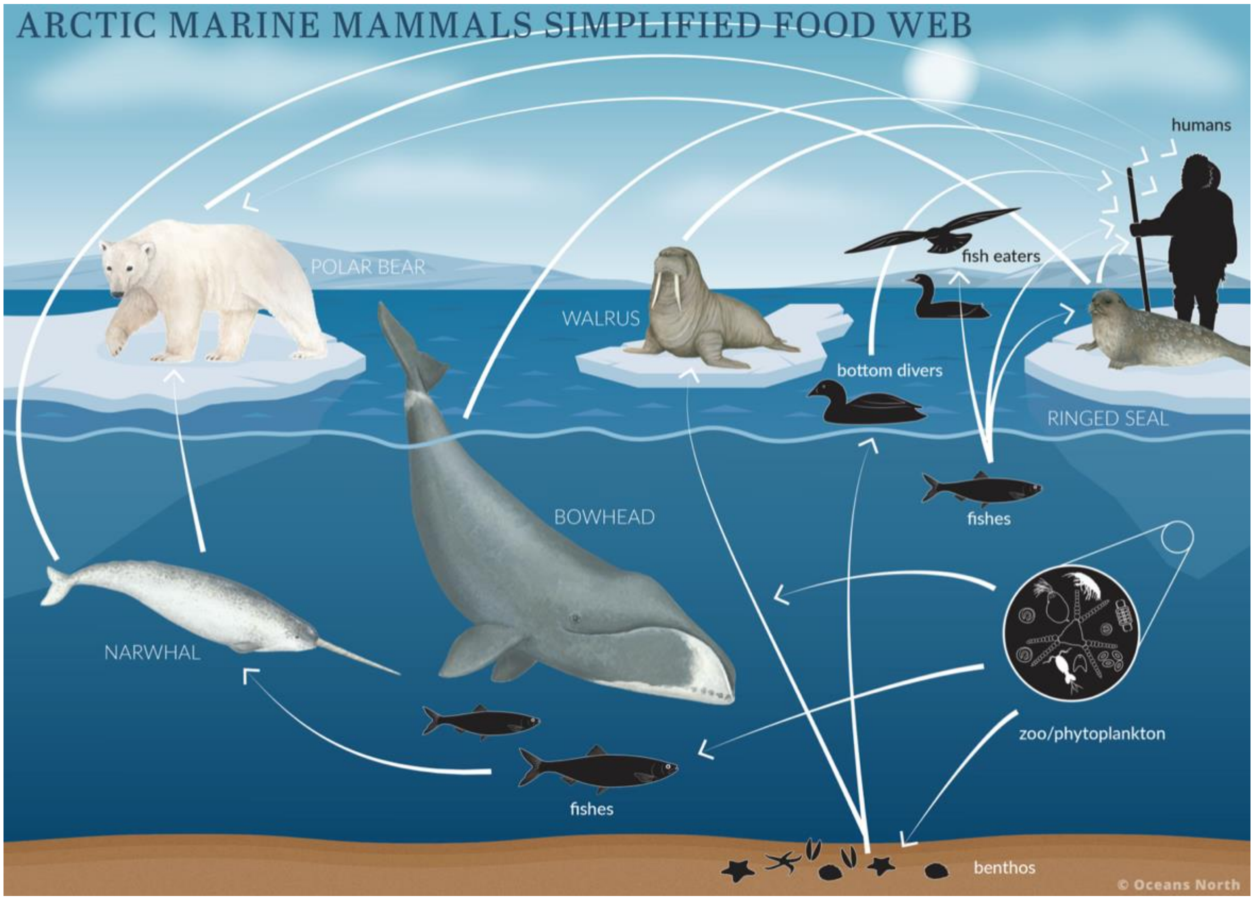


Figure 3.7. Arctic marine mammals simplified food web (Oceans North Conservation Society et al. 2018, p. 91)

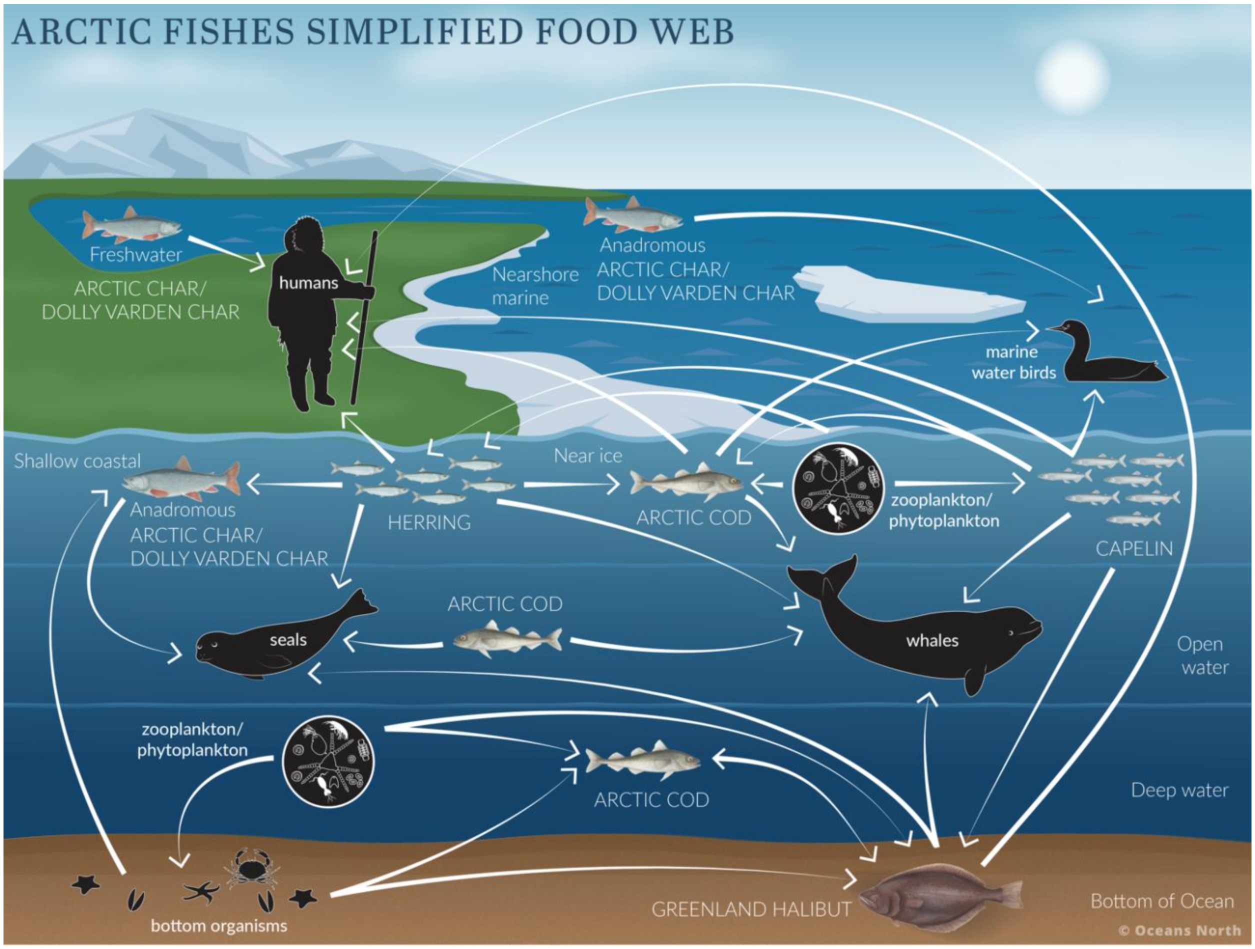


Figure 3.8. Arctic fishes simplified food web (Oceans North Conservation Society et al. 2018, p. 49)

3.3.2 Nunavik Inuit

Based on traditional foods consumed throughout the year, the aquatic taxa most commonly eaten in Nunavik households are anadromous fish, geese, and marine mammals, making up 60% of overall subsistence-based diets (Blanchet and Rochette 2008). These foods (e.g. Arctic char, seal, beluga blubber) are sometimes referred to as "real foods" or niqituinaaq, indicating a strong preference and importance (Kishigami 2013). Blanchette and Rochette (2008) report on traditional food consumption in Nunavik based on the results of the *Qanuippitaa? (How are we?)* 2004 Nunavik Inuit Health Survey (see Table 3.7). More recently, the Nunavik Board of Health and Social Services carried out the *Qanuilirpitaa? (How are we now?)* 2017 Nunavik Inuit Health Survey, the results of which were not released at the time of this report preparation and publication.

There is considerable Inuit Knowledge documented on the ecology and Inuit relationship with beluga in the Nunavik region (Lewis et al. 2009; Breton-Honeyman et al. 2016a; Breton-Honeyman et al. 2016b). This body of knowledge is indicative of the importance of the species to the Inuit food web throughout eastern Hudson Bay. The harvesting relationship with beluga shapes travels

Table 3.7. Distribution of aquatic traditional foods consumed by Nunavik Inuit over the course of a year (Blanchet and Rochette 2008)

Wild food grouping (excluding land animals)	% overall traditional food consumption	Foods	% traditional food consumption within species group
Fish and seafood	32%	Arctic char	59%
		Whitefish	13%
		Trout/salmon	10%
		Mussels/clams	8%
		Dried fish*	5%
		Other fish (fourhorn sculpin, pike)	4%
		Scallops/seaweed	1%
Marine mammals	12%	Seal	59%
		Beluga	35%
		Walrus	7%
Marine mammal fat	2%	Beluga	72%
		Seal	28%
Birds (excluding ptarmigan)	11%	Goose	64%
		Other birds (eider, scoter, pintail, murres)	2.5%
		Eggs	1.5%

* Dried fish is not defined by the authors.

patterns of Nunavimmiut, with a high degree of harvesting occurring in shallow coastal and estuarine areas throughout eastern Hudson Bay (Lewis 2009). It also prompted the establishment of summer harvesting camps for some communities (Brooke 1992). The presence of prey species, like capelin, and anadromous fish (e.g. Arctic char), likely draw beluga into coastal water and river mouths (Breton-Honeyman et al. 2016), making these species important to the Nunavimmiut food web as well.

Beluga are not only a valuable food and medicine species for Nunavik Inuit (Blanchet and Rochette 2008). Harvesting beluga also represents an expression of Inuit culture and lifestyle, a connection to traditions and ancestors, and a type of work (Gislason 2007). It strengthens social bonds through hunting together and harvest sharing (Kishigami 2013). For some, belugas also represent an expression of Inuit spirituality (Gislason 2007). These are all indicators of a cultural keystone species. As such, ensuring the long-term health of this species is of the utmost importance, but current day management of the species throughout the Hudson Bay portion of the Nunavik Marine Region is both sensitive and complex due to overlapping populations, past commercial harvesting, and existing management structures (Doniol-Valcroze et al. 2012).

Seals make up the largest proportion of marine mammals in the Nunavimmiut traditional food diet (Table 3.7) and are central to Inuit culture. However, documented Inuit knowledge of seal species in this region is sparse in the literature. Documented traditional knowledge regarding other species or issues can provide tangential insight into the life history and importance of seals (e.g. Nunavik Marine Region Wildlife Board 2016), but a more focused understanding of seals, especially ringed seals, appears to be a knowledge gap. As noted in section 3.3.1, the COSEWIC has designated ringed seals as Special Concern (Brown 2019), due to their importance within the food web of the Canadian Arctic, particularly for Inuit and polar bear. In response to the lack of documented knowledge available on ringed seals and expressed concern from hunters, the Nunavik Marine Region Wildlife Board (NMRWB) initiated a Natsiq (ringed seal) community-based research and monitoring project that brings together hunters, the Nunavik Research Centre, students and teachers to assess and monitor ringed seal health and diet in several communities across Nunavik.

Unlike seals and belugas, the walrus does not represent a large portion of Nunavimmiut traditional food diets (Blanchet and Rochette 2008). Before the transition to snow machines, Inuit relied on dog teams for transportation and during this time, walrus was harvested at a high rate in order to feed numerous dogs (Brooke 1992). This significant need is no longer present. There seems to be a generational shift, too, away from valuing walrus as a food source for Inuit (Brooke 1992).

Nunavimmiut hold a vast amount of knowledge about polar bears, which are harvested for food, clothes, tools, and gifts. Similar to belugas, they are often harvested in the coastal areas along the Nunavik portion of the Hudson Bay coast (Nunavik Marine Region Wildlife Board 2016). Beyond subsistence needs, polar bears are likely a keystone species as Inuit in the eastern Hudson Bay maintain a strong cultural connect with the species. They are seen as an intelligent apex predator with many similarities to humans and represent a source of strength for hunters on the land (Nunavik Marine Region Wildlife Board 2016). Polar bears are also woven into Inuit myths and rites of passage. They may not make up a large portion of the Nunavimmiut diet, but the cultural role of polar bears is an essential one.

Like many of the communities in Nunavut, Nunavimmiut rely heavily on caribou as a major contributor to meeting subsistence needs (Blanchet and Rochette 2008). However, as this report focuses on the aquatic environment, the role of caribou as a keystone species in Nunavik is not discussed further.

3.3.3 Eeyou Istchee Cree

Adjacent to Hudson Bay, James Bay is part of the Arctic Archipelago marine ecozone. 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 Rupert, Eastmain, La Grande, and Harricana rivers (McDonald et al. 1997). These rivers, along with strong marine currents, shape the distribution of plants and animals, but also guide how people move and harvest in this marine region.

The recent *First Nations Food, Nutrition and Environment Study* explored traditional food consumption by ecozone, sampling several communities in each ecozone (Chan et al. 2019). Whapmagoostui was sampled as part of the Taiga Shield, where the most frequently consumed aquatic traditional foods (in descending order) are geese, trout, whitefish, Northern pike, and walleye (Chan et al. 2019). Similarly, Waskaganish was sampled as part of the Hudson Plains ecozone where the most frequently consumed aquatic traditional foods are geese, walleye, Northern pike, ducks, whitefish, cisco, and sturgeon (Chan et al. 2019).

Canada geese represent a keystone cultural species for Eeyou Istchee Cree. They hold considerable knowledge about the species and its environment, as well as the effects of changing climate and development on population health. Geese are harvested by most Cree hunters, and geese make up a significant portion of the traditional food diet (Bussières 2005; Royer and Herrmann 2011; Chan et al. 2019; Peloquin and Berkes 2009) The majority of Wemindji residents leave the village and head to a communal spring camp in preparation for the goose hunt. This yearly event brings everyone together to spend time along the coast, sharing stories and supplies, helping each other, and harvesting together, under the "tallyman" system (see section 3.1.3) (Bussières 2005). Many of the geese caught at this time are brought home and either shared or stored for other times in the year. Geese are caught in the fall, as well, but the level of celebration and intensity of harvest is less (Bussières 2005).

Cree harvesters also modify this coastal landscape to encourage key plants and animals or features. For example, Wemindji Cree cut tuuhiikaan, corridors in the coastal forest, and construct dykes to encourage the kind of habitat geese prefer (Sayles and Mulrennan 2010). These actions provide enhanced habitat for geese, but also help Wemindji Cree meet their food needs. This type of habitat modification demonstrates how Cree communities play an active, reciprocal role in their local food webs.

Whitefish is a high-value food fish, along with brook trout and cisco, but these do not necessarily represent keystone species (Bussières 2005; Strangway et al. 2016). Cree living in Fort George used to maintain a significant community fishery for whitefish and cisco. This fishery may once have been similar in cultural and social importance to the goose harvest near Wemindji (Berkes 1977), but following large scale hydroelectric development, the community has since relocated to present day Chisasibi. Moose, beaver, ptarmigan, berries, among other foods, are all important to Eeyou Istchee Cree, but, as they are terrestrial species, are not discussed further here.

3.3.4 Omushkego Cree and Swampy Cree

The recent *First Nations Food, Nutrition and Environment Study* explored traditional food consumption by ecozone, sampling several communities in each ecozone (Chan et al. 2019). Attawapiskat, Fort Albany, and Moose Cree were sampled as part of the Hudson Plains ecozone where the most frequently consumed aquatic traditional foods are geese, walleye, Northern pike, ducks, whitefish, cisco, and sturgeon (Chan et al. 2019). Whitefish was also found to be an important food species for Cree on the Hudson Bay coast in the 1990s (Berkes et al. 1995).

An important feature of James Bay is 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. Recent declines in Canada geese numbers along the east coast are thus a cause for concern. There are also concerns among Cree coastal communities regarding declines in eelgrass, a change which some suspect may be linked at least in part to hydroelectric development. Declines in eelgrass beds have had consequences for waterfowl such as Canada geese and brant, and thus for harvests by Cree hunters. The eelgrass-goose system could be considered a keystone guild.

In the community of Fort Severn, geese are the most consumed traditional food, after caribou. Other aquatic species of importance are whitefish and pike, by weight consumed, but mussels, seaweed, and clams also provide required nutrients (Lawn and Harvey 2003). In fact, along with caribou and moose, geese (Canada and lesser snow) make up two thirds of the 1990 traditional food harvest across Omushkego Cree in the Hudson Bay and James Bay region (Fort Severn, Moose Factory, Moosonee, New Post, Fort Albany, Kashechewan, Attawapiskat, and Peawanuck) (Berkes et al. 1994). Geese have been key species throughout the region in the recent past, as well. In the 1970s, the vast majority of hunters living along Hudson Bay and James Bay harvested geese (Canada and lesser snow) (Prevett et al. 1983).

Aside from geese, fish are the next most important aquatic food source for Cree along Hudson Bay and James Bay, with fishing occurring throughout the year, both through fisheries and incidental to other harvesting activities (M'Lot 2002). Cree harvesters also hold knowledge of various fish species and the effects of environmental change on their populations (Hori 2010).

Other marine species may have been more important historically. Beluga were harvested at the mouth of the Severn River, mostly as food for dog teams, while seals were hunted up to eight miles up the Severn River in summertime (Pilon 1982). Polar bears represent an occasional harvest (Pilon 1982).

Before being relocated inland, the York Factory Cree living near the coast of Hudson Bay fished for whitefish, jackfish, and trout in the rivers that flow into the Bay, often using seine nets. Fish were sometimes frozen as winter food. Special whale nets were even used to catch beluga in the Bay (Fast 1996). At the time, whale meat and seal meat were not preferred by people but represented an important source of meat for dog teams. Seal skin was also used for repairing clothes and making leather goods (Fast 1996). Coastal waterfowl were central to the traditional Cree diet: lesser snow geese, Canada geese, ducks, brants, and shorebirds were all harvested regularly (Fast 1996). While key species were traditionally terrestrial or freshwater species (e.g. beaver, caribou, and moose), the marine environment certainly played an important role in the traditional York Factory Cree food web before their relocation.

3.4 REGIONAL EFFECTS ON INDIGENOUS FOOD SUPPLY WEBS

As with most regions in the Arctic, the HBME is experiencing multiple stressors. While atmospheric forcing due to climate warming is a significant driver of change driven by global factors (see chapter 5), there are also regional factors and activities that are having an impact on Indigenous food supply webs. Several key regional effects on Indigenous food supply webs are mentioned here, and discussed in detail in section 6.1 (cumulative effects).

Large-scale hydroelectric development along many of the river systems that feed into the HBME has shaped the terrestrial and marine environments of the southern parts of the region, as well as the legal, political, and socio-economic landscapes (see 6.1.1). Major hydroelectric developments within the HBME include the Nelson and Churchill rivers in Manitoba, the Moose River in Ontario, and La Grande Rivière (which diverts water from the Eastmain, Opinaca, and Caniapiscau Rivers) and Grande rivière de la Baleine (which includes development on the Nottaway, Rupert and other rivers) in Québec. Flooding of lakes and rivers to create dam reservoirs triggers a process that releases methylmercury into the aquatic environment, where it bioaccumulates in the food web. Elevated methylmercury levels in food webs remain for decades after flooding. Elevated methylmercury levels in foods traditionally consumed by Inuit and Cree communities as a result of hydroelectric development has been a significant concern in the HBME, and effects on subsistence harvesting have been adverse and long-lasting (Bodaly and Johnston 1992; Rosenberg et al. 1997). As described in Kuzyk and Candlish (2019), 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 considered in local travel, thus affecting subsistence harvesting access. There are also concerns among Cree coastal communities regarding declines in eelgrass (*Zostera marina*), a change which some postulate is linked, at least in part, to hydroelectric development (Kuzyk and Candlish, 2019). Declines in eelgrass beds are believed to have contributed to the lower numbers of waterfowl such as Canada geese and brant, which has impacted the harvests by Cree hunters. Kuyzyk and Candlish (2019) also describe the series of bilateral agreements between Hydro-Québec and Cree, including those related to research and monitoring.

Shipping is another significant pressure on marine ecosystems and harvesting activities (see 6.2.2). Ship traffic throughout the Canadian Arctic nearly tripled in the last decade (Dawson et al. 2020), with traffic in Hudson Strait and Hudson Bay (to and from Churchill) showing an increase in recent years (Andrews et al. 2017). In the HBME, it is projected that the average ice-free season (over the years 2041-2070) will lengthen by 49 days in Hudson Bay, 53 days in Foxe Basin, and 65 days in James Bay (Kuzyk and Candlish 2019b), increasing the safe shipping window and the feasibility of new northern ports. As Dawson et al. (2020) describe, shipping can enhance community wellbeing by bringing in much-needed supplies, including equipment and supplies needed to support subsistence harvesting. However, shipping can also pose substantial risks and adverse impacts to the marine environment through introduction of invasive species, pollution and noise effects on marine wildlife, direct strikes on wildlife, and effects on wildlife migration routes through breaking up sea ice. These effects impact communities that rely on healthy marine food webs for sustenance. Further, as the authors describe, icebreaking vessels can break up an already diminishing sea ice platform that is critical infrastructure for communities as it provides a platform to access wild food resources.

There are no offshore oil and gas developments in the HBME, but mining developments on land also have substantial impacts for the marine environment (see 6.1.3). There are at least five significant mineral developments that rely on shipping in the region, with ports at Baker Lake, Rankin Inlet, Roche Bay, and Steensby Inlet in Nunavut, and at Chisasibi in Québec, with a substantial number of mines that are proposed or in development (Gavrilchuk and Lesage 2014). While mines in the HBME currently conduct shipping during the ice-free season, coastal effects from port development and impacts of ship traffic are all adding to the constellation of factors affecting Indigenous food supply webs in the HBME.

3.5 SPECIES OF COMMERCIAL INTEREST

Beyond the subsistence harvest and community fisheries in the communities of the HBME, there are a number of commercial harvest interests, although current commercial harvests in the HBME are very limited. These are shaped by local availability and sustainability, but also by infrastructure (e.g. nearest processing facilities, transport costs, etc.), federal legislation, emerging markets, and international agreements (e.g. European Union ban on seal products in 2009). Further, the historical context of commercial fisheries exploitation in the HBME has left legacies in terms of impacts on species abundance that are still being felt today for species such as the beluga (Doniol-Valcroze et al. 2012). As stated in the *Northern Integrated Commercial Fisheries Initiative Final Report*, the connection to country food and traditional methods of trade are deeply rooted in the histories of Indigenous communities and across Canada. Local fishing, harvesting, and hunting activities were critical to food security and culture—as they are today—but were also the hub of community commerce (National Indigenous Fisheries Institute 2019). Traditional values around country food harvesting, processing, sharing, distribution, and trade are all critical for creating sustainable commercial harvesting ventures that benefit Indigenous communities. It should be noted that there are also differing views within some HBME communities about whether or not selling traditional food for commercial purposes is culturally appropriate (Gombay 2006).

Fish and invertebrates

In an overview of the ecosystems of Hudson Bay and James Bay, Stewart and Lockhart (2005) state that, excepting anadromous fish, no commercially attractive fish or invertebrate species has been found in sufficient abundance in these marine areas to justify development of an offshore commercial fishery to date, citing efforts that have attempted to explore the commercial fisheries potential of these bays since the 1930s. For example, test fisheries along the western and northeastern coasts of Hudson Bay, found that commercially attractive concentrations of macroinvertebrates (including shrimps and crabs) were not present. A commercial fishing venture in Richmond Gulf, near Umiujaq, was developed for a few years in the 1960s for anadromous brook trout, whitefish, cisco, and Arctic char, but declining catches and unfavourable economics led to the closure of this fishery. A marine test fishery was conducted in the late 1980s near Wemindji that yielded harvests of sculpins, Greenland cod, and anadromous whitefish, but not in sufficient numbers to justify commercial development. Small concentrations of commercially attractive benthic macroinvertebrates have been located near Sanikiluaq, including green sea urchin (*Strongylocentrotus droebachiensis*) and blue mussel (*Mytilus edulis*), which are smaller than their temperate counterparts, but limited abundance has meant that a commercial fishery has not been viable. In the late 1980s, Makivik surveyed northern Hudson Bay for shrimp, and in the early 1990s surveyed the Hudson Bay coast from Ivujivik to Inukjuak for Iceland scallops. In both cases, abundance was not sufficient to justify development of a commercial fishery. Besides limited abundance, viability of commercial fisheries in the HBME is also shaped by costs due to the short open water season and high costs of remote operation (Stewart and Lockhart, 2005). Also, small commercial harvest quotas were approved for exploratory clam, scallop, amphipod, shrimp and blue mussel fisheries in the Kivalliq area in the 1990s and early 2000s, but the lack of shellfish inspection services to ensure safety of commercial harvests may also have been a factor limiting further development of these fisheries (Stewart and Lockhart, 2005).

Throughout Nunavut, the fisheries industry faces challenges that include lack of marine infrastructure, local training, transportation costs, lack of Nunavut-specific fisheries regulations, and distance from the market (Government of Nunavut 2016). Despite these challenges, the territory has major commercial turbot, shrimp, and char fisheries, with the offshore turbot fishery acting as a major employer in the Qikiqtani region. In 2015, the offshore turbot quota allocation was over 11,350 metric tonnes and had a landed value of $78 million (Government of Nunavut 2016). In 2015, the landed value of shrimp in Nunavut, consisting of Northern shrimp (*Pandalus Borealis*) and striped shrimp (*Pandalus Montagui*), was $6.5 million for 1,897 tonnes harvested, representing approximately 17% of the Nunavut's total available quota for shrimp, while the landed value of Arctic char was $1.8 million for 72,574 kg harvested, representing 20% of Nunavut's total available quota for that species (Government of Nunavut 2016). Geographically, however, these commercial fisheries are outside of the HBME, with some shrimping occurring in Hudson Strait (Standing Senate Committee on Fisheries and Oceans 2009) (see Figure 3.9). Currently, Nunavut's major Arctic char fisheries are centred on areas around Cambridge Bay in the Kitikmeot region, with advanced preparations for an Arctic char fishery near Pond Inlet in the Qikiqtani region (Martin et al. 2018).

Like Nunavut, Nunavik maintains a commercial shrimping industry, including in Hudson Strait (National Indigenous Fisheries Institute 2018). Makivik is recognized as having a well-established and successful reputation in the northern fishing industry, and since 1978 has successfully researched and developed a viable shrimp fishery in Hudson Strait and Davis Strait (National Indigenous Fisheries Institute 2018). Makivik has also trained Inuit crews and developed partnerships with major national and international fishing companies. Through Unaaq Fisheries, Makivik shares a shrimp licence with Qikiqtaaluk Corporation of Nunavut and is full owner of an additional licence that it operates in partnership with Newfound Resources. Northern Shrimp Fishing Areas and Management Units of closest proximity to the HBME are within Hudson Strait and Ungava Bay. As the Nunavut West and Nunavik West Management Units are located within the Nunavut Settlement Area and Nunavik Marine Region, they are reserved for Nunavut and Nunavik shrimp harvesters (Figure 3.9).

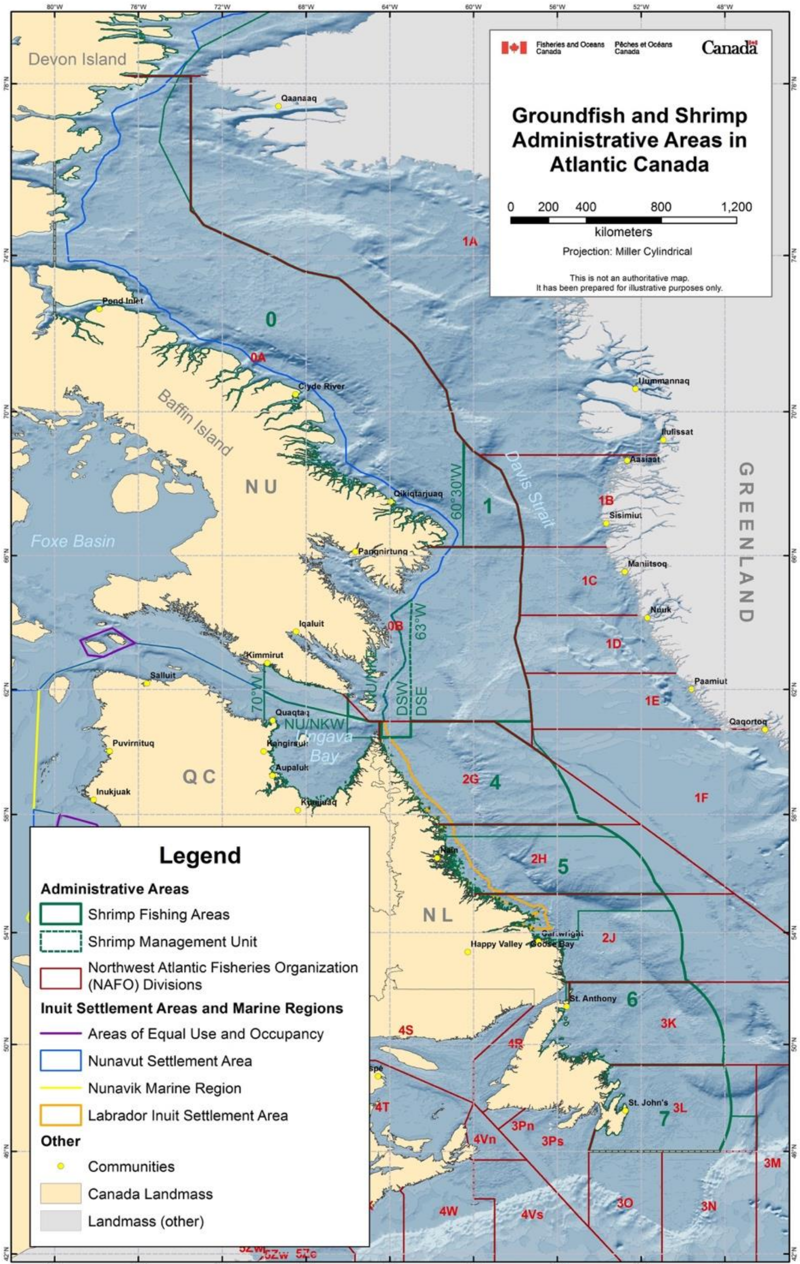


Figure 3.9. Northern shrimp fishing areas, effective 2013 (DFO 2018, p. 5)

Within the HBME, the most significant commercial processing facility is a char and whitefish processing plant in Rankin Inlet operated by Kivalliq Arctic Foods (Government of Nunavut 2016; Hurtubise 2016). Kivalliq Arctic Foods offers its Country Food Pak to Nunavummiut across the territory, including items such as char and maqtaq, while individual portions are also made available through partner retailers in Nunavut. This kind of local market distribution is valuable for food security and is also considered a bridge to commercial fishing models (National Indigenous Fisheries Institute 2019). Papiruq Fisheries is a small, seasonal fish processing facility in Whale Cove that has been operating since 1995. It is open from late July to the end of August and processes locally-caught Arctic char and maqtaq from Whale Cove residents (Nunavut Development Corporation, n.d.).

At the local scale (i.e. within communities), harvesters in Nunavik gather and sell mussels (Doidge et al. 2002). This commercial interest has yet to expand beyond its current local scale.

There are limited marine-based species of commercial interest in the James Bay Region, and no commercial fishing is currently underway. As part of a recent consultation on land use planning values, some Cree residents of Chisasibi expressed interest in commercial fisheries development, for example shrimp or mussels, while others expressed concerns that these developments may negatively impact the health of marine wildlife (EMRPC 2019). As in Eeyou Istchee, there are limited marine-based species of commercial interest along the Manitoba and Ontario coasts of Hudson Bay, and no commercial fishing is currently taking place in this area (Marshall and Jones 2011; Ontario Ministry of Natural Resources 2014; Labun and Debicki 2018).

Since the mid-2000s, the Government of Nunavut and its partners have been making significant efforts to develop the territory's commercial fisheries. Efforts have included establishing the Nunavut Fisheries Training Consortium in 2005 (now the Nunavut Fisheries and Marine Training Consortium), which provides training on all aspects of work in the marine industry in Nunavut. Training has also been delivered in Nunavik and the Northwest Territories, while the Nunavut Offshore Allocation Holders Association was established in 2012 (now the Nunavut Fisheries Association) to represent organizations engaged in the harvest of fish quotas in waters adjacent to Nunavut. Finally, the RV Nuliajuk, Nunavut's first dedicated fisheries research vessel, was procured in 2012. In 2016, the Government of Nunavut released the Nunavut Fisheries Strategy for 2016-2020 (Government of Nunavut 2016). Addressing harvest levels, access and allocation is one of seven priorities, and within this priority, one of the objectives is to explore avenues to feasibly and economically harvest existing char quotas in remote areas as 80% of the total Arctic char quota available is currently not captured in commercial harvests.

The Nunavut Fisheries Strategy also identifies fisheries of potential interest for development. Opportunities identified in or adjacent to the HBME include clams near Igloolik, scallops and mussels near Chesterfield Inlet, shrimp and whelks near Iqaluit, whitefish and lake trout in the Kivalliq region. Two communities are currently working with the World Wildlife Fund on developing small-scale sustainable commercial fisheries: Kinngait (Cape Dorset) is exploring the potential for an Arctic lyre crab fishery, and if successful, is planning to use the equipment for a small-scale shrimp fishery, and Sanikiluaq is exploring the potential for establishing an Arctic char fishery (Brown 2018; National Indigenous Fisheries Institute 2019). It is estimated that it may take up to five years to determine how these fisheries may be sustainable in the long-term.

Baseline data on fisheries in the HBME is limited (Zeller et al. 2011). A reconstruction of Arctic fish catches from 1950 to 2006 for the entire Hudson Bay Complex (HBC; HBME plus Hudson Strait and Ungava Bay) shows that the total fish catches peaked at 2,300 tonnes per year in the early 1960s, with a significant portion dedicated to sustaining dog teams, before declining to around 600 tonnes per year in recent years (Zeller et al. 2011). Arctic char accounted for 88% of catches, and Atlantic salmon contributed smaller components. In an assessment of current and future Arctic marine fisheries potential, Tai et al. (2019) state that fisheries catches are relatively modest in the HBC, with fish catches being primarily subsistence-based until the 2000s and becoming more evenly split since then. The authors estimated that the total marine fisheries catch (subsistence and commercial) for the HBC from 2005 to 2014 was approximately 1,300 tonnes, with the primary fish by tonnage being Arctic char and Northern prawn (Tai et al. 2019). Approximately 55% of the catch was estimated as being for subsistence purposes with the remaining 45% that contributed to commercial catches netting a total landed value of over $3.8 million USD for that period.

Tai et al. (2019) also modelled the current catch potential of the HBC, and projected it to be 3.2 (± 2.4) million tonnes and valued at $3.4 (± 3.2) billion USD annually. The large margins of error on these figures should be noted. There is a large difference between the modelled catch potential of the HBC and reported catches. The authors suggest that dangerous conditions for much of the year that limit the fishing season to a short period of time are likely the reason for this difference. A significant portion of the modelled current catch potential is from capelin and European conger (also known as the Conger eel), the potential of which the authors estimate to be 1.62 (± 0.80) and 1.08 (± 1.26) million tonnes, respectively. Neither of these species is currently part of commercial catches in the HBME or neighbouring marine waters.

Birds

Commercial harvests related to birds are very low, and limited to occasional commercial selling of eider down harvested in Sanikiluaq. The Nunavut Wildlife Harvest Study reported that in 2000 and 2001, down from approximately 1690 and 5070 nests, respectively, was harvested in Sanikiluaq and sold commercially (Nunavut Wildlife Management Board 2004). In 2015, the governments of Canada, Nunavut and the municipality of Sanikiluaq invested approximately $175,000 to establish a small-scale commercial eider down operation in the community (Canadian Northern Economic Development Agency 2015).

Aquatic plants

Efforts were made in the 1990s and early 2000s to develop a viable commercial harvest of kelp in the vicinity of Whale Cove (Stewart and Lockhart 2005). Kivalliq Land and Sea Resources harvested 35 tonnes of kelp from the Whale Cove area in 2000, and the NMWB approved a quota of 320 tonnes of dulse, kelp and rockweed for the 2001 season. No permits were issued for this fishery in 2003, and no information about the further development of this fishery was located.

Marine mammals

While not a current commercial interest, the history of commercial whaling and its impacts forms an important context for understanding any commercial marine harvesting in the HBME today.

Commercial whaling in the HBME in the 1700s, 1800s and first half of the 1900s significantly impacted bowhead and beluga whale populations (Stewart and Lockhart 2005; Hurtubise 2016). For example, in the late 1800s and early 1900s, the Hudson Bay Company and others operated commercial fisheries in eastern Hudson Bay. During this time, hundreds to thousands of belugas were taken each year, resulting in considerable population declines, particularly for the eastern Hudson Bay beluga population (Brooke 1992). By the mid-1900s, many Nunavimmiut were transitioning to settlements along the Hudson Bay coast, many of which are located near beluga habitat (river mouths, estuaries, shallow bays). The increased localized hunting pressure and disturbance may have had a negative effect on the beluga in the region (Brooke 1992). While there is no longer a commercial harvest of beluga, the population may still be depressed and sensitive to overexploitation (Doniol-Valcroze et al. 2012). Between 1840 and 1910, American and European whalers, including the Hudson Bay Company, overexploited the North Atlantic bowhead whale population, significantly affecting the availability of whales for subsistence harvesting (Hurtubise 2016). While the rising petroleum oil industry reduced the impetus for commercial whaling in the early 1900s, the Hudson Bay Company continued commercial bowhead whale harvests until 1951 (Higdon 2010; Hurtubise 2016).

Seals were of commercial interest for their pelts during the 20th century, although the market suffered severe price fluctuations in the 1960s due to southern animal welfare campaigns (Fast 1996). Throughout the latter part of the century, many Inuit made their living hunting seals and therefore, the market collapse was devastating for many communities. The European ban on seal products in 2009 excludes Inuit harvest, but it still caused further damage to the local industry.

Polar bears

While not a species of commercial interest, polar bears are included here as a species of significant recreational and sport hunting interest in the HBME. First, there is tourism interest in the form of "bear viewing" (Chanteloup 2013). While not without issues, it does represent a non-extractive economic opportunity. The other is Inuit-organized sport hunting. In Nunavut, bears harvested through a sport or "conservation hunt" bring in up to 20 times the monetary value of a polar bear harvested for subsistence, where the main source of income is the hide (Dowsley 2010). During a sport hunt, hunters from outside the region pay thousands of dollars for travel costs, permits, trophy fees, guide services, and taxidermy costs (Foote and Wenzel 2007), which offers a much more diverse set of economic opportunities compared with subsistence harvest. Because Inuit in Nunavut hold the entire polar bear quota for the region, the sale of a portion of this quota to sport hunters is at their discretion, although it is limited to a certain percentage of the total quota (Foote and Wenzel 2007). As noted above, this species has high cultural value. Any type of economic activities involving polar bears is often controversial (Foote and Wenzel 2007).

Churchill, with its larger population, train access and community services and infrastructure, has an advantage over the small, remote communities dotted along Hudson Bay and James Bay. Churchill has developed an internationally known polar bear viewing operation, with tourists and professional photographers traveling from around the world to participate in tours that offer a glimpse of the bears (Tannis 1999).

The polar bear represents an emerging economic opportunity in the James Bay region through the development of a tourism program. Following in the footsteps of better-known polar bear viewing locations, like Churchill, Manitoba and Svalbard, Norway, there is interest in examining the feasibility of a less commercialized polar bear experience in Wemindji (Lemelin and Dickson 2012). This opportunity has yet to be developed beyond an early concept, however, and the need for strong community involvement has been emphasized (Hossein 2017).

3.6 REFERENCES

Andrews JS, Babb D, Barber DG (2017) Climate change and sea ice: marine shipping access in Hudson Bay and Hudson Strait (1980 – 2014). Elem Sci Anth 5:15. doi: 10.1525/elementa.130

Aporta C (2010) The sea, the land, the coast, and the winds: Understanding Inuit sea ice use in context. In: Krupnik I, Aporta C, Laidler GJ, et al. (eds) SIKU: Knowing Our Ice: Documenting Inuit Sea Ice Knowledge and Use. Springer, London, pp 163–180

Arctic Council (2008) Arctic Council: Arctic marine shipping assessment 2009 Report. doi: 10.1163/ej.9789004177567.i-594.47

Armitage DR (2005) Community-based Narwhal management in Nunavut, Canada: Change, uncertainty, and adaptation. Society and Natural Resources 18:715–731. doi: 10.1080/08941920591005124

Berkes F (1977) Fishery resource use in a subarctic Indian community. Human Ecology 5:289–307. doi: 10.1007/BF00889173

Berkes F, George PJ, Preston RJ, et al. (1994) Wildlife harvesting and sustainable regional native economy in the Hudson and James Bay lowland, Ontario. Arctic 47:350–360. doi: 10.14430/arctic1308

Berkes F, Hughes A, George PJ, et al. (1995) The persistence of aboriginal land use: Fish and wildlife harvest areas in the Hudson and James Bay lowland, Ontario. Arctic 48:81–93. doi: 10.14430/arctic1227

Blanchet C, Dewailly É, Ayotte P, et al. (2000) Contribution of Selected Traditional and Market Foods to the Diet of Nunavik Inuit Women. Canadian Journal of Dietetic Practice and

Research 61:50–59.

Blanchet C, Rochette L (2008) Nutrition and Food Consumption among the Inuit of Nunavik. Québec

Bodaly RA, Johnston TA (1992) The mercury problem in hydro-electric reservoirs with predictions of mercury burdens in fish in the proposed Grande Baleine complex, Quebec, 1st ed. Montreal: North Wind Information Services, Montreal

Breton-Honeyman K, Furgal CM, Hammill MO (2016a) Systematic Review and Critique of the Contributions of Traditional Ecological Knowledge of Beluga Whales in the Marine Mammal Literature. Arctic 69:37–46. doi: 10.2307/43871397

Breton-Honeyman K, Hammill MO, Furgal CM, Hickie B (2016b) Inuit Knowledge of beluga whale (Delphinapterus leucas) foraging ecology in Nunavik (Arctic Quebec), Canada. Canadian Journal of Zoology 94:713–726. doi: 10.1139/cjz-2015-0259

Brooke LF (1992a) Report on the 1991 beluga whale and walrus subsistence harvest levels by the Inuit of Nunavik.

Brooke LF (1992b) Report on the 1991 Beluga Whale and Walrus Subsistence Harvest Levels by the Inuit of Nunavik.

Brown B (2018) Cape Dorset assesses Arctic lyre crab for community fishery. Nunatsiaq News

Brown B (2019) Label ringed seals a species of concern, wildlife advisers tell feds. CBC News.

Bussières V (2005) Towards a culturally-appropriate locally-managed protected area for the James Bay Cree community of Wemindji, Northern Quebec. Concordia University

Canadian Northern Economic Development Agency (2015) Governments of Canada and Nunavut Announce Support to Revitalize Sanikiluaq’s Eiderdown Industry.

Carter N, Dawson J, Joyce J, Ogilvie A (2017) Arctic Corridors and Northern Voices, Governing Marine Transportation in the Canadian Arctic: Arviat, Nunavut. doi: 10.20381/RUOR36924

Carter N, Dawson J, Joyce J, Ogilvie A (2019) Arctic Corridors and Northern Voices, Governing Marine Transportation in the Canadian Arctic: Coral Harbour, Nunavut. doi: 10.20381/RUOR38505.For

Chan L, Batal M, Sadik T, et al. (2019) FNFNES Final Report for Eight Assembly of First Nations Regions: Draft Comprehensive Technical Report. Ottawa

Chanteloup L (2013) Wildlife as a tourism resource in Nunavut. Polar Record 49:240–248. doi:

10.1017/S0032247412000617

Colbeck GJ, Duchesne P, Postma LD, et al. (2013) Groups of related belugas (Delphinapterus leucas) travel together during their seasonal migrations in and around Hudson Bay. Proceedings of the Royal Society B: Biological Sciences 280:9. doi: 10.1098/rspb.2012.2552

Dawson J, Carter N, van Luijk N, et al. (2020) Infusing Inuit and local knowledge into the Low Impact Shipping Corridors: An adaptation to increased shipping activity and climate change in Arctic Canada. Environmental Science and Policy 105:19–36. doi: https://doi.org/10.1016/j.envsci.2019.11.013

Denton D (2007) The Land as an Aspect of Cree History: Exploring Whapmagoostui Cree Place Names. Papers of the Thirty-Eighth Algonquian Conference 38:143–154.

DFO (2018) Integrated Fisheries Management Plan: Northern shrimp and striped shrimp – Shrimp fishing areas 0, 1, 4-7, the Eastern and Western Assessment Zones and North Atlantic Fisheries Organization (NAFO) Division 3M. Ottawa

Doidge W, May P, Gordon A, et al. (2002) Shellfish testing program in Nunavik. Phase I : database and logistics. Kuujjuaq, Québec

Doniol-Valcroze T, Lesage V, Hammill MO (2012) Management implications of closure of estuaries to hunting of beluga in Nunavik.

Downing A, Cuerrier A (2011) A synthesis of the impacts of climate change on the First Nations and Inuit of Canada. Indian Journal of Traditional Knowledge 10:57–70.

Dowsley M (2010) The value of a polar bear: Evaluating the role of a multiple-use resource in the nunavut mixed economy. Arctic Anthropology 47:39–56. doi: 10.1353/arc.0.0035

Duhaime G, Chabot M, Gaudreault M (2002) Food Consumption Patterns and Socioeconomic Factors Among the Inuit of Nunavik. Ecology of Food and Nutrition 41:91–118.

Duhaime G, Lévesque S, Caron A (2015) Nunavik in Figures 2015 - Full Version.

EMRPC (2019) Eeyou Marine Region Land Use Planning Values, Issues, and Visions: Report on community input on land use planning goals for the Eeyou Marine Region. Chisasibi, Quebec

Fast H (1996) Subsistence in the Hudson Bay Rioregion: Land use, economy and ethos. University of Manitoba

Fast H, Berkes F (1994) Native Land Use, Traditional Knowledge and the Subsistence Economy in the Hudson Bay Bioregion. The Hudson Bay Programme. doi: 10.1360/zd-2013-43-6-1064

Ferguson SH, Higdon JW, Westdal KH (2012) Prey items and predation behavior of killer whales (Orcinus orca) in Nunavut, Canada based on Inuit hunter interviews. Aquatic Biosystems 8:16 p. doi: 10.1186/2046-9063-8-3

Foote L, Wenzel G (2007) Conservation hunting concepts, Canada's Inuit, and polar bear hunting. In: Lovelock B (ed) Tourism and the Consumption of Wildlife: Hunting, Shooting and Sport Fishing, 1st ed. Routledge, New York, pp 115–128

Ford JD (2009) Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. Regional Environmental Change 9:83–100. doi: 10.1007/s10113-008-0060-x

Ford JD, Gough WA, Laidler GJ, et al. (2009) Sea ice, climate change, and community vulnerability in northern Foxe Basin, Canada. Climate Research 38:137–154. doi: 10.3354/cr00777

Ford JD, Smit B, Wandel J, et al. (2008) Climate change in the Arctic: Current and future vulnerability in two Inuit communities in Canada. The Geographical Journal 174:45–62. doi: 10.1111/j.1475-4959.2007.00249.x

Ford JD, Smit B, Wandel J, MacDonald J (2006) Vulnerability to climate change in Igloolik, Nunavut: what we can learn from the past and present. Polar Record 42:127–138.

Furgal C, Martin D, Gosselin P (2002) Climate change and health in Nunavik and Labrador: Lessons from Inuit knowledge. In: Krupnik I, Jolly D (eds) The earth is faster now: Indigenous observations of Arctic environmental change. Arctic Research Consortium of the United States, Arctic Studies Centre, Smithsonian Institution, Washington, D.C., pp 266–300

Gislason R (2007) Beluga co-management ; Perspectives from Kuujjuarapik and Umiujaq, Nunavik. University of Manitoba

Gombay N (2009) Sharing or commoditising? A discussion of some of the socio-economic implications of Nunavik's Hunter Support Program. Polar Record 45:119–132. doi: 10.1017/S003224740800778X

Gombay N (2006) From subsistence to commercial fishing in Northern Canada: The experience of an Inuk entrepreneur. British Food Journal 108:502–521. doi: 10.1108/00070700610676343

Government of Nunavut (2017) Nunavut Economy. https://www.gov.nu.ca/eia/documents/nunavut-economy.

Government of Nunavut (2019) Nunavut Polar Bear Co-Management Plan. Iqaluit, Nunavut

Government of Nunavut (2016) Nunavut Fisheries Strategy 2016-2020. Iqaluit, Nunavut

Henri D, Gilchrist HG, Peacock E (2010) Understanding and managing wildlife in Hudson Bay under a changing climate: Some recent contributions from Inuit and Cree ecological knowledge. A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay. Springer Netherlands, pp 267–289

Herrmann TM, Royer MJS, Cuciurean R (2012) Understanding subarctic wildlife in Eastern James Bay under changing climatic and socio-environmental conditions: Bringing together Cree hunters' ecological knowledge and scientific observations. Polar Geography 35:245–270. doi: 10.1080/1088937X.2011.654356

Higdon JW (2010) Commercial and subsistence harvests of bowhead whales (Balaena mysticetus) in eastern Canada and West Greenland. Journal of Cetacean Research and Management 11:185–216.

Higdon JW, Ferguson SH (2014) Inuit recollections of a 1950s Killer whale (Orcinus orca) ice entrapment in Foxe Basin, Nunavut, Canada. Aquatic Mammals 40:9–19. doi: 10.1578/AM.40.1.2014.9

Higdon JW, Westdal KH, Ferguson SH (2014) Distribution and abundance of killer whales (Orcinus orca) in Nunavut, Canada-An inuit knowledge survey. Journal of the Marine Biological Association of the United Kingdom 94:1293–1304. doi: 10.1017/S0025315413000921

Hoover C, Bailey M, Higdon J, et al. (2013) Estimating the economic value of narwhal and beluga hunts in Hudson Bay, Nunavut. Arctic 66:1–16. doi: 10.14430/arctic4261

Hori Y (2010) The Use of Traditional Environmental Knowledge to Assess the Impact of Climate Change on Subsistence Fishing in the James Bay Region, Ontario, Canada. University of Waterloo

Hossein T (2017) Polar bear wildlife viewing in Eeyou Istchee: An assessment of different perspectives and considerations. Concordia University

Hurtubise J (2016) Evolution of subsistence and commercial Inuit fisheries in the Territory of Nunavut, Canada. Marine Affairs Program Technical Report 14. Halifax

Institut de la statistique du Québec (2017) Administration régionale Kativik. http://www.stat.gouv.qc.ca/statistiques/profils/region_10/impr_mrc_10_992.htm.

ITK (2008) Inuit Statistical Profile.

Kishigami N (2015) Revival of Inuit Bowhead Hunts in Arctic Canada. Japanese Review of Cultural

Anthropology 16:43–58.

Kishigami N (2013) What Is A Subsistence Activity?: With a Special Focus on Beluga Whale Hunt by Inuit in Arctic Canada. National Museum of Ethnology 82:79–90.

KRG (2007) Lacs-Guillaume-Delisle-et-à-l'Eau-Claire Park Project. Status Report. Kuujjuaq, Québec

Krupnik I, Aporta C, Laidler GJ, et al. (2010) SIKU: Knowing our ice: Documenting Inuit sea ice knowledge and use. SIKU: Knowing Our Ice: Documenting Inuit Sea Ice Knowledge and Use. doi: 10.1007/978-90-481-8587-0

Kuzyk ZZ, Candlish L (2019a) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. Quebec City

Kuzyk ZZ, Candlish L (2019b) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. Synthesis and Recommendations. Quebec City

Labun P, Debicki C (2018) Western Hudson Bay and its beluga estuaries: Protecting abundance for a sustainable future. Ottawa

Laidler GJ (2008) Human geographies of sea ice: freeze/thaw processes around Cape Dorset, Nunavut, Canada. Polar Record 44:51–76. doi: 10.1017/S0032247407007061

Laidler GJ, Ford JD, Gough WA, et al. (2009a) Travelling and hunting in a changing Arctic: Assessing Inuit vulnerability to sea ice change in Igloolik, Nunavut. Climatic Change 94:363–397. doi: 10.1007/s10584-008-9512-z

Laidler GJ, Ford JD, Gough WA, et al. (2009b) Travelling and hunting in a changing Arctic: Assessing Inuit vulnerability to sea ice change in Igloolik, Nunavut. Climatic Change 94:363–397. doi: 10.1007/s10584-008-9512-z

Laidler GJ, Hirose T, Kapfer M, et al. (2011) Evaluating the Floe Edge Service: how well can SAR imagery address Inuit community concerns around sea ice change and travel safety? Canadian Geographer / Le Géographe canadien 55:91–107. doi: 10.1111/j.1541-0064.2010.00347.x

Lawn J, Harvey D (2003) Nutrition and food security in Fort Severn, Ontario: Baseline survey for the food mail pilot project. Ottawa

Lemelin RH, Dickson G (2012) Report Examining the Potential for Wildlife Tourism in Eeyou Istchee, Northern Quebec, Canada. The Northern Review 35:176–192.

Lewis AE, Hammill MO, Power M, et al. (2009) Movement and Aggregation of Eastern Hudson Bay Beluga Whales (Delphinapterus leucas): A Comparison of Patterns Found through Satellite Telemetry and Nunavik Traditional Ecological Knowledge. Arctic 62:13–24.

M’Lot M (2002) Kii Isiniikwiik Askfy: Using Cree knowledge to perceive and describe the landscape ofthe Wapusk National Park Area. University of Manitoba

MacDonald M, Arraqutainaq L, Novalinga Z, et al. (1997) Voices from the Bay: Traditional Ecological Knowledge of Inuit and Cree in the Hudson Bay Bioregion. Canadian Arctic Resources Committee, Environmental Committee of Municipality of Sanikiluaq, Ottawa, Ontario

Mallory ML, Loseto LL, Ferguson SH (2010) The future of Hudson Bay : new directions and research needs. A Little Less Arctic: Top Predators in the World’s Largest Northern Inland Sea, Hudson Bay. pp 291–303

Marshall TR, Jones NE (2011) Aquatic Ecosystems of the Far North of Ontario: State of Knowledge.

Martin Z, Harris L, Janjua M (2018) Brief update on DFO Science Arctic Char Program in Nunavut, 2018-19. Submission to the Nunavut Wildlife Management Board.

McDonald MA, Arragutainaq L, Novalinga ZZ, Canadian Arctic Resources Committee (1997) Voices from the Bay: Traditional ecological knowledge of Inuit and Cree in the Hudson Bay bioregion. Canadian Arctic Resources Committee, Environmental Committee of Municipality of Sanikiluaq, Ottawa, ON

Minkin DP (2008) Cultural preservation and self-determination through land use planning: a framework for the Fort Albany first nation. Queen’s University

National Indigenous Fisheries Institute (2019) Northern Integrated Commercial Fisheries Initiative: Final Report.

National Indigenous Fisheries Institute (2018) Northern Integrated Commercial Fisheries Initiative: Discussion Paper.

Noreen W, Johnson-Down L, Jean-Claude M, et al. (2018) Factors associated with the intake of traditional foods in the Eeyou Istchee (Cree) of northern Quebec include age, speaking the Cree language and food sovereignty indicators. International Journal of Circumpolar Health 77:11. doi: 10.1080/22423982.2018.1536251

Nunatsiaq News (2019) Researcher puts a dollar figure on Nunavut’s country food harvest | Nunatsiaq News. Nunatsiaq News

Nunavik Marine Region Wildlife Board (2016) Nunavik Inuit knowledge and observations of polar bear: Polar bears of the South Hudson Bay sub-population. Inukjuaq, Québec

Nunavut Development Corporation Papiruq Fisheries. https://ndcorp.nu.ca/we-invest/subsidiaries/papiruq-fisheries/. Accessed 20 Mar 2020

Nunavut Planning Commission (2016) Nunavut Land Use Plan: 2016 Draft.

Nunavut Wildlife Management Board (2004) The Nunavut Wildlife Harvest Study. Iqaluit, Nunavut

NWMB (2000) Final report of the Inuit bowhead knowledge study. Iqaluit

Oakes J (1991) Environmental Factors Influencing Bird-Skin Clothing Production. Arctic and Alpine Research 23:71. doi: 10.2307/1551440

Oceans North Conservation Society, WWF-Canada, Ducks Unlimited Canada (2018) Canada's Arctic Marine Atlas. Ottawa, Ontario

Ontario Ministry of Natural Resources (2014) Background report supporting Ontario's Provincial Fish Strategy. Ottawa, ON

Peloquin C, Berkes F (2009) Local Knowledge, Subsistence Harvests, and Social–Ecological Complexity in James Bay. Human Ecology 37:533–545.

Pilon J-L (2013) Settlement and Land Use Patterns in the Hudson Bay Lowlands of Northern Ontario, Canada. Gatineau, Québec

Pilon J-L (1982) Fort Severn Land Use and Occupancy Study. Toronto, Ontario

Prevett JP, Lumsden HG, Johnson FC (1983) Waterfowl Kill by Cree Hunters of the Hudson Bay Lowland, Ontario. Arctic 36:185–192. doi: 10.14430/arctic2261

Radu I, House LM, Pashagumskum E (2014) Land, life, and knowledge in Chisasibi: Intergenerational healing in the bush. Decolonization: Indigeneity, Education & Society 3:86–105.

Rosenberg DM, Berkes F, Bodaly RA, et al. (1997) Large-scale impacts of hydroelectric development. Environmental Reviews 5:27–54. doi: 10.1139/er-5-1-27

Royer M-JS (2016) Climate, Environment and Cree Observations James Bay Territory, Canada, 1st ed. SpringBriefs in Climate Studies. doi: 10.1007/978-3-319-25181-3

Royer MJS, Herrmann TM (2011) Socioenvironmental changes in two traditional food species of the Cree first nation of subarctic James Bay. Cahiers de Geographie du Quebec 55:575–601. doi: 10.7202/1008895ar

Royer MJS, Herrmann TM, Sonnentag O, et al. (2013) Linking Cree hunters' and scientific observations of changing inland ice and meteorological conditions in the subarctic eastern James Bay region, Canada. Climatic Change 119:719–732. doi: 10.1007/s10584-013-0773-9

Sayles JS, Mulrennan ME (2010) Securing a future: Cree hunters' resistance and flexibility to environmental changes, Wemindji, James Bay. Ecology and Society. doi: 10.5751/ES-03828-150422

Standing Senate Committee on Fisheries and Oceans (2009) Nunavut Marine Fisheries: Quotas and Harbours. Report of the Standing Senate Committee on Fisheries and Oceans. Ottawa

Statistics Canada 2016 Census: Statistics Canada Catalogue No. 98-316-X2016001. https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E. Accessed 3 Dec 2019

Stewart DB, Lockhart WL (2005) An overview of the Hudson Bay marine ecosystem.

Strangway RE, Dunn M, Erless R (2016) Monitoring Nûtimesânân Following the Diversion of Our River: A Community-led Registry in Eeyou Istchee, Northern Québec. Journal of Environmental Assessment Policy and Management 18:1–21. doi: 10.1142/S1464333216500010

Tai TC, Steiner NS, Hoover C, et al. (2019) Evaluating present and future potential of arctic fisheries in Canada. Marine Policy 108:11. doi: 10.1016/j.marpol.2019.103637

Tannis T (1999) Ecotourism in Churchill, Manitoba: Principles, Attitudes and Opportunities. University of Manitoba

Wallace S (2014) Inuit health: Selected findings from the 2012 Aboriginal Peoples Survey.

Wein EE, Freeman MMR, Makus JC (1996) Use of and preference for traditional foods among the Belcher Island Inuit. Arctic 49:256–264. doi: 10.14430/arctic1201

Wenzel GW (2019) Canadian Inuit subsistence antinomies of the mixed economy. Hunter Gatherer Research 3:567–581. doi: 10.3828/hgr.2017.29

Wenzel GW (2009) Canadian Inuit subsistence and ecological instability-if the climate changes, must the Inuit? Polar Research 28:89–99. doi: 10.1111/j.1751-8369.2009.00098.x

Westdal KH, Higdon JW, Ferguson SH (2013) Attitudes of nunavut inuit toward killer whales (Orcinus orca). Arctic 66:279–290. doi: 10.14430/arctic4307

White A (2012) A synthesis of narwhal (Monodon monoceros) scientific advice and Inuit knowledge collected during Nunavut community consultations (May 25-31, 2011). Ottawa

Wong PBY, Murphy RW (2016) Inuit methods of identifying polar bear characteristics: Potential for Inuit inclusion in polar bear surveys. Arctic 69:406–420. doi: 10.14430/arctic4605

Zeller D, Booth S, Pakhomov E, et al. (2011) Arctic fisheries catches in Russia, USA, and Canada: baselines for neglected ecosystems. Polar Biology 34:955–973. doi: 10.1007/s00300-010-0952-3

4 MARINE HABITAT: STRUCTURE AND FUNCTION

4.1 MARINE HABITAT

4.1.1 Bathymetry and geology

Three Canadian geological provinces come together in the Hudson Bay Marine Ecosystem (HBME): Superior and Churchill, comprised of crystalline Precambrian Shield, and the Hudson Platform, primarily consisting of limestone and dolostone sedimentary rock. The basin of Hudson Bay is one of the largest Paleozoic sedimentary basins in Canada (Roger et al. 2011) formed from Canadian Precambrian shield and covered primarily by unconsolidated materials that are a result of glaciogenic sedimentation (Stewart and Barber 2010). When moving from the nearshore towards the central bay, these materials transition from coarse gravel to fine silt and clay. Due to the high riverine output into the HBME, sedimentation rates are higher along the shelves than the middle of the bay with most sediment accumulation being less than 5 metres thick, however, there are moraines located with sediments up to 55 metres thick (Stewart and Lockhart 2005; Kuzyk et al. 2009). Along the southern coasts of James and Hudson Bay is the Hudson Bay Lowland while the eastern coasts are characterized by highly irregular cliffs of Precambrian Canadian Shield (Grainger 1960). It has been noted as early as 1959 that the bathymetry of the HBME is largely distinguished by its geological provinces and can be seen as an extension of the coastal features (Campbell 1959; Stewart and Barber 2010).

Glaciation was the most prominent influence in the geological and bathymetric shaping of the HBME. The Laurentide Ice Sheet retreated during the late Pleistocene and the Tyrrell Sea, which had formed in the depression caused by the ice sheet's weight, began to recede to the present-day margins of Hudson and James Bay as isostatic rebound raised the continental crust approximately 300 metres (Stewart and Lockhart 2005). The HBME is still currently undergoing isostatic rebound at approximately 0.7 to 1.3 metres per century, resulting in coastal emergence, but this emergence will likely be slowed as sea level rise and thermal expansion result from a warming climate (Stewart and Barber 2010).

The HBME is typified by extremely shallow waters for a marine waterbody of its size. The average depth of Hudson Bay is 125 metres with a pseudo-shelf that extends 20 to 100 kilometres off the coast at a depth of 80 metres that gradually levels out at approximately 250 metres (Kuzyk et al. 2009). There are two bathymetric features that define the central portion of Hudson Bay: Midbay

Bank runs south to north, rising to less than a 40-metre depth, and Winisk Trough, running parallel to Midbay Bank to depths of 370 metres (Figure 4.1; Stewart and Howland 2009). Deep water exchange is largely limited between the sub-regions of HBME due to the presence of shallow sills. In the case of Hudson Bay and Hudson Strait, deep water exchange is restricted to a singular deep channel between sills at 130 and 185 metres (Prinsenberg 1987). The bathymetry of James Bay is not well understood, but is known to be extremely shallow, predominately less than 50 metres in depth, with water exchange between Hudson and James Bay being generally unrestricted (Prinsenberg 1978; Stewart and Lockhart 2005).

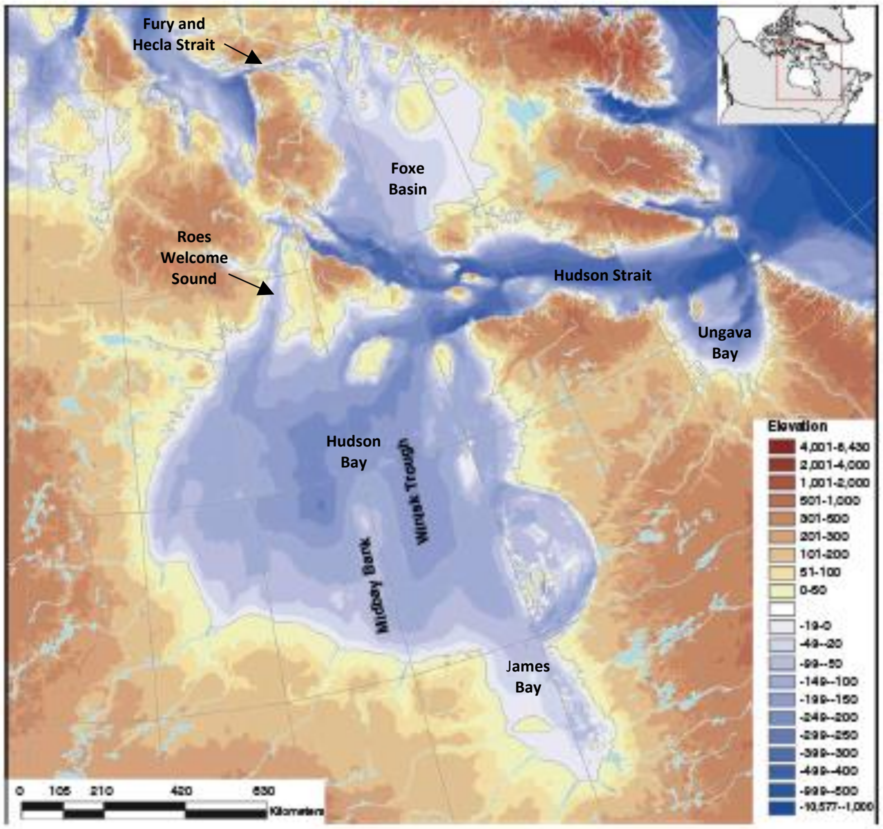


Figure 4.1. Topographic and bathymetric map of the HBME (Stewart and Howland 2009 p.67; Adapted from the Arctic Monitoring and Assessment Program)

Foxe Basin is also a relatively shallow water body, with most of the basin having depths of less than 100 metres. There is a singular deep channel that cuts across the southern portion of Foxe Basin, referred to as Foxe Channel, that has depths of approximately 400 metres which deepen to 1000 metres as it runs through Hudson Strait towards Ungava Bay (Campbell 1964; Stewart and Barber 2010). Water flows between Foxe Basin and Hudson Bay through Roes Welcome Sound to the west and is restricted by a sill at a depth of 60 metres (Stewart and Howland 2009). More recently, multibeam bathymetric surveys have been carried out in the HBME through the ArcticNet research program. This enabled the identification of circular depressions found in northern

Hudson Bay that are likely caused by fluid being released from beneath the sediment. Ring-like structures were also found, but the origin of this feature is currently unknown (Roger et al. 2011).

4.1.2 Inflow, outflow and circulation

The movement of waters through the HBME is influenced by many different drivers. Traditional ecological knowledge (TEK) of Hudson Bay circulation describes the dominant circulation as counterclockwise (see Figure 4.2), influenced by tidal flow and river discharge, with the strongest currents occurring throughout the winter from December to March (MacDonald et al. 1997). Hudson Bay has a drainage basin of 3 x 10^6 km^2 which yields a substantial amount of freshwater runoff (760 km^3 per year; Granskog et al. 2011) and also contributes significantly to the stratification of Hudson Bay and James Bay (Stewart and Barber 2010), creating a surface layer with a velocity of approximately 0.05 to 0.20 metres per second with higher velocities occurring along the eastern side of Hudson Bay (El-Sabh and Koutitonsky 1977; Prinsenberg 1978). Recent modelling work by Ridenour et al. (2019) indicates that while the annual mean circulation of Hudson Bay is cyclonic (counterclockwise), the flow in the eastern part of the bay becomes weakly anticyclonic during the months of May and June due to the spring freshet (rapid melt of ice and

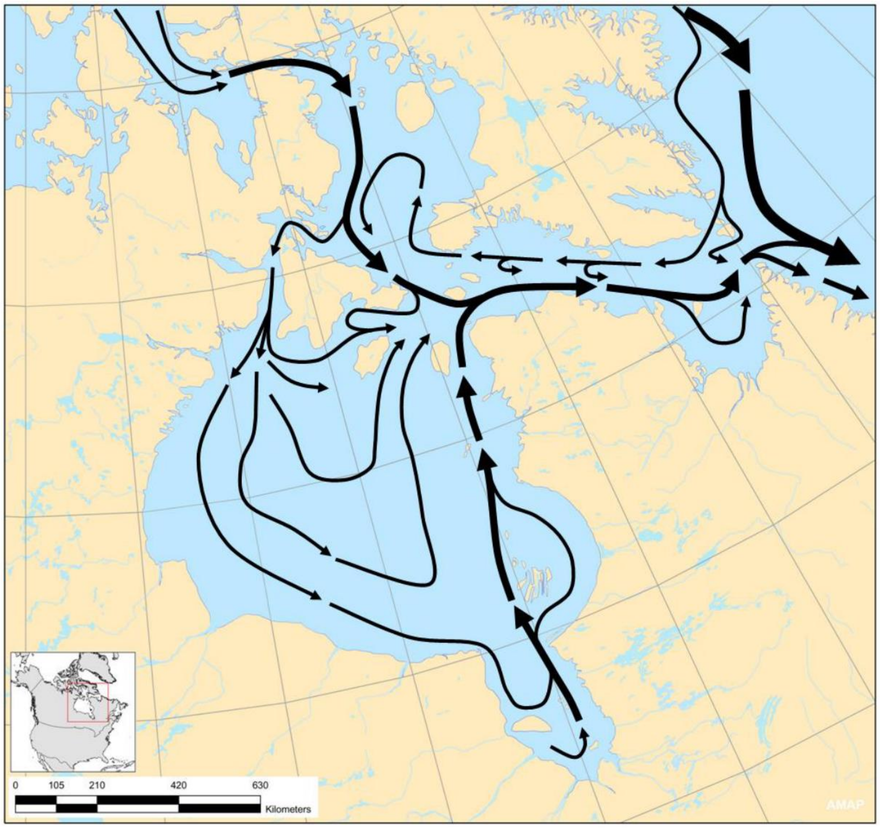


Figure 4.2. Summer circulation of water through the HBME (Stewart and Howland 2009, p. 68)

snow leading to seasonally increased rates of river outflow (Czarnecki and Goodman 2012)) and a change in wind direction. Circulation along the eastern coast in James Bay is constrained along the coastline by the Coriolis force and is further influenced by wind stress. A three-tiered profile is known to occur when northerly winds exceed 15 knots, with inflow occurring at the top and bottom layers of the bay and outflow occurring in the middle (Prinsenberg 1978).

Inflow of seawater into the HBME occurs, in part, through the Fury and Hecla Strait into Foxe Basin (Figure 4.1). This seawater originates in the Pacific and passes through the Arctic Archipelago (Stewart and Barber 2010). Transport through the Fury and Hecla Strait (15-30 km wide and 120 km long) is 0.04 Sverdrup (Sv = 1 x 10^6 m^3 s^{-1}) in the winter and 0.1 Sv in the summer (Defossez et al. 2008; Straneo and Saucier 2008a). Currents moving through the Strait have been measured at 3 metres per second, which drives a cyclonic current in Foxe Basin (Stewart and Howland 2009). Water that is exchanged between Foxe Basin and Hudson Bay is limited by a 60 m sill as it passes through Roes Welcome Sound (Stewart and Barber 2010). The rest of the Foxe Basin outflow is retained in the cyclonic current or passes into Hudson Strait (Tan and Strain 1996; Stewart and Barber 2010).

The coastal current that flows along the boundary of Hudson Bay entrains much of the freshwater output and moves largely separate from the offshore waters of the bay. These offshore waters circulate more slowly having occasional coastal freshwater being introduced via Ekman transport (the horizontal net movement of water masses resulting from a balance between wind stress on the water's surface and the Coriolis force (Wenegrat and Thomas 2017)) into the central portion of the bay (Eastwood 2017). Water movement from Hudson Bay into James Bay occurs across the entirety of the stratified bottom layer, while in the surface layer, only the western portion of James Bay receives input at a velocity of 0.02 to 0.05 metres per second (Prinsenberg 1978). Water that does not flow into James Bay remains in the cyclonic circulation of Hudson Bay and meets up with the current flowing along the eastern side of James Bay towards Hudson Strait (El-Sabh and Koutitonsky 1977). Net transport out of Hudson Bay is estimated at 0.1 Sv (Straneo and Saucier 2008b).

Hudson Strait is the location of both inflow into and outflow from the HBME. Arctic waters from Baffin Bay and Davis Strait (along the northeast coast of Baffin Island), as well as Atlantic waters from the Labrador Sea, flow from the west along the northern side of Hudson Strait where they circulate within the Strait to flow back out or continue westward to enter into the HBME (Azetsu-Scott et al. 2010; Sutherland et al. 2011). These cold, high-salinity waters either move into Foxe Basin initially before entering into Hudson Bay or may enter Hudson Bay directly (Stewart and Barber 2010). It is estimated that one third of the outflow from Davis Strait enters into Hudson Strait and waters that move into Hudson Bay may have a residence time of 1 to 6.6 years (Straneo and Saucier 2008b; Stewart and Barber 2010). Outflow from Hudson Bay moves eastwards towards the Labrador Sea, with buoyant freshwater river outflow remaining within 20 km of the Quebec shoreline (White et al. 2007; Stewart and Howland 2009). This outflow (1-1.2 Sv) moves out to join the Labrador Current at 1 metre per second (Straneo and Saucier 2008a). The mean net volume flux (0.17 Sv) into the Labrador Sea through Hudson Strait is almost balanced, however, the freshwater signal is high and there is evidence that it plays a role in deep water convection (McGeehan and Maslowski 2012). While the outflow from Hudson Bay through Hudson Strait is often described as a continuous current, a significant portion (40%) of this outflow occurs in surface-trapped, anticyclonic eddies which develop in response to atmospheric forcing caused by storms over Hudson Bay (Sutherland et al. 2011).

Tidal motion is a significant wave force within the HBME as this region has been identified as one of the most important areas in the world ocean for tidal energy dissipation with 313 GW of tidal energy being dispelled. Semi-diurnal tides (also known as M2 tides) move up through Hudson Strait from the Atlantic, creating some of the highest tides ever recorded including a 16.7 metre tide in Ungava Bay (Stewart and Barber 2010; Webb 2014). In Hudson Bay, the tidal wave creates the largest tides in the northern part of the bay as it follows the cyclonic circulation pattern (Grainger 1960).

4.1.3 Marine and freshwater stratification

Stratification in the HBME is greatly influenced by freshwater runoff from both river output and sea-ice melt which both show substantial seasonal variation. The total input of 760 $km^3 yr^{-1}$ in river runoff not only contributes to driving the circulation in the bay but promotes stratification of its waters (Granskog et al. 2011). It is for this reason that Hudson Bay is considered to have estuarine circulation (Eastwood 2017). Water mass characteristics are not well understood in the HBME as field work is difficult to carry out in Hudson Bay and direct measurements are largely limited in Arctic waters (Ingram et al. 1996; Chanona et al. 2018) In the last few decades substantial amounts of research have been initiated by the hydroelectric companies (Manitoba Hydro, Ontario Power Generation and Hydro-Québec) of the provinces which border the HBME due to ongoing and possible future hydroelectric projects in the region (Déry et al. 2011).

Stratification of the HMBE waters are strongest in Hudson and James Bay with Foxe Basin experiencing more vertical mixing due to tidal waves. Hudson Bay is strongly stratified due to buoyant freshwater discharge contributing approximately 0.86% of the volume of the bay (Roff and Legendre 1986). This contributes to salinity being the primary determinate of the pycnocline (boundary in the water column at which density rapidly increases with depth) in Hudson Bay as opposed to temperature. Salinity is lowest in coastal waters (<24-28) and increases towards the centre of the basin (~30) with the highest salinity occurring in bottom waters (32-34; Table 4.1; Kuzyk et al. 2010; Granskog et al. 2011). The depth of the surface mixed layer varies seasonally, with a summer surface mixed layer remaining at 15 to 25 m deep. Temperatures can be extremely divergent throughout the water column with surface temperatures climbing to 12 °C and bottom waters that are almost at freezing (-1.7 °C; Roff and Legendre 1986). The winter surface mixed layer is found from 60 to 100 m which is increased in part by brine rejection during ice formation that causes the water to become denser and increase downward advection. Brine production is elevated in the western portion of Hudson Bay during the winter causing a deeper mixed layer that occasionally persists in areas of the bay into the summer (Granskog et al. 2011).

Table 4.1. Summary of salinity ranges from different regions of Hudson Bay, James Bay and Foxe Basin

Source	Region	Salinity
Hudson Bay		
Kuzyk et al. 2010	Offshore surface	31.2 - 31.8
	Offshore deep	32.7 - 33.1
	Inshore surface	30 - 31
	Inshore deep	31.9 – 32.5
James Bay		
Grainger (1960)	Surface waters	<15 - 22
	Bottom waters	~27
Foxe Basin		
Jones and Anderson 1994	Entering from Fury and Hecla Strait	~32.2
Kuzyk et al. 2010	Foxe Channel	32.9 – 33.1

El-Sabh and Koutitonsky (1977) conducted research on James Bay prior to a number of extensive hydroelectric projects commenced which have caused a “flattening” of the HBME hydrography (Déry et al. 2011). The summer pycnocline is found at 15-20 meters in James Bay along the eastern side with the western side lacking a defined pycnocline due to vertical mixing. Elevated wind stress during the fall along the surface increases the mixing and causes a reduction in the pycnocline with a mixed layer that can extend to the benthic zone. The bottom layer of James Bay experiences considerable interannual variability in stratification due to the shallowness of the bay (El-Sabh and Koutitonsky 1977).

Foxe Basin, as previously mentioned, tends to be much more well-mixed than the rest of the HBME due to tidal action. This is more pronounced in the eastern side of the basin with the western and southern regions being more stratified (Stewart and Barber 2010). Early work in Foxe Basin by Campbell (1964) identified a cold, high-salinity pulse (<1.8 °C; >33.75) of water during a field survey in 1955, but subsequent studies could not locate the same water mass. Campbell hypothesized that the reduced temperature could have been brought about by water freezing on the tidal flats. Defossez et al. (2008) identified a similar cold, saline water mass from data collected in 2004 to 2006 which was found to be influenced by the nature of the previous winter. Defossez found Campbell’s explanation for the pulse to be improbable as the volume of water would be insufficient to create a signature of this size. Brine rejection occurring at a polynya in western Foxe Basin is considered to be the likely source of the pulse.

4.1.4 Marine food web

Inuit and Cree peoples are an integral part of the marine food web in the HBME, and their diets show high seasonality based upon the availability of different plant and animal species throughout the year. The Voices from the Bay Report (1997) demonstrates this seasonality through the words of a Wemindji Elder who describes the goose hunts during the spring and fall migrations as well as the trapping of animals throughout the winter and fishing in the summer. Traditional ecological knowledge of the sea ice enables Inuit to have detailed knowledge of how animals use sea ice as habitat and therefore, hunt them (Laidler 2007). See sections 3.2 and 3.3 for more information on the role of Inuit and Cree within the food web of the HBME. For information specific to wildlife harvests by Cree hunters within the Hudson and James Bay Lowlands, see Berkes et al. (1995).

Ice algae and under-ice food web

Sea ice is an integral part of the Arctic food web as it provides a platform on which many species can forage, but also for species who spend at least some part of their life cycle inhabiting the ice, known as the sympagic community (Horner et al. 1992). One of the most important groups in this community is that of ice algae which form the base of the ice food web (Deal et al. 2011). Sea ice is an ideal location for algae as they remain close to solar radiation, which can penetrate through the ice, allowing for photosynthesis to occur. However, there is some evidence that the algal community may utilize heterotrophy (nutrient uptake reliant upon external sources of organic carbon (Gutekunst 2018)) throughout the winter when snow cover may be too thick for irradiance to pass through to the ice (Dalman 2018). Most ice algae are found free-floating in the skeletal layer or loosely attached to the bottom layer of the ice, often producing gel or mucus-forming mats (Michel et al. 1993).

Diatoms are the dominant ice algae taxa in Hudson Bay, in particular, pennate diatoms such as *Nitzschia*, *Navicula* and *Pinnularia* species (Poulin and Cardinal 1982). Work by Gosselin et al. (1990) in Manitounuk Sound found pennate diatoms comprised 56-84% of all cells sampled, with centric diatoms (primarily *Chaetoceros* spp.) and microflagellates comprising 2-8% and 6-33% respectively. The taxonomic diversity of ice algae is largely determined by the salinity of the waters and, therefore, can be influenced by proximity to a river plume (Stewart and Lockhart 2005). Legendre et al. (1987) applied size-fractionation to a sample of Hudson Bay ice algae and confirmed the presence of picoalgae but did not classify them. More research should be done to identify the species of picoalgae and characterize their role within the sympagic community. The ice algae support a meiofauna grazing community within the sea ice including nematodes, copepods, flatworms and rotifers (Bluhm et al. 2018).

The ice algal bloom in Hudson Bay occurs from April to June as the sea ice melts and initiates an early grazing season for zooplankton, providing a carbon source prior to the phytoplankton spring bloom (Tremblay et al. 1989; Runge et al. 1991) As the sea-ice continues to melt, the algae are released into the water column to be ingested by zooplankton or sink into the benthic zone. Tremblay et al. (1989) estimated that due to consumption within the pelagic food web, approximately only 10% of the ice algal production sinks through the water column, demonstrating a probable coupling between pelagic and ice-algae food webs. Zooplankton, such as *Calanus* and *Pseudocalanus*, undergo diel migrations to beneath the ice surface at night to graze on ice algae (Runge et al. 1991). The egg production of *Calanus* females appears to be linked to the nutrition provided by these algae and is evidence that the timing of the ice algal bloom and the zooplankton bloom are linked. Larval fish first feeding is also ideally timed to coincide with the release of copepod eggs and is therefore influenced by the ice melt as well (Runge et al. 1991).

Pelagic Food Web

The seeding hypothesis suggests that it is the ice algae that initiates the summer phytoplankton bloom approximately 6 weeks later in the water column of Arctic waters such as the HBME (Drolet et al. 1991). After this second peak in primary productivity, biomass of copepod nauplii (primarily *Calanus glacialis*, *Pseudocalanus* spp., *Oithona similis*) as well as other zooplankton increases, providing food to fish larvae. Copepods are an important source of energy in Hudson Bay's food webs due to their substantial lipid reserves (Darnis et al. 2012). Cushing's match-mismatch hypothesis (initially put forward to describe the relationship between the timing of zooplankton peak production and larval fish mortality, as misalignment between the two results in increased larval fish mortality rates) is relevant here as success at first feeding of larval fish is directly related to timing in zooplankton peak production. Earlier melting of sea ice in Hudson Bay may have negative implications upon the alignment of this timing. Evidence also shows that sea ice loss has been linked to physiological stress in ice algae and mortality in zooplankton, which would result in cascading effects into higher trophic levels (Runge et al. 1991; Moline et al. 2008). Both Arctic cod (*Boreogadus saida*) and American sand lance (*Ammodytes americanus*), critical forage fish in Hudson Bay, are both very vulnerable to starvation and predation during the transition from endogenous to exogenous feeding and rely upon peak zooplankton biomass to ensure a successful first feeding (Drolet et al. 1991).

There are three fish species that are crucial nodes in the Hudson Bay pelagic food web: Arctic cod, capelin (*Mallotus villosus*) and, to a lesser extent, American sand lance. Arctic cod is a key link in Arctic food chains as it is one of the most energy-rich prey foods to be found in Arctic waters (Harter et al. 2013). 75% of energy moving from lower to upper trophic levels is transferred by Arctic cod, however, little is known about the species (Fortier 2012; Bouchard et al. 2015). While researching the diet of thick-billed murre nestlings (*Uria lomvia*) from 1981 to 2013, Gaston and Elliot (2014) found that, over the 33 years of the study, Arctic cod had decreased as a primary prey item and capelin had increased. Arctic cod are reliant upon sea ice and are a specialist that often forages along the productive ice edge. In Hudson Bay, there is evidence that Arctic cod are being replaced in the food web by capelin, a subpolar generalist, in the diet of top consumers such as the thick-billed murre (for a more detailed explanation, see section 5.6). This may indicate that a shift is occurring from an Arctic ecosystem to a temperate one in the HBME (Fortier 2012). Capelin had been previously described in the 1970s as having relict populations throughout the HBME, however, by the late 1980s, their distribution was considered continuous from Nova Scotia to Hudson Bay (Beck et al. 1993). Sand lances have also been increasing within Hudson Bay over the last few decades and tend to be distributed in lower salinity areas including estuaries (Stewart and Lockhart 2005). The rainbow smelt (*Osmerus mordax*), an invasive species in Hudson Bay, has been found in the stomach of juvenile ringed seals (*Phoca hispida*), perhaps indicating some integration into the food web (Chambellant et al. 2013). The Greenland cod (*Gadus ogac*) is another fish species that inhabits Hudson Bay, but due to seeming lack of key predators and no commercial fishery, little is known about this fish species (Mikhail and Welch 1989).

Table 4.2 summarizes the prey species for some significant top consumers in Hudson Bay. Three cetacean species have traditionally foraged in the HBME: beluga (*Delphinapterus leucas)*, bowhead (*Balaena mysticetus*) and narwhal (*Monodon monoceros;* see Figure 4.3 for their distribution throughout the HBME). Belugas are generally opportunistic feeders with Hudson Bay belugas consuming more capelin than other beluga populations which tend to rely more on Arctic cod (Kelley et al. 2010, 2014). Capelin have been cited as a beluga prey item since 1953 in Hudson Bay (Sergeant 1973), so it is possible that their presence is not solely a recent phenomenon linked to a regime shift.

Bowhead whales, the Arctic's only mysticete (baleen whale), experienced substantial population declines due to commercial whaling from the late 1800s to early 1900s (~90% loss of population) but have recently started increasing in numbers again (Higdon and Ferguson 2010). Estimates of

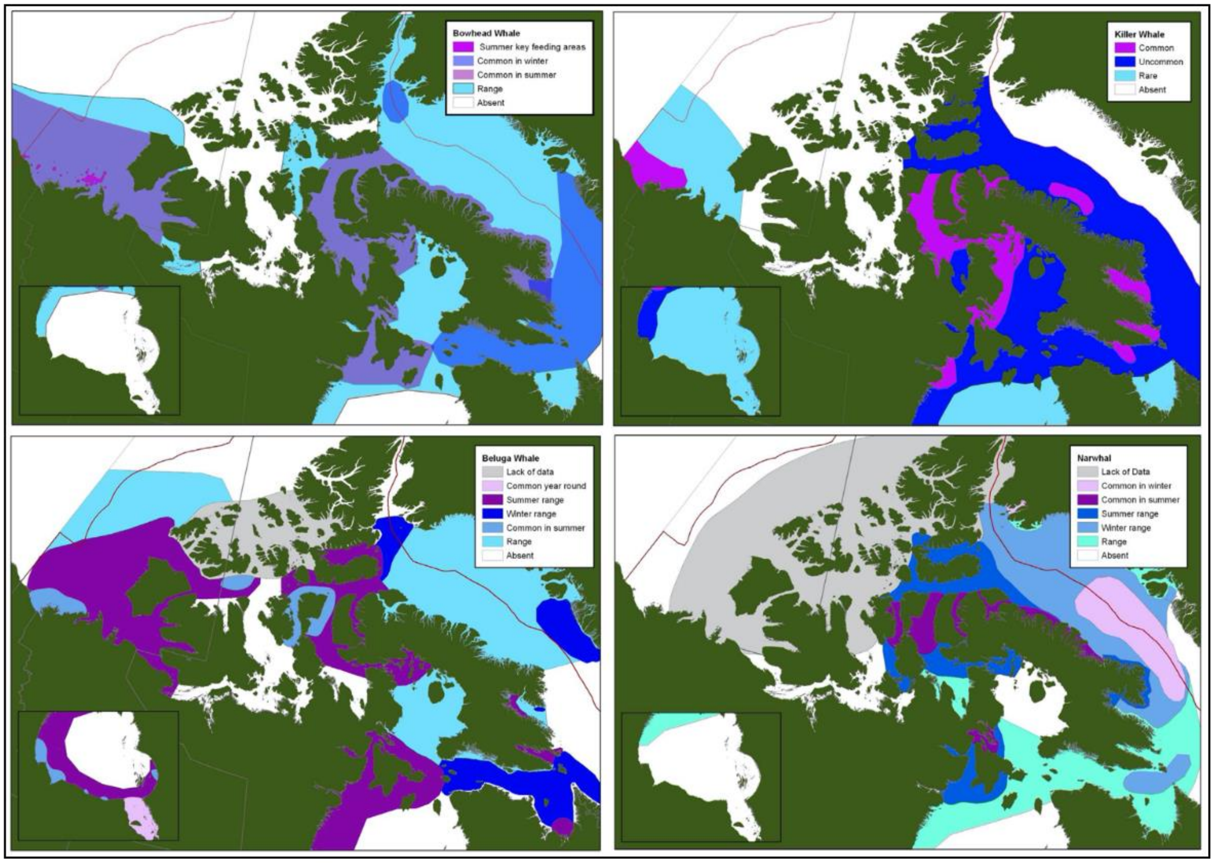


Figure 4.3. Distribution of four cetaceans (bowhead, killer whale, beluga and narwhal) throughout the HBME (adapted from Stephenson and Hartwig 2010)

Table 4.2. Summary table of prey species foraged by top consumer species in the Hudson Bay Marine Ecosystem. Dominant prey species are listed first.

Consumer Species	Source	Prey Species
Pelagic species		
Thick-billed murres	Gaston and Elliot (2014)	Capelin, Arctic cod
Beluga	Bluhm and Gradinger (2008)	Capelin, sand lance, Atlantic cod (*Gadus morhua*), tomcod (*Microgadus tomcod*) and invertebrates (crustaceans and polychaetes)
Bowhead	Higdon and Ferguson (2010)	Pelagic crustacean zooplankton: copepods (*Calanus*) and euphausiids (*Thysanoessa*)
Narwhal	Watt et al. (2013)	Shrimp (*Pandalus borealis*), capelin, squid (*Gonatus fabricii*), Greenland halibut (*Reinhardtius hippoglossoides*), Arctic cod
Killer whale	Ferguson et al. (2009)	Bowhead, beluga, narwhal, seal
Ice-edge specialists		
Black guillemots (*Cepphus grylle*)	Cairns (1987)	Arctic cod, Arctic shanny (*Stichaeus punctatus*), crustaceans, polychaetes, gastropods
Ice-obligate species		
Ringed seal	Chambellant (2010)	Capelin, sand lance, Arctic cod with occasional Greenland cod, sculpin (*Triglops* sp.), Arctic char (*Salvelinus alpinus*) and invertebrates
Polar bear (Foxe Basin)	Galicia et al. (2016)	Ringed seal, bearded seal (*Erignathus barbatus*), harp seal (*Pagophilus groenlandicus*), harbour seal (*Phoca vitulina*), bowhead†
Polar Bear† (western Hudson Bay)	Gormezano and Rockwell (2013)	Grasses, mushrooms, snow geese (*Anser caerulescens*), Canada geese (*Branta canadensis*), caribou (*Rangifer tarandus caribou*), seal, polar bear, garbage

† Indicates terrestrial scavenging

pre-whaling population size range from 450 – 680 whales with a recent corrected aerial survey estimating the present population at 313 whales. This past decline may have led to prey release of zooplankton enabling other species, such as the Arctic cod and the ringed seal, to take advantage of the more plentiful resources and thereby, increase in population. Bowhead whales have substantial energetic needs which they meet by grazing marginal ice zones for lipid-rich zooplankton (Ferguson et al. 2010). Their subsequent recovery may start to negatively impact polar bear and ringed seal populations. However, it is very challenging to disentangle the effects of climate change from the impacts that an increased bowhead population is having on the zooplankton. Further altering the food chains of the HBME is the recent expansion of the killer whale (*Orcinus orca*) range into the region as the summers become more ice free (see Figure 4.3). The ecotype of these killer whales has not been identified and there is little indication that they are consuming fish but appear to be predating primarily upon marine mammals such as bowhead and beluga (Ferguson et al. 2009; Darnis et al. 2012). Interviews with Inuit hunters have provided the majority of the information on killer whale predation in the HBME. A comprehensive review of killer whale predation events throughout the Canadian Arctic by Higdon et al. (2011) indicates that predation upon bowhead whales tends to be seasonal and coincides with summer calving. Killer whales focus their efforts on calves or juvenile bowhead, however, will sometimes prey upon larger whales when in groups (Ferguson et al. 2009). Participants in these interviews describe the cooperative hunting strategies of the killer whales such as covering the blowhole of bowhead whales to suffocate it or biting the whale, primarily on its underside or flippers. The arrival of killer whales could be the herald of a shift in the apex predator of the HBME away from polar bears and future stock assessments of the resident cetacean populations should consider the possible impacts of this novel predator.

The last of the cetacean species is the narwhal, of which little is known of their diet, however, work by Watt et al. (2013) indicates that there are differences in diet between the three Arctic narwhal populations. The Hudson Bay narwhals tend to have a more benthic diet, consuming mostly shrimp, with pelagic prey such as capelin being less important. As a species that is recognized as being very sensitive to climate change, this is a good indication that there may be some adaptability within the narwhal’s foraging strategy.

Ice food web

For many species, predictable sea ice conditions are a prerequisite for successful foraging (Luque et al. 2014). Many marine mammals are the top consumers in the Arctic, and they have evolved to be in sync with the anticipated seasonality of the sea ice. Polynyas, which are a spatially reoccurring area of open water or low ice density (Hannah et al. 2009), are crucial overwintering habitat in the HBME for many waterfowl such as black guillemots, glaucous gulls (*Larus hyperboreus*) and common eiders (*Somateria mollissima sedentaria*). They provide air holes for marine mammals and are areas of increased productivity, due to the irradiance that is able to penetrate into the water column year-round, as evidenced by high densities of belugas, walrus (*Odobenus rosmarus*), ringed and harbour seals, many of which overwinter in polynyas in the HBME (Stirling and Cleator 1981).

Pinniped life histories in Hudson Bay are highly attuned to sea ice-conditions as typified by the ringed seal, the predominate pinniped in Hudson Bay, which is the southern limit of its range in the Arctic. Similar to Arctic cod, ringed seals provide a key linkage between upper and lower trophic levels. Over much of the Arctic, ringed seals prefer Arctic cod, but primarily consume sand lance and capelin in Hudson Bay. Ontogenic shifts occur between juveniles, which consume more invertebrates, and adult diets which rely more upon fish (Yurkowski et al. 2016). Other pinnipeds found in the HBME include the bearded seal, the harp seal, the harbour seal and the walrus (Stephenson and Hartwig 2010). There is some speculation about how changing ice conditions will impact pinnipeds as ice conditions that are favourable to ringed seals are declining. Although harbour seals are currently uncommon throughout the HBME, it is possible that reduced ice cover may provide more ideal coastal habitat, resulting in an increase in the population (Bajzak et al. 2013).

Of all the species that inhabit the HBME, none has received as much attention from the scientific community as the polar bear (*Ursus maritimus*). Polar bears are top consumers in the HBME, a position they share with the Inuit hunters who harvest them (Hammill 2013). Reliant upon endogenous fat accumulated in the spring by hunting on the sea ice, polar bears are thought to fast during the ice-free months. Research by Gormezano and Rockwell (2013) suggests that fasting is perhaps not the most appropriate term. Traditionally designated as a specialist that hunts on ice for seals, scat samples show that opportunistic land-based scavenging takes place throughout the summer with grasses, berries, caribou, eggs and marine algae providing nutrients during the ice-free months (Gormezano and Rockwell 2013).

As previously mentioned, sightings of killer whales in the HBME have been more common as it becomes increasingly ice free in the summer. The earlier spring ice melt also reduces hunting time for seals, the primary prey of polar bears, which increases the need for alternate food sources. When killer whales prey upon bowhead, they often eat only the head and mouthparts, leaving the carcass to drift. Galicia et al. (2016) found that bowhead whale comprised 4 ±0.7% of the diet in 56% of the bears tested from Foxe Basin when a fatty acid analysis was performed. This is consistent with increased sightings by local Inuit of polar bears scavenging bowhead carcasses. A more opportunistic foraging strategy might be possible for polar bears if killer whales take on the role of the new apex predator in the HBME. Data collected from scat analysis of polar bears in James Bay show a much higher proportion of birds (mostly Anatidae: ducks, geese, and swans) comprising their diet (Russell 1975). Russell (1975) mentions several observations of polar bears stalking and killing Canada geese on land as well as a description by an Inuit hunter who observed a polar bear swimming among king eiders. When the hunter shot the bear, the stomach contents contained the remains of king eiders indicating that some polar bears may have learned to hunt birds in the water. These regional hunting strategies may indicate some plasticity in consumption patterns, but it remains to be seen if these alternative prey items can be an adequate substitute for their energy-rich seal prey.

4.1.5 Ice dynamics

Historical data regarding trends in sea ice are lacking in the HBME due to the difficulties of conducting field work in the region during winter resulting from limited access and mobility from weather and sea ice conditions. Records from the Hudson’s Bay Company, such as employee diaries that were written as early as 1714, are some of the oldest European records of the breakup and freeze-up of ice in Hudson and James Bay (Catchpole and Ball 1981). These records often referenced weather and sea ice conditions as their environment had a large impact on the lives and work of these employees. Even as recently as World War II, many in the scientific community believed Hudson Bay to be primarily ice free during the winter, but pilots flying over the bay noted that there was ice cover present for most of the year (Gunn 2014). More widespread acknowledgement within the scientific community that TEK held by Inuit peoples contributes to a greater understanding of the HBME (Aporta and Macdonald 2011) has enabled a broader comprehension of sea ice that will be underscored in other sections of this report (see Chapter 3 and section 5.7).

Voices from the Bay: Traditional Ecological Knowledge of Inuit and Cree in the Hudson Bay Bioregion, released in 1997, is one of the earliest publications of documented Indigenous Knowledge for the HBME and describes Inuit Knowledge (IK) of environmental change (MacDonald et al. 1997). Building upon projects like Voices from the Bay, SIKU: The Indigenous Knowledge Social Network is a mobile app created by the Arctic Eider Society that integrates TEK with an online platform and allows Inuit Knowledge holders to access, share and upload their own data including information on sea ice conditions (Arctic Eider Society).

In the paragraphs that follow, the process of ice formation within the HBME is described using the lens of Western science. However, Inuit Knowledge of sea ice is highly descriptive, complex and often regionally specific, integrating information about the impacts of wind, wind direction and currents (Laidler 2007). Voices from the Bay (1997) describes five stages of sea ice development: 1) Early ice formation from shoreline to land points in inlets, bays and peninsulas, 2) development of land fast ice, 3) development of floe-edge ice, 4) spring cracks and 5) after breakup from spring to early summer (MacDonald et al. 1997). Within these five stages of ice development, Voices from the Bay notes that there are 71 different terms that can be used to describe different ice conditions. Laidler (2007) explores sea ice processes in three Inuit communities, including Igloolik, where *qinu* describes the slush-like ice that first forms when open water beings to freeze, then thickens, forming smooth striations referred to as *quvviquat*. Freeze-up is referred to as *sikuvalliajuq*. However, there are different names for the distinct ways that sea ice can freeze. Inuit hunters with years of experience are able to recognize the age of ice they are hunting on, its geographic origins and the movement patterns of multiyear ice. To further document IK of sea ice and sea ice use, the Inuit Sea Ice Use and Occupant Project (ISUIOP) was developed which also allows for continued community-based sea ice monitoring (Aporta 2017). Imrie (2009) records IK and adaptations to changing sea ice in Sanikiluaq, a community on the Belcher Islands, resulting from climate change and hydroelectric developments.

With seasonal reductions in atmospheric temperatures, the heat flux that occurs at the air-water interface causes the water temperature to drop below the freezing point of sea water. Frazil ice crystals then form and consolidate into nilas ice (thin, continuous sheets of smooth ice) which is flexible enough to remain intact in relatively calm conditions. Pancake ice occurs when conditions are too rough for nilas ice to form and a critical mass of rounded ice pans must develop from fractured frazil crystals to dampen the wave action, allowing nilas ice to fuse the ice pans into a continuous ice sheet (Gunn 2014). Sea ice in the HBME can be classified into two groups: mobile pack ice (ice floes), found predominately in the interior of the bay and influenced by current and wind dynamics, and fast ice that is connected to the land along the coastline and remains in place until the beginning of breakup (Andrews et al. 2017; Eastwood 2017). Much of the research conducted in the HBME does not distinguish between fast ice and the mobile ice floes that are generally more dynamic due to ridging that occurs when floes are pushed together (Taha et al. 2019).

The HBME functions essentially as a closed system with regards to sea ice as the coastline constrains the maximum sea ice extent (Wang et al. 1994). Sea ice formation in the HBME is largely determined by wind, precipitation, atmospheric temperatures and circulation. Hochheim and Barber (2010) found that both the North Atlantic Oscillation (NAO) and Southern Oscillation Index (SOI) are linked to variability in Hudson Bay sea ice concentration (SIC; measured as the percentage of sea ice within a study area) and sea ice extent (SIE; presence/absence within a geographic region) with the largest variability in SIC and SIE resulting from a strong negative SOI in the summer and a strong positive NAO during winter. Freshwater runoff can also have an influence on ice formation as ice develops first in areas of low salinity as freezing temperatures are higher in less saline waters (Hochheim et al. 2010).

The HBME annually undergoes a full cryogenic cycle of ice freeze-up and thaw, therefore, almost all the ice in the region is first-year ice. A small amount of second-year ice may remain in Foxe Basin which sometimes moves into Hudson Bay after breakup (Andrews et al. 2017). Ice is first to form in the HBME in Foxe Basin in early October (Gagnon and Gough 2006). Approximately a month later, in the first few days of November, freeze-up begins along the north and northwest coasts of Hudson Bay, continuing to move offshore and down along the west coast. Production of ice bands begins along the south coast of James Bay with previously formed ice beginning to consolidate (>80% SIC). By the first week of December, ice is beginning to form offshore in the central portion of the bay as it moves from north to south with consolidation of the bay occurring by late December to early January (Figure 4.4; Hochheim and Barber 2010). The ice along the north and northwest coasts of Hudson Bay is also the first to experience breakup in early May, resulting from wind stress, with the east coast into James Bay following shortly after. As river ice melts in James Bay, irradiance warms the river water which aids in breaking up the ice as it moves out into the bay (El-Sabh and Koutitonsky 1977). Ice coverage in southwestern and central Hudson Bay remains until August to September when the bay is then considered ice free (<15% SIC; Hochheim et al. 2010; Barber et al. 2012). Of primary concern to the HBME environment is the extension of the ice-free season with trends indicating earlier breakups in the spring and later freeze-ups in the fall (see section on ice loss).

Table 4.3 summarizes maximum ice thickness, along with freeze-up and breakup dates, measured by Gagnon and Gough (2006) at seven different stations around the HBME. The data collected by Gagnon and Gough (2006) is one of the few studies that are inclusive of ice thickness, breakup and freeze-up dates from Foxe Basin, Hudson Bay and James Bay. Ice thickness in the HBME tends to increase from south to north in relation to temperature and from west to east due to ice transport via cyclonic currents and northwesterly winds (Andrews et al. 2016). Figure 4.5

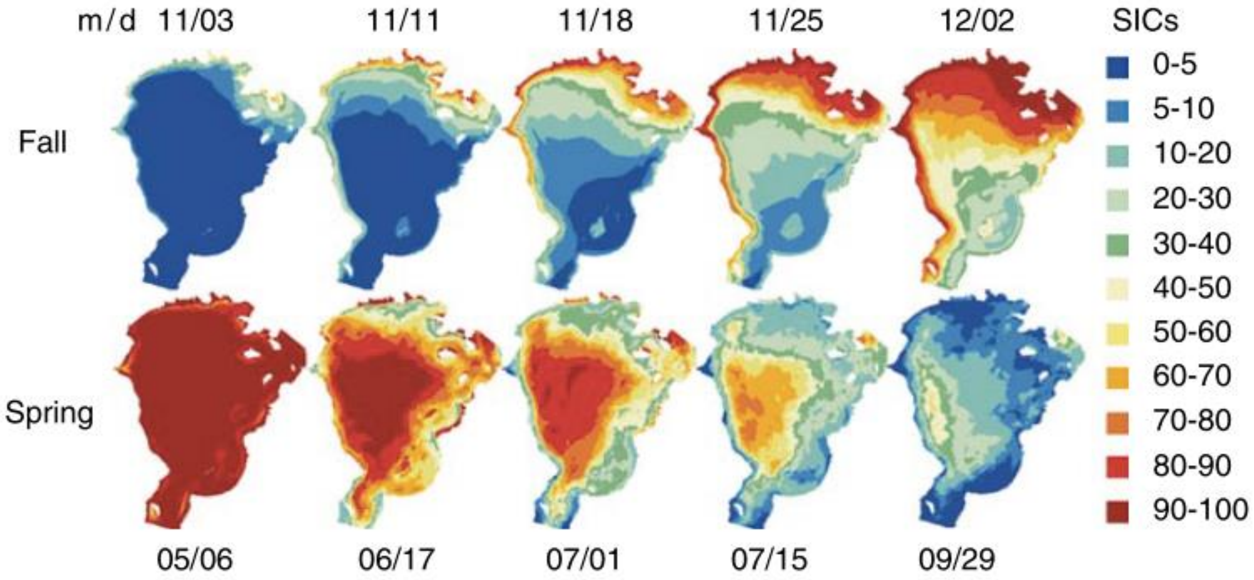


Figure 4.4. Progression of Hudson Bay and James Bay ice formation and breakup using 1980 – 2005 mean sea ice concentrations (SIC; measured as a percentage) from the Canadian Ice Service database (Hochheim et al. 2010, p. 45)

Table 4.3. Ice thickness (cm) measured at seven stations across the Hudson Bay Marine Ecosystem with ice freeze-up, breakup, and maximum thickness dates (Gagnon and Gough 2006, p. 181) © Inter-Research 2006

Station	Region of HBME	Measurement dates	Freeze-up date	Max. ice thickness (cm)	Date of max thickness	Breakup date
Chesterfield Inlet	NW Hudson Bay	1959-1981	Oct 29 ± 11.1	189 ± 20.3	Apr 27 ± 16.7	June 7 ± 19.3
Churchill	SW Hudson Bay	1960-1987	Oct 20 ± 15.7	174 ± 14.3	Apr 25 ± 16.0	May 22 ± 17.8
Coral Harbour	N Hudson Bay	1958-2003	Oct 17 ± 11.0	180 ± 16.7	May 20 ± 16.0	June 19 ± 15.7
Hall Beach	NW Foxe Basin	1959-2003	Oct 8 ± 11.9	212 ± 26.3	May 23 ± 21.9	June 15 ± 15.9
Inukjuak	E Hudson Bay	1959-1990	Oct 25 ± 13.7	237 ± 26.5	Apr 30 ± 17.4	May 19 ± 17.3
Kuujjuarapik	SE Hudson Bay	1972-1991	Nov 20 ± 15.1	140 ± 27.2	Apr 10 ± 17.4	May 6 ± 11.8
Moosonee	S James Bay	1959-1993	Nov 11 ± 7.6	93 ± 16.0	Mar 26 ± 13.0	Apr 19 ± 12.5

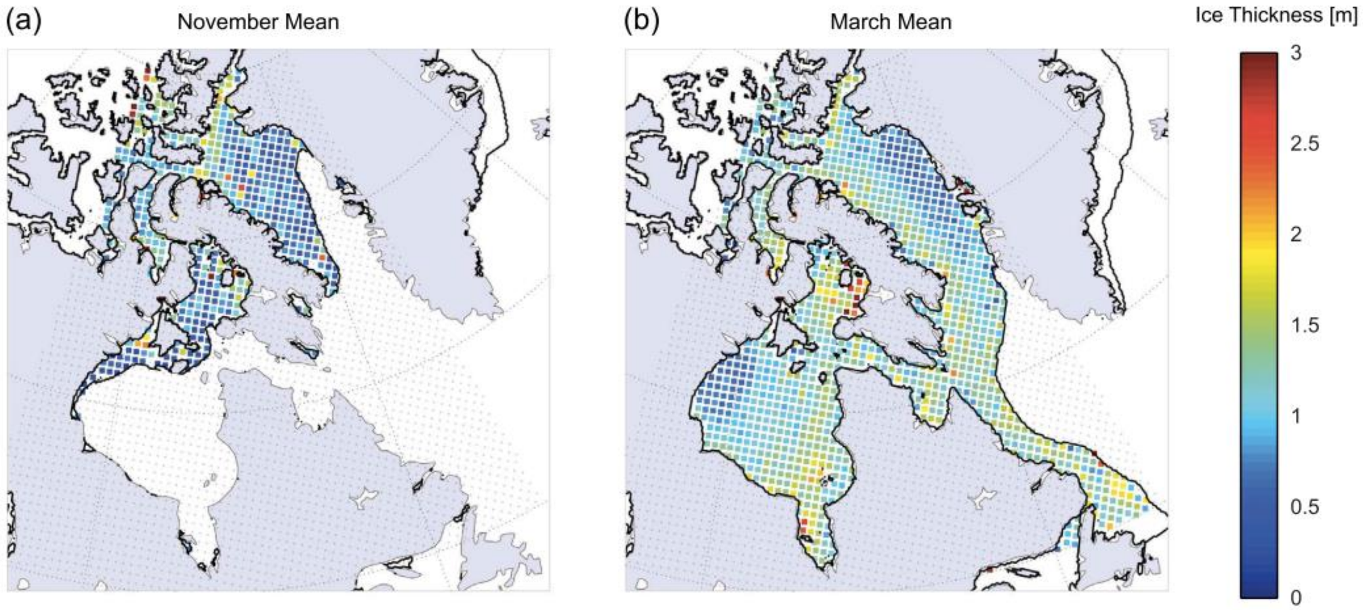


Figure 4.5. Mean sea ice thickness in the Hudson Bay Marine Environment for November (a) and March for the years 2003-2016 using radar (Cryosat-2) and laser (ICESat) altimetry (Landy et al. 2017, p. 287)

demonstrates mean sea ice thickness in the HBME and Baffin Bay for both November and March averaged over the years 2003–2016 using laser and radar altimetry data. The thicker sea ice on the eastern side of Hudson Bay is heavily impacted by advection and ridging which occurs when ice is thick (>15 cm) and comes under pressure (Hochheim and Barber 2014; Mussells et al. 2016). Landy et al. (2017) measured the southeast ice drift speed as 1.31 km per day for December to April and 0.85 km day^{-1} mean ice drift from west to east. This contributes to the asymmetry in the ice thickness observed across the west-east axis of the bay.

4.1.6 Ice features and polynyas

Polynyas are areas of open water or reduced ice cover that regularly recur in the same spatial location (Barber and Massom 2007). Tides, currents and winds all influence the formation of polynyas which are often classified by the forcing mechanisms that create them: sensible-heat or thermodynamically forced polynyas, which result from warm water masses emerging from depth due to currents or bathymetry, and latent heat or mechanically forced polynyas that are maintained by consistent wind force (Gunn 2014). Polynyas are often found between islands and near shoals in fast ice. Flaw leads, similar to polynyas, are also areas of open water but differ in that they are not as geographically consistent. Usually formed by currents or offshore winds, these linear ice fronts can be 10 to 100s of metres wide and kilometers long and are primarily a divergence of ice from land or fast ice. See William et al. (2007) for a detailed discussion on the physical processes of polynya formation.

In the HBME, significant polynyas have been identified along the northwestern entrance to Hudson Bay (Churchill to Roes Welcome Sound), the eastern shore of James Bay, northern Foxe Basin and around the Belcher Islands (SE Hudson Bay; Gunn 2014; Eastwood 2017). Polynyas and shore leads in the HBME are not well described in the literature with even large polynyas being only recently communicated about in scientific research. The polynya in northwestern Hudson Bay is approximately 600 km long and 60 km wide with open water present for approximately 70% of the winter for periods of 1 to 5 days resulting from wind stress. Saucier et al. (2004) identified this polynya as a location of high ice production (2.4 cm day^{-1} in late Dec., 1-2 cm day^{-1} Jan-March; Eastwood 2017). The northwestern coast of Hudson Bay is also characterized by the presence of a shore lead system. In Foxe Basin, a horseshoe-shaped polynya in Fury and Hecla Strait is maintained by strong tidal currents with other smaller latent-heat polynyas also present in the basin (Barber and Massom 2007; Sibert et al. 2010). Brine rejection (a process in which salt is rejected from sea ice as it freezes) in these polynyas has been linked to a deep-water formation in the HBME including a cold, saline annual pulse that has been identified in Foxe Basin and which is known to overflow into Hudson Bay, replenishing its bottom waters (Defossez et al. 2008). See Figure 4.6 for locations of recurrent polynyas in the HBME.

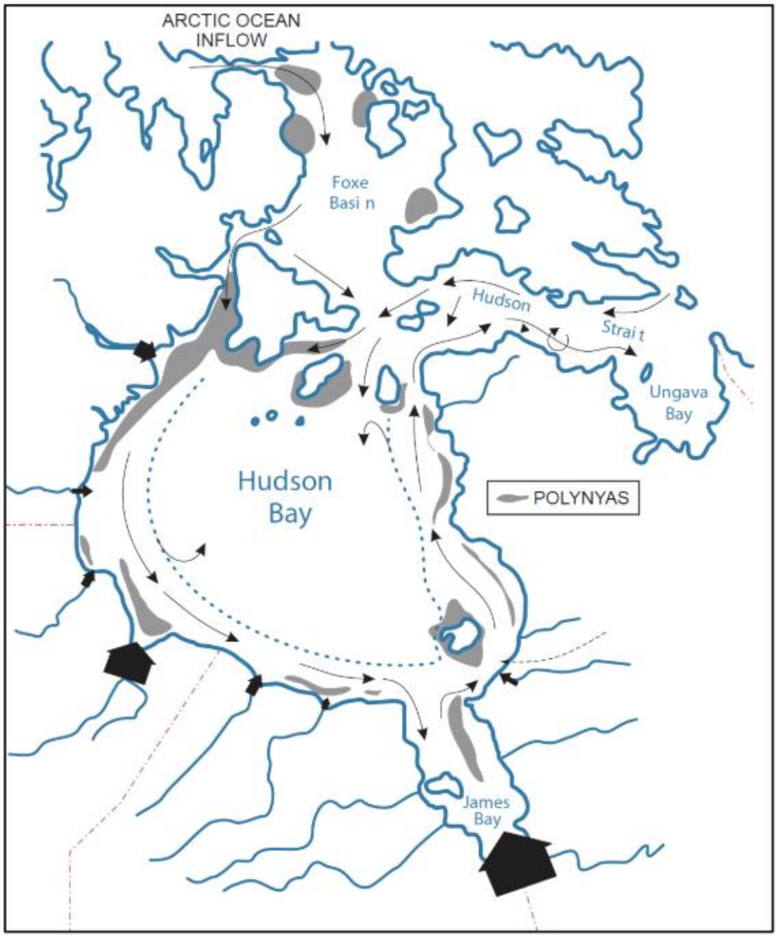


Figure 4.6. Recurrent polynyas in the HBME with circulation (narrow arrows) and riverine inflow (wide arrows) (Eastwood 2017, p. 15; adapted from Macdonald and Kuzyk 2011, p. 338)

Polynyas and flaw leads are the most biologically productive areas in the Arctic during the winter and provide an over-wintering area for many different species (see Marine Food Web section). Residents of Sanikiluaq, a Nunavut Inuit community on the Belcher Islands, have traditionally hunted common eider in the polynyas found around these islands. In the last few decades, these 16 polynyas have been more consistently experiencing rapid freezing over (Gilchrist and Robertson 2000). During the winters of 1991 and 1992, freezing over of the polynyas caused a mass die-off of common eider contributing to the 75% population decline observed since the 1980s. Hydroelectric developments and climate change may be having a synergetic effect on these changing ice conditions in the HBME (Eastwood 2017). Further research into polynya formation in the HBME integrating TEK will help clarify how these factors are impacting the stability of these important biologically productive areas.

4.1.7 Ecologically significant areas

The Convention on Biological Diversity developed seven scientific criteria with which to identify Ecologically and Biologically Significant Areas (EBSAs). As a signatory to this treaty, Canada (through the work of the DFO) has used these criteria to designate ten EBSAs in the HBME. Figure 4.7 indicates the geographic location of these EBSAs within the HBME as well as the EBSAs identified within Hudson Strait. These criteria are as follows (Cobb et al. 2011):

1) Uniqueness or rarity
2) Special importance for life history stages of species
3) Importance for threatened, endangered or declining species and/or habitats
4) Vulnerability, fragility, sensitivity or slow recovery
5) Biological productivity
6) Biological diversity
7) Naturalness

Table 4.4 synthesizes information based on these criteria and as identified by the DFO for the EBSAs recognized in the HBME. Previously recorded local and traditional ecological knowledge was utilized in the evaluation of the EBSAs (DFO 2011). Arctic EBSAs are often geographically large, due to lack of fine-scale information, interannual ice variability (which causes spatial and temporal use change by many animals) and the long migrations that many Arctic animals undertake (Cobb et al. 2011). There is currently very little information on the marine fishes of the HMBE, therefore, current EBSA boundaries do not account for important marine fish habitat. While designation of an EBSA does not confer protections (Chénier et al. 2017), this information can be beneficial in informing an ecosystem-based management approach for situations such as understanding risks associated with the projected increase in Arctic marine shipping as well as the development of future Marine Protected Areas (DFO 2011; AMAP 2013). As part of the Canadian government's Target 1 Challenge to conserve 25% of the land and oceans within Canada, two Indigenous Protected and Conserved Area establishment projects will be taking place within the HBME: Arqvilliit (Ottawa Islands) in northeastern Hudson Bay led by the community of Inukjuak and Qikiqtait, a community-driven project led by the Arctic Eider Society for the Belcher Islands Archipelago in southeastern Hudson Bay (Government of Canada 2020).

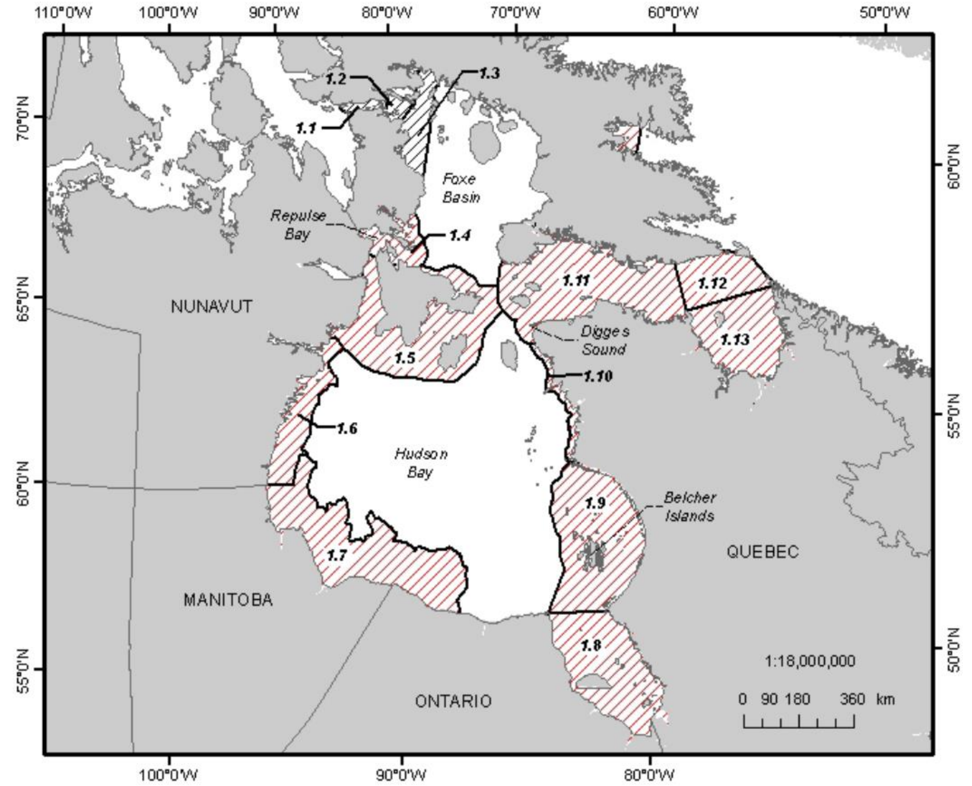


Figure 4.7. Ecologically and Biologically Significant Areas (EBSAs) within the HBME as identified by the DFO (2011). The ten EBSAs are as follows: Fury and Hecla Strait (1.1), Igloolik Island (1.2), Rowley Island (1.3), Repulse Bay/Frozen Strait (1.4), Southampton Island (1.5), Western Hudson Bay Coastline (1.6), Southwestern Hudson Bay Estuaries (1.7), James Bay (1.8), Belcher Islands (1.9), Eastern Hudson Coastline (1.10) (DFO 2011)

Table 4.4. Selected characteristics of Ecologically and Biologically Significant Areas (EBSAs) of the HBME based on DFO (2004) evaluation criteria (adapted from DFO 2011, p. 12)

Physical Features	Uniqueness	Species Importance	Rare or Endangered Species
Fury and Hecla Strait			
- Strong currents	- Migration corridor	- Polar bear denning - Bowhead nursery - Migration corridor for marine mammals	- Eastern Canada-West Greenland Bowhead (ECWG Bowhead)
Igloolik Island			
- Polynya		- Walrus feeding and haul-outs - Bowhead nursery - Arctic char feeding - Migration corridor for marine mammals and Arctic char	- ECWG Bowhead
Rowley Island			
- Sea ice-edge and islands	- Preferred walrus habitat	- Walrus feeding and haul-outs	- ECWG Bowhead
Repulse Bay/Frozen Strait			
- Strong currents - Polynya	- Marine mammal summering area	- Summer feeding area for marine mammals and seabirds	- Northern Hudson Bay narwhal - ECWG bowhead - Northern Hudson Bay-Davis Strait Atlantic walrus
Southampton Island			
- Islands	- Largest single colony of common eiders in Nunavut	- Seabird nesting and foraging - Polar bear denning and feeding - Walrus feeding and haul-outs - Marine mammal migration pathway	- ECWG bowhead
Western Hudson Bay coastline			
- Consistent frontal zone - Winter shore lead	- Macrophytes (aquatic plants)	- Arctic char feeding and migration corridor - Beluga aggregation - Fall migration area for polar bears	

Physical Features	Uniqueness	Species Importance	Rare or Endangered Species
SW Hudson Bay estuaries			
- Estuaries (Churchill, Nelson and Seal rivers)	- World's largest summering beluga aggregation - Harbour seals	- Polar bear denning and feeding - Beluga aggregation - High food supply for benthos and benthic diversity	- Western Hudson Bay beluga - Ross's gull - Western Hudson Bay polar bear (threatened under Province of Manitoba)
James Bay			
- Shallow waters - Lower salinities - Large estuary	- Supports variety of relict warm water species - Summer and wintering beluga - Eelgrass beds - Intl importance for Hudsonian godwit and red knot	- Walrus haul-outs and feeding - Polar bear denning and feeding - Beluga aggregation - Shorebird, sea duck and waterfowl staging and foraging area - Black scoter moulting - Cisco and broad whitefish feeding and migration	- Northern Hudson Bay-Davis Strait Atlantic walrus - Eastern Hudson Bay beluga - red knot *rufa* subspecies
Belcher Islands			
- Polynyas - Small estuaries - Landfast ice around islands - Currents around islands - Cooler water temperatures	- Possible overwintering beluga - eelgrass - world population of resident Hudson Bay common eider subspecies	- Walrus feeding and haul-outs - Summer beluga aggregations at estuaries - Seaduck nesting and foraging - High food supply for benthos and benthic diversity - Polar bear feeding - Entire world population of Hudson Bay common eider subspecies summers and winters here	- Northern Hudson Bay-Davis Strait Atlantic walrus - Eastern Hudson Bay beluga
Eastern Hudson Bay Coastline			
-	-	- Migration pathway for eastern Hudson Bay beluga	- Eastern Hudson Bay beluga

Important Bird Areas (IBAs) are sites that have been identified based on their significance to threatened birds, large aggregations, or birds with restricted habitats. Numerous IBAs have been identified across the HBME with 3 in Foxe Basin, 8 in James Bay (which comprise a substantial portion of the coastline) and 27 within Hudson Bay, in particular along the southwestern coast (Bird Studies Canada 2015; see Figure 4.8). Table 4.5 describes each of these IBAs including the important bird aggregations which they support. For geospatial data on conservation areas in the HBME, see the Canadian Protected and Conserved Areas Database (Government of Canada 2020). The James Bay coastline and the southwestern coast of Hudson Bay are critical habitat for black scoters (*Melanitta nigra*) as approximately 50% of the breeding population of the entire species is known to moult here. Digges Sound in northeastern Hudson Bay maintains two substantial thick-billed murre colonies (26% of the Canadian population) and East Bay in Southampton Island has the largest eider breeding colony in the Arctic (3% of the Canadian population). Mallory et al. (2019) identified key marine habitat sites throughout the Canadian Arctic that support at least 1% of the national population of marine birds. They found that only 1% of the current marine conservation areas (including migratory bird sanctuaries, national wildlife areas or national parks) overlapped with these identified sites. Recently designated marine conservation areas serve to increase marine bird habitat protections from only 1% to 13%. Continued research efforts, particularly through the use of telemetry, is crucial to understand how many of these species may adapt their land use in a changing Arctic (Mallory et al. 2019).

Table 4.5. Important Bird Areas within the HBME including their conservation status if protected. Ramsar sites are designated a Wetland of International Importance under the Ramsar Convention (Bird Studies Canada 2015)

Location	Important Bird Area	Bird populations of significance (Global, Continental or National)	Conservation Status
Foxe Basin			
Northwestern Foxe Basin	Foxe Basin Islands	snow goose, brant, Sabines gull, semipalmated sandpiper, black-bellied plover, American golden-plover, ruddy turnstone, red phalarope, white-rumped sandpiper	-
Southeastern Baffin Island	Great Plain of the Koukdjuak	snow goose	Migratory bird sanctuary, Ramsar site, Wildlife sanctuary
Southwestern Foxe Basin	Turton Island	common eider	-
Hudson Bay			
Southwestern Southampton Island	Boas River and Wetland	snow goose	Migratory bird sanctuary
Southampton Island, east of Coral Harbour	East Bay/Native Bay	Iceland gull, Ross's gull, snow goose	Migratory bird sanctuary
Northern Hudson Bay	Coats Island/Cape Pembroke	Iceland gull, Ross's gull	-

Location	Important Bird Area	Bird populations of significance (Global, Continental or National)	Conservation Status
Island at the opening into Hudson Strait	Fraser Island	common eider	-
North coast of Nunavik	Digges Sound	black guillemot, thick-billed murre	-
Northeastern Hudson Bay	Awrey Island	common eider	-
Western coast	McConnell River	Ross's goose, snow goose,	Migratory bird sanctuary, Ramsar site
	Seal River Estuary	black scoter, buff-breasted sandpiper, pectoral sandpiper	National heritage river
	Churchill & Vicinity	black scoter, buff-breasted sandpiper, little gull, loggerhead shrike, red-throated loon, Ross's gull, ruddy turnstone, rusty blackbird, snow goose, whimbrel	Overlaps with Wapusk National Park
	Nelson River Estuary and Marsh Point	Hudsonian godwit, red knot, rusty blackbird	-
Southwest coast	Pen Islands	Hudsonian godwit, black scoter, red knot	Recommended to be part of the Western Hemisphere Shorebird Reserve Network
Southwestern coast	Kaskattama River Mouth	cackling goose, Hudsonian godwit	Wildlife management area
	Niskibi Cape	black scoter, snow goose	-
	Severn River Coastline	yellow rail	-
	Shagamu River & Coastline	black scoter, Hudsonian godwit, pectoral sandpiper	Overlaps with Polar Bear Provincial Park
	Winisk River and Estuary	snow goose	Overlaps with Polar Bear Provincial Park
	Sutton River Coastline	pectoral sandpiper	Overlaps with Polar Bear Provincial Park
	Cape Henrietta Maria	brant, pectoral sandpiper, snow goose	Overlaps with Polar Bear Provincial Park
Part of the Belcher Islands in southeastern Hudson Bay	South Flaherty Islands	common eider	-
Southeastern Hudson Bay	North Belcher Islands	common eider	-
	Salikuit Islands	common eider	-
	Sleeper Islands	common eider	-
Southeastern coast	Grande rivière de la Baleine	harlequin duck	-

Location	Important Bird Area	Bird populations of significance (Global, Continental or National)	Conservation Status
	Petite rivière de la Baleine	harlequin duck	-
	Rivers of the Lac Guillaume-Delisle Basin	harlequin duck	-
	Rivière Nastapoka	harlequin duck	-
Eastern coast	Koktac River Archipelago	common eider	-
James Bay			
Western coast	Ekwan to Lakitusaki Shores	black scoter, pectoral sandpiper, red-throated loon, semipalmated sandpiper, snow goose	Overlaps with Polar Bear Provincial Park
	Akimiski Strait	brant, cackling goose, snow goose	-
	Albany River Estuary and Associated Coastline	black scoter, brant, dunlin, greater yellowlegs, Hudsonian godwit, semipalmated sandpiper, white-rumped sandpiper	-
Western James Bay	Akimiski Island	brant, marbled godwit, semipalmated sandpiper, snow goose	Migratory bird sanctuary
Southern coast	Pei lay sheesh kow	American black duck, black scoter, brant, dunlin, greater yellowlegs, Henslow's sparrow, Hudsonian godwit, little gull, loggerhead shrike, long-tailed duck, pectoral sandpiper, peregrine falcon, red knot, red-throated loon, rusty blackbird, semipalmated sandpiper, snow goose, white-rumped sandpiper	Migratory bird sanctuary, Ramsar site, Western Hemisphere Shorebird Reserve Network; Overlaps with Tidewater and Kesagami Provincial Parks
	Miinshtuk-Wiinebek	brant, little gull, rusty blackbird, semipalmated plover	-
Northeast coast	Northeast James Bay Coast	black guillemot, black scoter, brant, semipalmated plover	-
Central James Bay	Twin Islands	Semipalmated plover	James Bay Preserve, Wildlife sanctuary

Figure 4.8. Key habitat sites and Important Bird Areas within the HBME. These sites support important bird aggregations or at least 1% of the Canadian population of a species (adapted from Oceans North et al. 2018)

4.1.8 Primary productivity

Identification and characterization of the ice algal and phytoplanktonic communities of the HBME has not advanced as rapidly as the rest of the Arctic. Within the HBME and Hudson Strait, 586 phytoplankton taxa (including sympagic species who sank into the water column during ice melt) have been identified: diatoms (281 taxa), dinoflagellates (150 taxa) and a smaller number of chlorophytes, choanoflagellates, chrysophytes and prasinophytes (Archambault et al. 2010). However, this number may be an underestimate of the diversity of the HBME due to low sampling effort. Very little research has been conducted on the primary productivity of macrophytes, such as macroalgae and eelgrass, in the HBME. James Bay has many highly productive eelgrass beds, that despite being in decline, their contributions to overall productivity have not been measured (Stewart and Lockhart 2005). Primary productivity is influenced by many factors, with the taxonomy of the plankton species being an important biotic component (Lapoussière et al. 2009).

The primary productivity of the sympagic community (comprised of organisms that temporarily inhabit the sea ice) is a necessary consideration in an Arctic ecosystem that is ice covered for much of the year. Despite having an overall lower primary productivity than planktonic algae, there are estimates that ice algae contribute up to 40% of total primary production in Hudson Bay (Dupont 2012). The biomass in fast ice is generally found to be higher than pack ice but has a lower overall rate of photosynthesis. It is likely that this disparity is due to higher grazing rates occurring in the pack ice (Arrigo 2016). Water column stability, tidal mixing, freshwater runoff and ice melt all influence the primary production of ice algae (Gosselin et al. 1990). Light is the initial limiting factor for the ice algal bloom, with the post-bloom being characterized by nutrient limitations. Nitrogen is the limiting nutrient in the Arctic and nutrient renewal to ice algae comes from the water column via upwelling and tidal currents (Dalman 2018). River runoff into the HBME also impacts taxonomy and primary productivity which often varies across salinity gradients. Ice algae often experience osmotic stress accompanying decreases in salinity that results from freshwater runoff. This has implications resulting from hydroelectric projects that alter river outputs throughout the year (Archambault et al. 2010).

Similar abiotic factors influence the phytoplankton bloom with temperature, sea ice cover and light being the primary factors (Harrison and Cota 1991). The phytoplankton bloom starts after the ice algal bloom (May - June) and lasts until August – September. The bloom is instigated, in part, by adequate irradiance reaching the water column which is dependent on ice thickness. This creates a temporal gradient along western to eastern Hudson Bay with the bloom commencing first in the western side of the bay where ice cover is comparatively reduced (Sibert et al. 2011). The stratification of the HBME, particularly in the eastern side of the bay during and after the spring freshet, limits nutrient availability to phytoplankton in the euphotic zone (surface layer in which photosynthesis occurs), therefore, tidal mixing, upwelling and riverine inputs are important sources of nutrients for the spring phytoplankton bloom (Heikillä et al. 2014). Phosphate and nitrate are imported into the oligotrophic (low levels of nutrients) waters of the HBME through the Hudson Strait to restore nutrients to the nitrate-limited offshore waters and the phosphate-limited estuaries (Kuzyk et al. 2008; Lapoussière et al. 2013). There is also some indication that silica levels are a limiting factor, particularly for diatoms, which is required for frustule (silica cell wall) development. By late summer, increased and consistent solar radiation creates more ideal photosynthetic conditions further down the water column, therefore, much of the primary production occurs at a subsurface maximum in proximity to the nutricline (layer of the ocean in which nutrient concentrations decline rapidly with depth) at 30 – 60 metres (Sibert et al. 2011; Schuback et al. 2017).

Estimates of primary productivity and chlorophyll *a* biomass vary significantly across independent studies (Table 4.6). Figure 4.9 demonstrates the spatial-temporal differences found in chlorophyll *a* biomass (Chl *a*) throughout the year across the HBME and Hudson Strait as modelled by Sibert et al. (2011). Most estimates of primary productivity in the HBME do not include ice algae or the spring algal bloom. Ferland et al. (2011) estimated total primary production at 24 Mt C yr^{-1} (not including ice algae or spring bloom) in Hudson Bay, which is higher than the total areal production for the Canadian Archipelago at 5 Mt C yr^{-1}, likely due to the increased tidal mixing and irradiance found in the HBME. Small planktonic cells have been identified as contributing disproportionately

Table 4.6. Summary of measurements of primary productivity (mg C m^{-2} d^{-1})†, volumetric chlorophyll *a* biomass (mg Chl *a* m^{-3})‡ and chlorophyll *a* biomass per unit area (mg Chl *a* m^{-2}) in Hudson Bay and Foxe Basin sea ice, water column and the Churchill estuary.

Source	Location	Study Months	Primary Production (mg C m^{-2} d^{-1})	Biomass (mg Chl*a* m^{-3})	Biomass (mg Chl*a* m^{-2})
Hudson Bay					
Roff & Legendre (1986)	Water column	-	96	0.04 – 1.1	-
Roff & Legendre (1986)	Sea ice	-	27	-	-
Welch et al. (1991)	Sea ice	April – May	-	-	170
Kuzyk et al. (2008)	Churchill estuary	May (peak river flow)	-	<0.3 – 1.4	-
Kuzyk et al. (2009)	Sea ice/water column	-	137 – 192	-	-
Ferland et al. (2011)	Water column	Aug - Sept	320 (236-486)	-	30 (26-38)
Lapoussière et al. (2013)	Water column	Sept – Oct	435	-	-
Foxe Basin					
Irwin et al. (1983)	Water column	Aug – Sept	-	0.23 – 2.14	-
Ferland et al. (2011)	Water column	Aug - Sept	370 (279-489)	-	61 (35-87)
Lapoussière et al. (2013)	Water column	Sept – Oct	70	-	-

†milligrams carbon per square metre per day
‡milligrams chlorophyll *a* per cubic metre

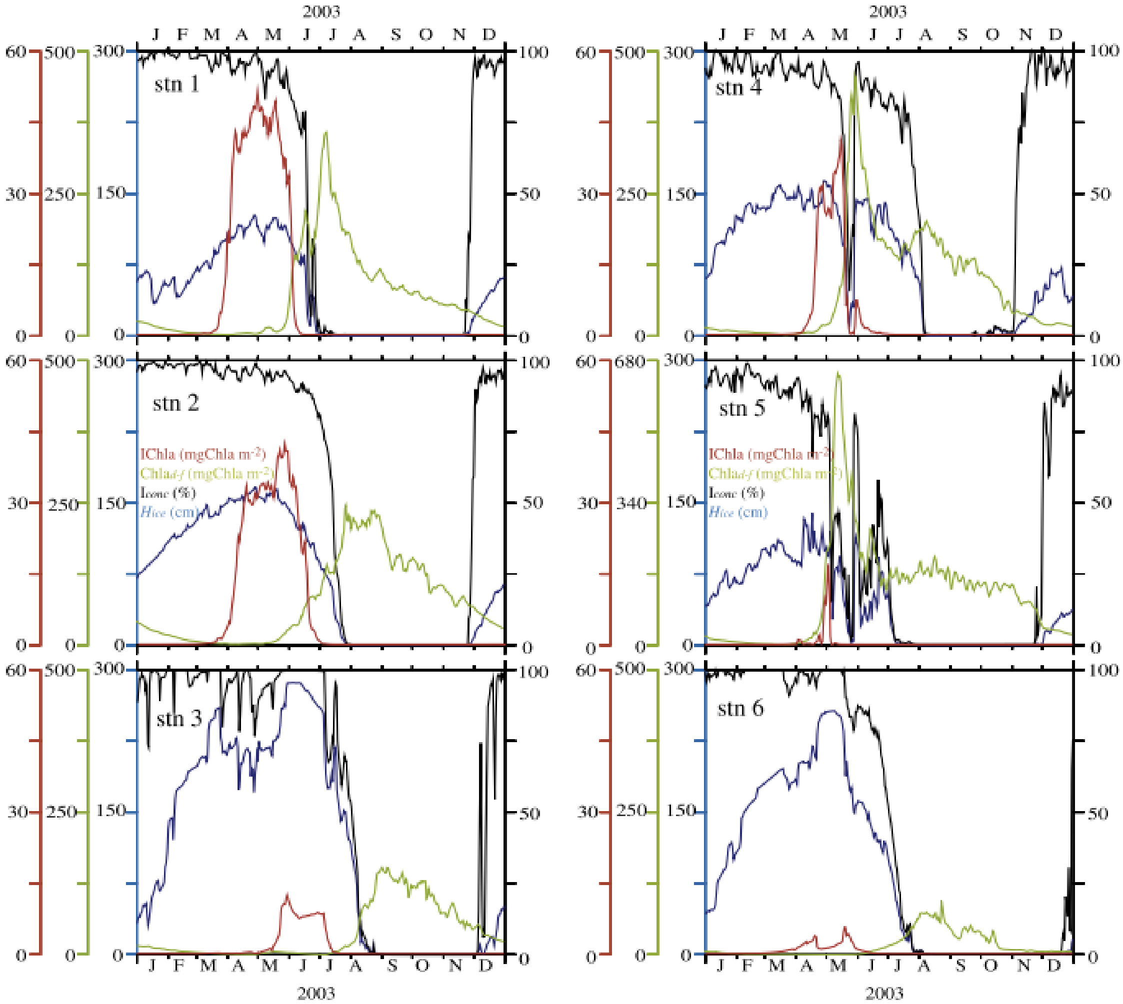


Figure 4.9. Chlorophyll *a* biomass estimates (mg Chl*a* m^{-2}) of ice algae (red) and plankton (green) along with sea ice coverage (black) and thickness in cm (blue) for western Hudson Bay (HB; Stn 1); central HB (Stn 2); eastern HB (Stn 3); southern Foxe Basin (Stn 4); western Hudson Strait (Stn 5) and James Bay (Stn 6) (Sibert et al. 2011, p. 412).

to the overall productivity, whereas diatoms, due to their large size, make up a significant portion of carbon exports to the benthic zone (Lapoussière et al. 2013). Kuzyk et al. (2009) report new production values (the rate of organic carbon exported downward from the euphotic zone) of 25 to 35 grams of carbon per square metre per year (g C m^{-2} yr^{-1}) which comprises approximately 50% of total primary production in Hudson Bay. Particulate organic carbon (POC) is estimated to make up 80% of new production and 20% is estimated to be dissolved organic carbon (DOC) annually.

4.1.9 Benthos

The benthos in the HBME has received little research effort, even in comparison to other habitats in the region. However, more recent research has been carried out by ArcticNet researchers and the Canadian Healthy Oceans Network within the last decade. Fisheries and Oceans Canada also collects data on the benthic community through analysis of research trawl bycatch (Kenchington et al. 2011). Hudson and James Bay have been identified as having the lowest taxonomic richness in the Canadian Arctic, with 789 benthic species having been described in the HBME, as compared to 1,151 species in the Canadian Arctic Archipelago. Of these 789 classified species, arthropods were the most abundant, followed by polychaetes, then molluscs. (Archambault et al. 2010; Jørgensen et al. 2017). The coastal benthic region in Hudson Bay provides habitat for many invertebrates such as sea spiders, clams, shrimps, crabs, and bryozoans, while echinoderms, polychaetes, sea anemones, and decapods dominate the interior of the bay (Stewart and Lockhart 2005). While taxonomic diversity of the HBME itself is low, its sub-regions are distinct from one another. Hudson Strait has been identified as an ecologically significant area with high concentrations of cold-water sponges and corals. However, these concentrations do not appear to extend into the HBME. Hudson Strait also has a more diverse benthic infaunal community than that of Hudson Bay. Within Hudson Bay itself, the western side is less diverse than that of the east, although overall abundance has been observed to be higher (Kenchington et al. 2012).

The primary productivity of the benthic zone in the HBME is broadly undefined. Hudson Bay supports 81 species of macroalgae, while James Bay has 47 identified species. The lower numbers in James Bay are likely due to high freshwater discharge and ice scouring (Darnis et al. 2012). Ulvoid green algae dominate the ecosystem, while two ubiquitous cosmopolitan species, *Ascophyllum nodosum* and *Fucus vesiculousus*, are notably absent. Some species, such as *Spyridia filamentosa*, have been identified in James Bay which represents a northern extension of their range. Migrating waterfowl may have introduced fragments of this algae into James Bay where it can now succeed due to warming waters. *Dumontia contorta*, an introduced species from Europe, has also been identified in James Bay (Mathieson et al. 2010). Eelgrass beds found in southwestern Hudson Bay and eastern James Bay help form the foundation of the food chain in James Bay. They provide habitat for molluscs, annelids, cnidarians, bryozoans and nursery grounds for sculpin, Greenland cod and lake trout (Stewart and Lockhart 2005).

A connection between the sea ice and the benthos of the HBME has been established. The loss of pack-ice will result in a reduction of carbon exports to the benthos having a negative impact on the benthic community (Archambault et al. 2010). Many benthic invertebrates (e.g. polychaetes, pelecypods and gastropods) spend their larval stage as allochthonous sympagic species. Benthic organisms may also colonize the sea ice if the distance between the ice and benthos is generally less than 70 metres (Gulliksen and Lønne 1991). Continuous benthic monitoring in the HBME would allow for the sympagic-benthic coupling to be better described in this region.

4.1.10 Keystone species

The term “keystone species” has been a valuable concept for ecologists, with keystone species continuing to be identified in the literature every year. However, there has been discussion about what the functional definition of this term is and how it should be used. Originally defined as a species that maintains biodiversity in the system through top-down action by consuming species that would otherwise come to dominate the system (Garibaldi and Turner 2004), current usage in the literature implies a keystone species is one that has discernable importance for maintaining the stability of the ecosystem (Cottee-Jones and Whittaker 2012). Quantitatively establishing that the impact of the species is disproportionate to its biomass is very difficult, which is one of the inherent limitations to the original definition. As such, this section will rely upon the definition used in current literature, as well as stated in Chapter 3, to discuss three keystone species of the HBME: ringed seal, Arctic cod and lesser snow goose (*Chen caerulescens caerulescens*). There is little information in the literature about what species might be keystone species in the HBME and often those that are described as keystone species do not provide substantial justification for the application of the term. However, each of the three species adhere to the generalized literature usage of the term keystone species and therefore will be described here. For information on keystone species within Indigenous food webs, see section 3.3. In the appendices of Stewart and Lockhart's (2005) overview of the HBME, there are lists of the reported macro species that inhabit the HBME.

Ringed seal

The ringed seal is the most abundant pinniped species found in the Arctic (Chambellant et al. 2013), with Hudson Bay making up the most southern part of its range. There is limited knowledge about ringed seals that is specific to Hudson Bay, with some research on their diet that is particular to the region (Chambellant 2010). As noted in section 3.3.1, documented Inuit Knowledge of seals in the HBME is very limited, however, in documented Inuit Knowledge of sea ice, it becomes clear that Knowledge is extensive regarding the ringed seal including understanding preferences for different ice conditions based upon the age of the seal (Laidler 2007). Polar bears are their main predator (Reeves 1998), but Arctic foxes (*Vulpes lagopus* Linnaeus 1758) have also been known to predate on them, particularly the seal pups (Luque et al. 2014). They are a monomorphic (sexes are similarly sized), capital-breeding (reproduction uses stored energy rather than simultaneous energy intake) species that is known to supplement by foraging during their lactation period and are reliant upon fast ice for breeding (Ferguson et al. 2005).

Despite being named as a keystone species in numerous papers, there are no explicit explanations given for this term being applied. However, the ringed seal is an abundant predator of many different fish species (capelin, sand lance, occasionally Greenland cod, sculpin and Arctic char), as well as another keystone species, Arctic cod. They provide a top-down control on Arctic cod and therefore influence the HBME ecosystem. Research specific to ringed seals in Hudson Bay shows that capelin and sand lances are a large portion of their diet, rather than Arctic cod. However, this is possibly due to regime shifts that are taking place within the HBME, which are further discussed in section 4.1.4 (Chambellant 2010).

Arctic cod

These small (<200 mm) fish live for approximately three to seven years and are often found near ice edges where they can also seek refuge under the pack ice as well as occasionally schooling near icebergs and in the open water (Harter et al. 2013). Arctic cod are responsible for 75% of energy moving from lower trophic levels to upper trophic levels in the circumpolar Arctic (Fortier 2012). Therefore, acting as a crucial link in the food web and providing substantial amounts of energy transfer between different trophic levels designates Arctic cod as a keystone species. Despite its prominence in Arctic food webs, little research has been conducted on Arctic cod, including its possible top-down influence on zooplankton abundance (Bouchard et al. 2015) and documented Inuit Knowledge is also lacking.

Research by Gaston and Elliot (2014) on the diets of thick-billed murre chicks indicated a shift from Arctic cod to capelin occurring over 33 years (1981 to 2013). This is a symptom of warming waters and changing ice conditions which may cause a polar specialist such as Arctic cod, reliant upon sea ice, to be outcompeted or displaced within the food web by a temperate generalist such as capelin (Fortier 2012). Laboratory studies indicate that Arctic cod are able to acclimate to 6.5ºC water temperatures, but this was accompanied by a decline in cardiorespiratory performance, which indicates limited potential for acclimation to warming waters (Drost et al. 2016). The loss of Arctic cod in the HBME may have significant ramifications as they are one of the most energy-rich prey species and this could reduce the foraging efficiency of many predators (Harter et al. 2013).

Lesser snow goose

This waterfowl has been described as a keystone species by Kerbes et al. (1990) because of the impact its grazing has on the plant community of brackish marshes. Lesser snow geese nest along the western Hudson Bay lowland, primarily around McConnell River, to breed during the months of May and June. During early spring they grub for roots and rhizomes which can reduce the vegetative cover to barren ground. *Puccinellia phryganodes* and *Carex subspathacea* are the primary species in these marshlands and, due to their clonal reproductive strategies, are unable to recolonize the bare ground, which leads to a displacement of the plant community. The number of breeding pairs of lesser snow geese are increasing along western Hudson Bay which is causing an overall loss of vegetation. This will have impacts on other marine birds and animals that access the saltmarshes for foraging, although the authors do not describe explicitly which animals will be impacted and how (Kerbes et al. 1990). Berkes and Fikret (1994) describe the lesser snow goose as dominating the fall waterfowl hunt of the Omushkego Cree in western James Bay with 88 000 kilograms per year harvested in the 1990 bush harvest indicating its importance to these communities.

4.2 ESTUARINE HABITAT (RIVERINE-COASTAL DOMAIN)

The drainage basin for the entire Hudson Bay Complex, including Hudson, James and Ungava Bays as well as Hudson Strait and Foxe Basin stretches across five Canadian provinces and one territory (Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and Nunavut) as well as into five American states (Montana, North Dakota, South Dakota, and Minnesota) covering a total area of 3.7×10^6 km^2 (Déry et al. 2005). The drainage area for the HBME is slightly smaller at 2.75×10^6 km^2, from which approximately 760 km^3 of river runoff enters the Hudson and James Bays annually (Macdonald and Kuzyk 2011) with higher runoff rates occurring on the eastern side of the bays.

Table 4.7 provides data derived from Déry et al. (2005) on 35 rivers that flow into the HBME as well as discharge rates and contributing drainage areas. 60% of freshwater input (342.52 km^3 yr^{-1}) originates from the seven largest rivers and the remaining 40% comes from the 28 smaller rivers. The freshwater runoff also has a significant impact on the circulation of the HBME contributing to the cyclonic movement of its waters as seen in Figure 4.2 (Stewart and Barber 2010).

Table 4.7. List of the top 35 rivers that flow into the HBME ranked according to their annual discharge, with associated outlet province or territory, contributing area, and peak flow from meltwater based on 1964–2000 data (after Déry et al. 2005) © American Meteorological Society. Used with permission.

	River	Outlet	Province/ territory	Discharge (km^3 yr^{-1})	Contributing area (km^2)	Peak flow (m^3/s)
1	Nelson	HB	MB	94.24	1,125,520	4,110.3
2	La Grande	JB	QC	66.57	96,600	4,961.7
3	Chesterfield Inlet[a]	HB	NU	48.52	259,979	6,616.9
4	Moose	JB	ON	40.00	98,530	7,459.5
5	Nottaway	HB	QC	32.30	57,500	2,784.4
6	Eastmain	JB	QC	31.20	44,330	3,266.7
7	Albany	JB	ON	30.69	118,000	4,368.7
8	Rupert	JB	QC	26.65	40,900	1,328.5
9	Severn	HB	ON	21.20	94,300	1,983.0
10	Churchill	HB	MB	20.57	288,880	1,320.1
11	Grande rivière de la Baleine	HB	QC	19.77	43,200	1,735.7
12	Hayes	HB	MB	18.62	103,000	1,944.1
13	Winisk	HB	ON	14.69	54,710	1,561.6
14	De Puvirnituq (previously de Povungnituk)	HB	QC	11.63	28,000	869.8
15	Seal	HB	MB	11.19	48,100	936.8
16	Attawapiskat	JB	ON	11.08	36,000	1,315.7
17	Harricana	JB	QC	10.92	21,200	1,721.1
18	Broadback	JB	QC	9.94	17,100	768.1
19	Nastapoka (previously Nastapoca)	HB	QC	7.86	12,500	483.3
20	Thlewiaza	HB	NU	6.92	27,000	334.5
21	Tha-anne	HB	NU	6.17	29,400	1,049.9

	River	Outlet	Province/ territory	Discharge (km^3 yr^{-1})	Contributing area (km^2)	Peak flow (m^3/s)
22	Kogaluc	HB	QC	4.88	11,300	485.1
23	Chanel Goulet[b]	HB	QC	4.49	5,970	289.6
24	Roggan	JB	QC	3.98	9,560	551.8
25	Petite rivière de la Baleine	HB	QC	3.74	11,700	288.9
26	Innuksuac	HB	QC	3.25	11,200	295.2
27	Pontax	JB	QC	3.15	6,090	500.1
28	Ekwan	JB	ON	2.76	10,400	611.0
29	Lorillard	HB	NU	2.64	11,000	1,131.5
30	Ferguson	HB	NU	2.59	12,400	413.8
31	Opinaca	JB	QC	2.25	3,700	263.2
32	Kirchoffer	HB	NU	0.84	3,160	491.7
33	Boutin	HB	QC	0.64	1,390	74.2
34	Brown	HB	NU	0.52	2,040	240.6
35	Diana	HB	NU	0.30	1,460	56.6

[a] Combined Thelon and Kazan Rivers

[b] Known as Le Goulet or Tursujuaq, a channel connecting the brackish Lac Guillaume-Delisle or Tasiujaq (previously named Richmond Gulf) with Hudson Bay

The physical (e.g. temperature and density), chemical (e.g. salinity) and biological (e.g. nutrients and contaminants) properties of the HBME waters are all influenced by riverine inputs (Déry et al. 2018). This includes contaminants such as mercury, of which rivers are a significant contributor, such as the Nelson and Churchill Rivers which annually export 113 ± 52 and 37 ± 28 kg of mercury into Hudson Bay (Kirk and St. Louis 2009). Kirk and St. Louise (2009) hypothesize that the amount of mercury in the Churchill River is influenced by mercury export from the wetlands that make up a significant proportion of the lower Churchill drainage basin. Elevated concentrations of mercury were also linked to years with high rates of precipitation, and therefore high rates of flow, in both rivers. Reservoir creation from hydroelectric projects, such as those developed along both the Nelson and Churchill Rivers, also influences mercury cycling as inundated soils release stored mercury. The geology, sediments and vegetation in the environment through which each river runs will shape the amount of carbon, sedimentation and contaminants (such as mercury) that flow into the HBME. Dissolved organic carbon (DOC) is typically higher in southern rivers running through vegetated regions than northern tundra (Hudon et al. 1996). The southwest coast of Hudson Bay and much of the coastline of James Bay fall within the Hudson Plains ecozone, which is characterized by wetlands dominated by peat, known to be a major contributor of DOC (Godin et al. 2017). 5.5 teragrams per year (Tg yr^{-1}) of DOC is moved through rivers into Hudson Bay which is approximately 23% of the riverine total organic carbon (TOC) entering into the Arctic Ocean (Godin et al. 2017). The eastern coast of James Bay and southeast coast of Hudson Bay are within the Taiga Shield ecozone which is comprised of tundra with some tree cover and the northern coastline of Hudson Bay lies within the Southern Arctic, a shrub-herb tundra landscape (Wiken et al. 1996) For more information on the ecozones of the HBME refer to Chapter 2.

Figure 4.10 demonstrates the materials that comprise the coastline of the HBME developed using CanCoast, a geospatial database that can be used to analyze coastal data (Manson et al. 2019).

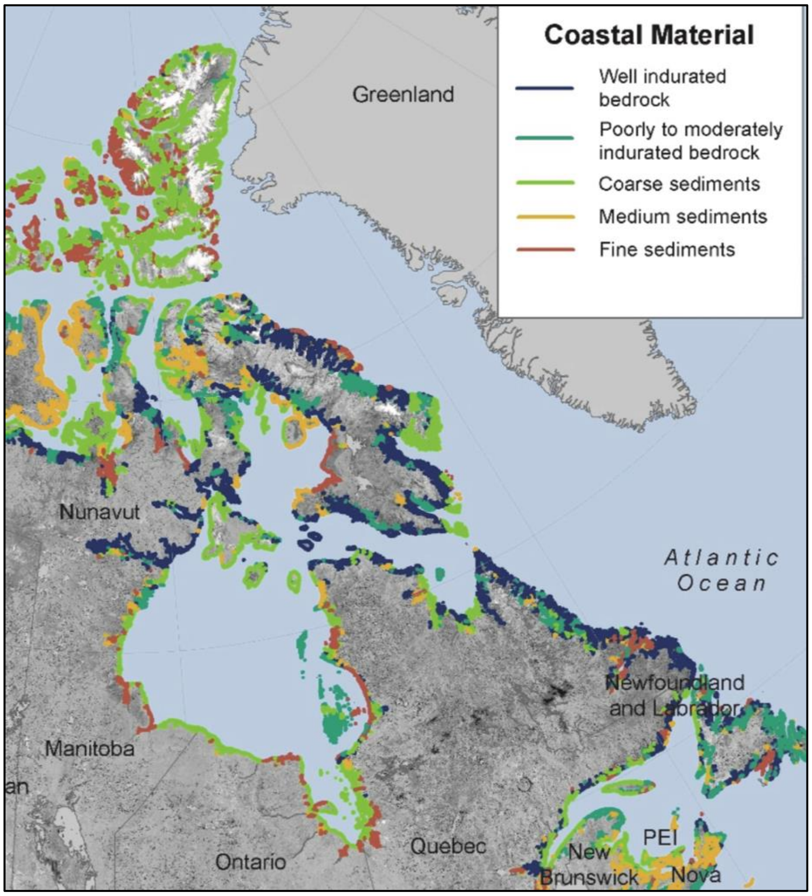


Figure 4.10. Materials that comprise the bedrock and surficial geology of Canada's coastlines, from CanCoast geospatial database. (Indurated refers to bedrock that has been hardened/consolidated through heating or cementing) (Manson et al. 2019, p. 10)

Estuaries are described as the changeover point from a freshwater to a marine system, located where a river meets the ocean (Schneider-Vieira et al. 1994). Estuaries are often classified based on how they are stratified or vertically mixed, which is a product of topography and tidal currents versus river flow. The river plume extends out from the mouth of the river on top of the denser, saline marine waters, extending further during the winter when there is ice cover (Stewart and Barber 2010). A saltwater intrusion flows upstream along the bottom with the distance also being determined by the relative strength of the river flow and tidal currents. While the estuaries in Hudson Bay are nutrient-poor by estuarine standards, in relation to the marine waters of the HBME, they are much more productive (Schneider-Vieira et al. 1994). Estuaries are unique as the conditions created by saltwater and freshwater mixing creates a range of salinities that can be tolerated by both freshwater and marine species. The stratification generates density gradients which can bring about concentrated aggregations of organisms such as phytoplankton or zooplankton (Baker et al. 1993). Anadromous fishes such as Arctic char also spend a significant amount of their time in estuarine habitats while in the marine environment (Harris et al. 2020).

One of the most significant determinants in the characteristics of an estuary is the freshwater input. The rivers of the HBME have a long history of development for hydroelectric projects and as of 2008, only 30% (<0.6x10^6 km^2) of the gauged area in the Hudson Bay basin can be considered naturally flowing (Déry et al. 2010). While the diversion of rivers and retention of waters for hydroelectric projects does not significantly change the annual outputs, the seasonality of the water flow does change, which contributes to a "flattening" of the hydrograph as seen in Figure 4.11 (Déry et al. 2011). The rest of this chapter section will focus on a number of significant HBME rivers and their estuaries (see Figure 4.12 for river locations).

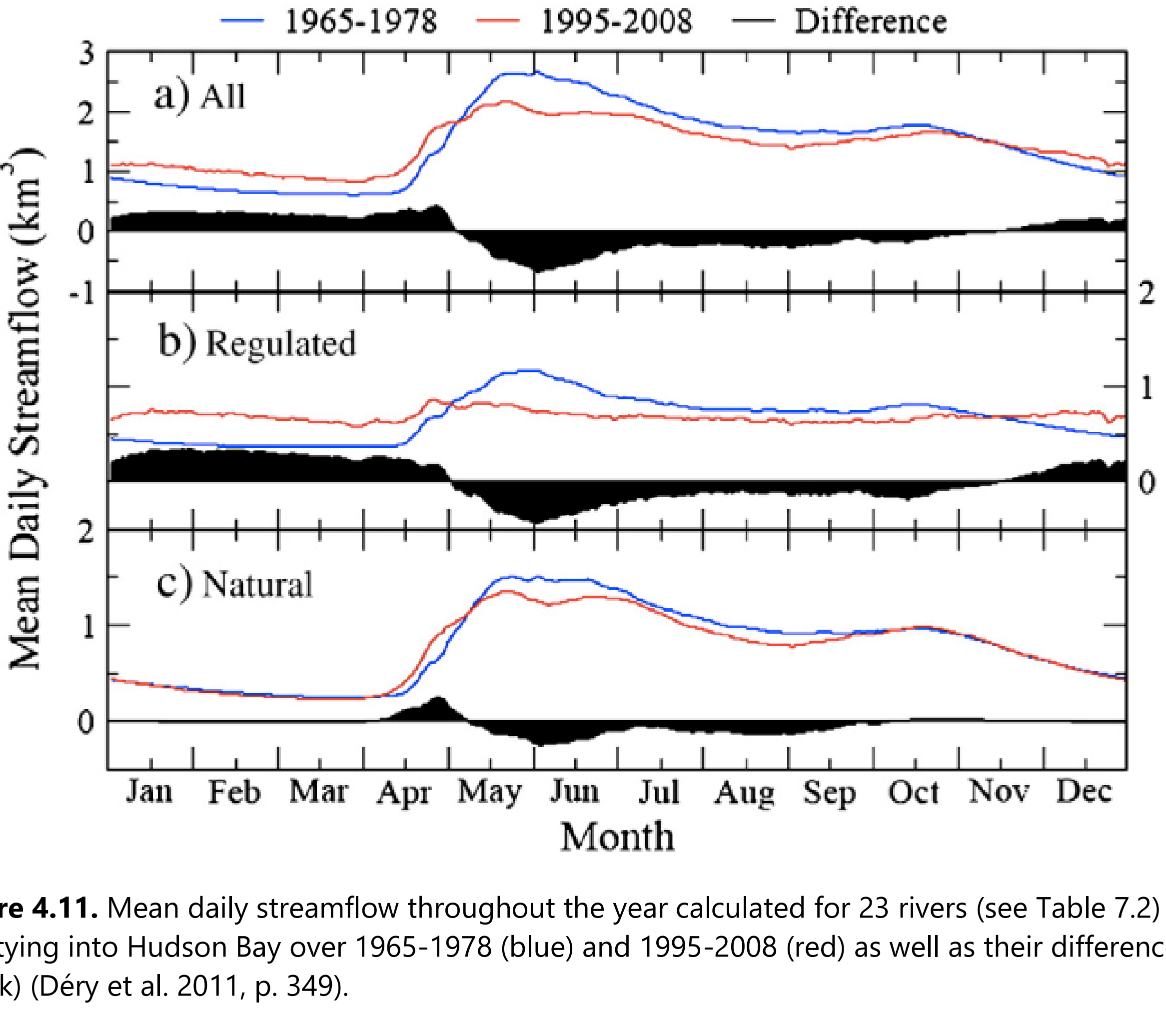


Figure 4.11. Mean daily streamflow throughout the year calculated for 23 rivers (see Table 7.2) emptying into Hudson Bay over 1965-1978 (blue) and 1995-2008 (red) as well as their difference (black) (Déry et al. 2011, p. 349).

Figure 4.12. Map of the drainage basin of Hudson Bay (inset - shaded in grey) and location of major rivers flowing into the bay (Déry et al. 2011, p. 343)

4.2.1 Chesterfield Inlet: Thelon River and Kazan River

Chesterfield Inlet drains into the northwestern Hudson Bay in Nunavut, not far from where Arctic waters inflow from Roes Welcome Sound. The Inlet itself is 220 km long, starting inland at Baker Lake, with a drainage basin of 290,000 km^2 (Budgell 1976). Two rivers, the Thelon River and Kazan River, meet in Baker Lake and flow down Chesterfield Inlet into Hudson Bay. Both are classified as Canadian Heritage Rivers, based upon meeting numerous heritage values (natural, cultural and recreational; DSD 2000). The headwaters of the Thelon River are northeast of Great Slave Lake in NWT and the river runs 940 km, moving from taiga through to tundra, into Baker Lake (Shaverdo and Giberson 2004). The Thelon River is considered a pristine wilderness river with importance for wildlife, in part due to its proximity to Thelon Wildlife Sanctuary, which provides calving areas for caribou along its corridor, habitat for the muskox and nesting and molting areas for Canada and lesser snow geese. Thelon River's 240,400 km^2 drainage basin is considered to be the largest unaltered basin to empty into Hudson Bay (DSD 2000; Grimwood and Doubleday 2013).

The Kazan River flows from Ennadai Lake in Nunavut, near the border with NWT, north towards Baker Lake (Gagnon and Gough 2002). Despite its heritage designation, minimal natural science research has been conducted there, although archaeological work has been more prevalent due to the region's importance for the Caribou Inuit who lived there year-round (prior to government resettlement) and relied primarily on caribou for subsistence (Friesen and Stewart 2004). Gagnon and Gough (2002) found that, since the mid-1960s, the Kazan River has been experiencing increasing streamflow at the Ennadai Lake outlet due to elevated amounts of precipitation.

As the waters of the Kazan and Thelon rivers enter into Chesterfield Inlet, they flow over a primarily rocky bottom that changes over to silt as the river mouth opens up into Hudson Bay. The Inlet was formed through glacial action and the walls that lead into the bay are made of granitic gneiss (a type of metamorphic rock) with a trench running east-west at approximately 100 m depth as the mouth (Budgell 1976). This is the largest naturally flowing river system into Hudson Bay (Déry et al. 2011). The estuary is vertically mixed at the mouth of the river and demonstrates constant nutrient concentrations throughout. Welch et al. (1991) found higher nitrate and chlorophyll *a* concentrations near the estuary than near Saqvaquac Inlet to the north (Welch et al. 1991). Research specific to the Chesterfield Inlet estuary is largely absent.

4.2.2 Nelson River

The Nelson River is the largest river by volume to enter into the HBME with a discharge rate of 94.24 km^3 yr^{-1}. During the winter, the Nelson River contributes as much as 34% of daily discharge for Hudson, James and Ungava Bays, although this diminishes during the spring and summer (Déry et al. 2005). The headwaters of the river are in the Canadian Rockies with the Assiniboine, Winnipeg and Red Rivers making up some of its tributaries. However, with hydroelectric development ongoing in northern Manitoba since the 1960s, the Churchill River was diverted into the Nelson River and six generation stations were developed along the Nelson River, with another (Keeyask) soon to be completed (Déry et al. 2018). The Churchill River was previously the fifth-largest river (by annual flows) into Hudson Bay with an annual discharge of approximately 37 km^3 yr^{-1}, which is now reduced to 20.57 km^3 yr^{-1} due its partial diversion. One third of the waters now flowing through the Nelson River are held over from summer and released in the winter, changing the amount of freshwater entering the estuary during the winter season. The Nelson River estuary no longer forms ice during the winter due to these increased flows (ArcticNet 2012).

As previously mentioned, southern rivers of the HBME that run through wetlands have high concentrations of particulate organic carbon (POC) and dissolved organic carbon (DOC). The Nelson River has DOC concentrations of 2-6 times greater than other rivers in the HBME system (Kazmiurk 2018). These inputs are important to quantify to understand the overall carbon budget of Hudson Bay (Kuzyk et al. 2010). Total dissolved solids, DOC and lignin (component of the cell wall of plants) concentrations were found by Godin et al. (2017) to be elevated in the Nelson River. These high concentrations could be influenced by the hydroelectric projects that have impacted this river. Increased dissolved organic matter, including DOC, can impact the function and composition of marine bacterial communities, possibly increasing bacterial respiration which can result in increased competition for inorganic nutrients (Traving et al. 2017). Satellite images indicate a turbid plume that extends 100 km from the mouth of the Nelson River (ArcticNet 2012).

The Nelson River estuary has been the subject of more research than most of the other estuaries of the HBME. The Nelson River empties along the southwestern shore of Hudson Bay along with the Hayes River, a smaller unregulated river to the east, which also contributes to the Nelson River estuarine characteristics (Guéguen et al. 2016). Baker et al. (1993) identify four physical zones of the partially stratified Nelson River estuary moving from river into marine environments: 1) freshwater, 2) a vertically mixed nearshore estuarine zone (salinity: 1-8 ppt), 3) a stratified zone between nearshore and offshore zones (8-20 ppt) and 4) an offshore estuarine zone which is also vertically mixed (>20 ppt). The width of each section varies with the tides and is compressed during high tide (up to 4.8 m). The Coriolis force (force resulting from the Earth’s rotation) causes the freshwater moving outward to flow along the south shore and the saltwater wedge to move in along the north (Baker et al. 1993).

This shallow, flat estuary, with a fine silt and clay bottom, is primarily less than 5 m in depth with a deeper channel of 8-30 meters depth running through the centre and is dominated by mudflats from the nearshore to offshore. The salt marshes and coastal plains that frame the estuary are crucial habitat for many of the more than 170 migratory bird species that annually return to the estuaries of southwestern Hudson Bay (Labun and Debicki 2018). This estuary is one of the most productive in Hudson Bay with the highest biomass of phytoplankton found in the nearshore part of the estuary and declining towards offshore, whereas zooplankton abundance and diversity, dominated by copepods, increased towards offshore. Fishes found in zones 1 and 3 were largely fresh or brackish water species: fourhorn sculpin (*Myoxocephalus quadricornis*), lake cisco (*Coregonus artedii*) and nine-spine stickleback (*Pugnitius pungitius*). Marine fishes such as sand lance, capelin and eelblenny (*Lumpenus fabricii*) were found in zones 2-4 (Baker et al. 1993). The Nelson River estuary is also the location of large beluga aggregations with a 2015 corrected (for availability bias) abundance estimate of 23,248 whales (CSAS 2017). It is unclear why belugas congregate in estuaries, although foraging, calving or utilizing the thermal advantage of warmer waters for their annual moult have all been suggested (Smith et al. 2017).

4.2.3 Hudson Bay Lowland: Albany and Moose Rivers

The Moose and Albany are two of the five large, shallow and slow-moving rivers that flow through the Hudson Bay Lowland, identified as the biggest continuous peatland expanse in the world. The influence of the glacial history of the Lowlands can be seen in the glacial till deposits that, along with marine and fluvial till deposits, make up the sediments of this region. However, they are covered in a peat layer that can extend up to 200 m in depth (McCrea et al. 1984). The Albany River is 982 km long and cuts through the plains of the Lowlands to empty out into the western side of James Bay. Its most substantial tributary is that of the Kenogami River. Three of the headwater regions (Lake St. Joseph, Ogoki Reservoir and Long Lake) of the Albany have been diverted for hydroelectric developments causing a reduction in annual discharge by 17% Marshall and Jones 2011).

The Moose River empties out along the tidal flats of southern James Bay, northeast of the community of Moosonee (Desroches et al. 2010). The river and its tributaries have become highly fragmented by more than 40 dams and water control structures along its 547 km length which generate more than 1000 MW of power (Déry et al. 2011; Marshall and Jones 2011; Heerschap 2018). Two of the tributaries, the Matagami and Abitibi Rivers, had 10 generating stations established along them by the 1910s, while the rest have been mostly built since the 1960s. The long industrial history of this river, not only hydroelectric projects but also pulp and paper mills, has degraded the benthic community of the riverbed and negatively impacted its water quality (Chiasson et al. 1997).

Little specific research on the Albany or Moose River estuaries was found. However, both estuaries were designated as critical birding areas by the Canada Wildlife Service with coastal marsh lining the mouth of both rivers (Martini and Morrison 1980). Anadromous fishes such as lake whitefish, cisco and brook trout (*Salvelinus fontinalis*) inhabit both estuaries (Heerschap 2018). Lake sturgeon (*Acipenser fulvescens*) have been traditionally found throughout the watersheds of northern Ontario but are now absent throughout much of their former range. COSEWIC has listed lake sturgeon as a species of special concern in northeast Ontario (MNR 2009). As primarily benthic foragers, water quality and other factors that impact benthic organisms have a large effect on lake sturgeon.

4.2.4 Rivière Nottaway

Nottaway River empties into Rupert Bay, a 60 by 20 km embayment, in southern James Bay along with other smaller rivers (Broadback, Rupert and Pontax rivers). The Nottaway-Broadback-Rupert rivers were scheduled for hydroelectric development. However, the project was eventually discarded in favour of the La Grande project due to the unstable glacial clay soils of these rivers (Prinsenberg 1980). Strong tidal currents ensure a vertically well-mixed estuary with a chlorophyll maximum found at the freshwater zone slightly upstream from the saltwater intrusion (De Sève 1993). There was limited information available to be reported on for the Nottaway River.

4.2.5 La Grande Rivière

The La Grande Rivière headwaters are found in north-central Québec and flow 800 km into eastern James Bay. The 9.7×10^4 km^2 drainage basin encompasses the Sakami, de Pontois, Kanaaupscow and Laforge rivers, which are major tributaries of the La Grande Rivière (Hernández-Henríquez et al. 2010; Déry et al. 2018). Prior to hydroelectric development, La Grande Rivière contributed 28% of the riverine outflow into James Bay (Grainger et al. 1976). Phase I and Phase II of La Grande Complex hydroelectric development, completed in 1996, involved diverting 92% of Eastmain River’s outflow, 32% of the Caniapiscau River’s outflow and creating eight reservoirs through flooding approximately 10,800 km^2 of land. The decay of organic matter in the reservoirs has caused the formation of methylmercury which is magnified as it moves up through the trophic levels of the food web (Kuzyk and Candlish 2019). The winter flow of La Grande Rivière has increased eight-fold in the winter since the diversion of Eastmain and Opinaca Rivers with a plume that is three times larger than previously. Loss of critical James Bay waterfowl breeding habitats has also occurred with this development along with degradation of eelgrass beds which also negatively impact waterfowl (Chartrand et al. 1992; Kuzyk and Candlish 2019).

After the majority of the flow from the Eastmain River was diverted into La Grande Rivière, Lepage and Ingram (1986) reported that a few weeks later there was a substantial salt intrusion that entered the Eastmain River estuary and the collapse of the Eastmain River plume was also documented. In 2012, the completion of another phase of the project involved the diversion of the Rupert River into La Grande Rivière. Rupert Bay, where the Rupert River empties, experienced a reduction of 18% in river discharge and saltwater intrusions into the rivers also occurred (Kuzyk and Candlish 2019). The increased discharge in La Grande Rivière ensures that there are no saltwater intrusions into the mouth of La Grande Rivière. The La Grande Rivière estuary makes up the last 37 km of the La Grande Rivière as it flows along clay banks around its many sand islands. Previous to development, La Grande Rivière estuary was nutrient poor and by 1994, these concentrations had not changed substantially since the completion of Phase I of the complex (Schneider-Vieira et al. 1994). Monitoring of Hudson Bay rivers has declined in recent years, creating difficulties for understanding long-term effects of hydroelectric development in the region (Hernández-Henríquez et al. 2010).

4.2.6 Inputs of smaller rivers

Table 4.7 shows the discharge of 35 rivers that empty out into the HBME. 40% of the river outflow (233 km^3 yr^{-1}) is derived from a drainage area of 945,660 km^2 entering into the HBME from 28 smaller rivers (Déry et al. 2005). This drainage area totals 34% of the total drainage area for the HBME. Therefore, the smaller rivers contribute more to riverine inputs per square kilometer of drainage area than the top seven rivers. Little of this input occurs during the winter, but during the spring freshet and summer, there is sizeable runoff. Northern rivers more typically demonstrate this hydrograph including the Lorillard and the Tha-anne in Nunavut and the Arnaud and Aux Feuilles in northern Québec (Déry et al. 2005).

Déry et al. (2011) analyzed the interannual variability in streamflow input for 23 different rivers emptying into the HBME (for a list of these rivers, see Table 7.2). There was almost no clear demonstrable trend for the streamflow of the rivers as the negative and positive trends for each single river negated any overall trend. Smaller rivers can also be significant contributors of particulate inorganic matter (PIC), POC and DOC. As an example, the Grande rivière de la Baleine, in southeastern Hudson Bay, annually contributes 135,000 tonnes of PIC, 21,000 tonnes of POC and 90,000 tonnes of DOC with a discharge of only 19.77 km^3 yr^{-1} (Hudon et al. 1996). Sedimentation is also projected to increase alongside warming temperatures. Terrestrial organic matter flowing into Nastapoka Sound from the Nastapoka, Petite rivière de la Baleine and Grande rivière de la Baleine has exceeded marine organic matter deposition, increasing overall by 30%, since the Little Ice Age (Jolivel et al. 2015). Smaller rivers also provide important habitat for migratory birds such as the Attawapiskat River in Northern Ontario, due to its large area of coastal marshes (Glooschenko and Martini 1983). Many of these smaller rivers are currently unregulated by hydroelectric projects and continue to provide environmental conditions that allow for specific types of wetland and marsh development. These are crucial ecosystems for many fish species as well as waterfowl and other migratory bird species (Glooschenko and Martini 1983).

4.2.7 Estuarine food webs

The meeting of fresh and saline waters in estuaries creates stratified conditions that allow for high nutrient concentrations to be entrained within the density gradients, producing pockets of high phytoplankton biomass (Baker et al. 1993). Estuarine food webs often have two sources for the base of the food chain: river-based detritus and autochthonous (from within the estuary) phytoplankton (Schneider-Wieira et al. 1994). The Nelson River estuary is likely the most well-studied with regards to estuarine food webs in Hudson Bay. Nutrient concentrations within this estuary have been found to be highest in the offshore estuarine zone with phytoplankton diversity and abundance decreasing from inshore to offshore. Zooplankton abundance and diversity increased from inshore to offshore with calanoid copepods comprising 97% of all zooplankton found. These trends are likely a function of salinity, as most of the phytoplankton species identified were freshwater, while the zooplankton tended to be mostly marine species (Baker et al. 1993). While estuarine food webs retain many unique characteristics, there are similarities with marine food webs, as the ice algal bloom is still an important source of primary productivity in estuaries (Schneider-Wieira et al. 1994).

The elevated productivity of estuaries in comparison to surrounding marine waters supports high numbers of upper trophic level consumers. Anadromous fish species, such as cisco, are often found in estuaries and may even overwinter there (Reist et al. 2007). Greendale and Hunter (1978) analyzed the diets of fishes in the La Grande Rivière estuary finding that many fish will opportunistically feed on larval or adult insects (e.g. Notonectidae or backswimmers, a family of aquatic insects, and Coleoptera or aquatic beetles) that enter the estuary from the river. Smaller marine or estuarine fishes such capelin, sand lance and eelblennies are typically consumed by larger anadromous fishes such as ciscoes, brook trout and lake whitefish, although the latter is often considered a bottom feeder. Estuaries are an environment where freshwater and marine food webs meet and interact, particularly as many of these anadromous fishes will later move back upstream to freshwater environments.

Belugas are well known for spending their summers in estuaries of the HBME, in particular that of the Churchill, Seal and Nelson Rivers. 55,000 belugas, comprising 28% of the global population, migrate to southwestern Hudson Bay estuaries (Labun and Debicki 2018). Though the reason for their presence in the estuaries is largely unknown, some researchers have suggested that they are there to forage. Belugas have been found to consume capelin (which spawn in estuaries), whitefish, decapods and occasionally Greenland cod (Sergeant 1973; Mikhail and Welch 1989; Baker et al. 1993). The upstream shallow water of estuaries may help provide a refuge from killer whales which have been known to move into estuary areas to predate upon belugas (Smith et al. 2017).

4.3 REFERENCES

Andrews J, Babb D, McKernan M, et al (2016) Climate Change in the Hudson Bay Complex: Opportunities and Vulnerabilities for the Port of Churchill's Marine Operations. The Centre for Earth Observation Science (CEOS), Winnipeg, Manitoba

Andrews JS, Babb D, Barber DG (2017) Climate change and sea ice: marine shipping access in Hudson Bay and Hudson Strait (1980 – 2014). Elem Sci Anth 5:15. https://doi.org/10.1525/elementa.130

Aporta C (2017) Shifting perspectives on shifting ice: documenting and representing Inuit use of the sea ice. Can Geogr 55:6-19

Aporta C, Macdonald J (2011) An elder on sea ice: an interview with Aipilik Inuksuk of Igloolik, Nunavut. 55:32–35. https://doi.org/10.1111/j.1541-0064.2010.00342.x

Archambault P, Snelgrove PVR, Fisher JAD, et al (2010) From sea to sea: Canada's three oceans of biodiversity. PLoS One 5:26. https://doi.org/10.1371/journal.pone.0012182

ArcticNet (2012). Pienitz R, Lemay M, Michaud J, Blasco K, Veillette J (Eds), Impacts of Environmental Change in the Canadian Coastal Arctic: A Compendium of Research Conducted During Arctic Net Phase I (2004-2008), Volume 2, 256pp. ArcticNet Inc., Quebec City, Quebec, Canada.

Arctic Eider Society (2020) SIKU: The Indigenous Knowledge Social Network. https://siku.org

Arctic Monitoring and Assessment Programme (AMAP) (2013) AMAP Assessment Report: Arctic Pollution Issues. Oslo, Norway xii + 859 pp.

Arctic Monitoring and Assessment Programme (AMAP) (2013) Identification of Arctic Marine Areas of Heightened Ecological and Cultural Significance: Arctic Marine Shipping Assessment (AMSA) IIc

Arrigo KR (2016) Sea ice as a habitat for primary producers. In: Thomas DN (ed) Sea Ice: Third Edition, Third Edit. John Wiley & Sons, Ltd., Stanford, pp 352–369

Azetsu-Scott K, Clarke A, Falkner K, et al (2010) Calcium carbonate saturation states in the waters of the Canadian Arctic Archipelago and the Labrador Sea. J Geophys Res Ocean 115:C11021. https://doi.org/10.1029/2009JC005917

Baker RF, Lawrence MJ, Schneider F (1993) Oceanographic and mid-summer distribution and abundance of plankton and fish in the Nelson River Estuary, Hudson Bay. Winnipeg

Barber DG, Massom RA (2007) The Role of Sea Ice in Arctic and Antarctic Polynyas. In: Smith WO, Barber DG (eds) Polynyas: Windows to the World, 1st edn. Elsevier Science Publishers, pp 1–54

Barber DG, Asplin MG, Raddatz RL, et al (2012) Change and variability in sea ice during the 2007-2008 Canadian International Polar Year program. Clim Change 115:115–133. https://doi.org/10.1007/s10584-012-0477-6

Bajzak CE, Bernhardt W, Mosnier A, Hammill MO, Stirling I (2013) Habitat use by harbour seals (*Phoca vitulina*) in a seasonally ice-covered region, the western Hudson Bay. Polar Biology 36:477–491

Beck G, Michael C, Smith TG (1993) Seasonal Variation in the Diet of Harp Seals (*Phoca groenlandica*) from the Gulf of St. Lawrence and Western Hudson Strait. Can J Fish Aquat Sci 50:1363-1371

Berkes F (1994) Wildlife harvesting and sustainable regional native economy in the Hudson and James Bay Lowland, Ontario. Arctic 47:350-360

Berkes F, Hughes A, George PJ, Preston RJ, Cummins BD, Turner J (1995). The Persistence of Aboriginal Land Use: Fish and Wildlife Harvest Areas in the Hudson and James Bay Lowland, Ontario. Arctic 48:81-93

Bird Studies Canada. 2015. Important Bird Areas of Canada Database. Port Rowan, Ontario: Bird Studies Canada. http://www.ibacanada.org

Bluhm BA, Gradinger R (2008) Regional variability in food availability for arctic marine mammals. Ecol Appl 18:77–96. https://doi.org/10.1890/06-0562.1

Bluhm BA, Hop H, Vihtakari M, et al (2018) Sea ice meiofauna distribution on local to pan-Arctic scales. Ecol Evol 8:2350–2364. https://doi.org/10.1002/ece3.3797

Bouchard C, Thorrold SR, Fortier L (2015) Spatial segregation, dispersion and migration in early stages of polar cod Boreogadus saida revealed by otolith chemistry. Mar Biol 162:855–868. https://doi.org/10.1007/s00227-015-2629-5

Budgell W Tidal Propagation in Chesterfield Inlet, N.W.T.

Cairns DK (1987) Diet and foraging ecology of Black Guillemots in northeastern Hudson Bay. Can J Zool 65:1257–1263

Campbell NJ (1959) Some Oceanographic Features of Northern Hudson Bay, Foxe Channel, and Hudson Strait

Campbell NJ (1964) The Origin of Cold High-Salinity Water in Foxe Basin. J Fish Res Board Canada 21:45–55. https://doi.org/10.1139/f64-006

Catchpole AJW, Ball TF (1981) Analysis of historical evidence of climate change in western and northern Canada

Chartrand N, Doucet J, Egré D, et al (1992) Lessons From Environmental Monitoring of the La Grande Complex-Phase 1*. Energy Explor Exploit 10:183–198

Chiasson WB, Noakes DLG, Beamish FWH (1997) Habitat, benthic prey, and distribution of juvenile lake sturgeon (Acipenser fulvescens) in northern Ontario rivers. Can J Fish Aquat Sci 54:2866–2871. https://doi.org/10.1139/cjfas-54-12-2866

Chambellant M (2010) Hudson Bay ringed seal: Ecology in a warming climate. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay, 1st edn. Springer, pp 137–157

Chambellant M, Stirling I, Ferguson SH (2013) Temporal variation in western Hudson Bay ringed seal Phoca hispida diet in relation to environment. Mar Ecol Prog Ser 481:269–287. https://doi.org/10.3354/meps10134

Chanona M, Waterman S, Gratton Y (2018) Variability of internal wave-driven mixing and stratification in the Canadian Arctic Ocean. J Geophys Res Ocean 123:9178–9195. https://doi.org/10.1029/2018JC014342

Chénier R, Abado L, Sabourin O, Tardif L (2017) Northern marine transportation corridors: Creation and analysis of northern marine traffic routes in Canadian waters. Trans GIS 21:1085–1097. https://doi.org/10.1111/tgis.12295

Cobb DG (2011) Identification of Ecologically and Biologically Significant Areas (EBSAs) in the Canadian Arctic. Winnipeg

Cottee-Jones HEW, Whittaker RJ (2012) perspective: The keystone species concept: a critical appraisal. Front Biogeogr 4:. https://doi.org/10.21425/f5fbg12533

Czarnecki A, Goodman S (2012) Status and trends of flow, water quality and suspended sediment quality in the Peel River watershed. Aboriginal Affairs and Northern Development Canada, Yellowknife.

Dalman L (2018) Physical gradient influences on sea ice algae in the Canadian Arctic. University of Manitoba

Darnis G, Robert D, Pomerleau C, et al (2012) Current state and trends in Canadian Arctic marine ecosystems: II. Heterotrophic food web, pelagic-benthic coupling, and biodiversity. Clim

Change 115:179–205. https://doi.org/10.1007/s10584-012-0483-8

Deal C, Jin M, Elliott S, et al (2011) Large-scale modeling of primary production and ice algal biomass within arctic sea ice in 1992. J Geophys Res Ocean 116:1–14. https://doi.org/10.1029/2010JC006409

Defossez M, Saucier FJ, Myers PG, et al (2008) Multi-year observations of deep water renewal in Foxe Basin, Canada. Atmosphere-Ocean 46:377–390. https://doi.org/10.3137/ao.460306

Department of Sustainable Development Parks and Tourism Department (DSD)(2000) Thelon Heritage River : Ten-Year Review

Déry SJ, Stieglitz M, McKenna EC, Wood EF (2005) Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964-2000. J Clim 18:2540–2557. https://doi.org/10.1175/JCLI3440.1

Déry SJ, Mlynowski TJ, Hernández-Henríquez MA, Straneo F (2011) Interannual variability and interdecadal trends in Hudson Bay streamflow. J Mar Syst 88:341–351. https://doi.org/10.1016/j.jmarsys.2010.12.002

Déry SJ, Stadnyk TA, MacDonald MK, et al (2018) Flow alteration impacts on Hudson Bay river discharge. Hydrol Process 32:3576–3587. https://doi.org/10.1002/hyp.13285

De Sève M (1993) Diatom bloom in the tidal freshwater zone of a turbid and shallow estuary, Rupert Bay (James Bay, Canada). Hydrobiologia 269:225–233

Desroches JF, Schueler FW, Picard I, Gagnon LP (2010) A herpetological survey of the James Bay area of Québec and Ontario. Can Field-Naturalist 124:299–315. https://doi.org/10.22621/cfn.v124i4.1101

DFO (2011) Identification of Ecologically and Biologically Significant Areas (EBSA) in the Canadian Arctic. Winnipeg

Drolet R, Fortier L, Ponton D, Gilbert M (1991) Production of fish larvae and their prey in subarctic southeastern Hudson Bay. Mar Ecol Prog Ser 77:105–118. https://doi.org/10.3354/meps077105

Drost HE, Lo M, Carmack EC, Farrell AP (2016) Acclimation potential of Arctic cod (*Boreogadus saida*) from the rapidly warming Arctic Ocean. J Exp Biol 219:3114-3125

Dupont F (2012) Impact of sea-ice biology on overall primary production in a biophysical model of the pan-Arctic Ocean. J Geophys Res Ocean 117:1–18. https://doi.org/10.1029/2011JC006983

Eastwood RA (2017) Physical properties and isotopic characteristics of the winter water column and landfast sea-ice surrounding the Belcher Islands, southeast Hudson Bay. University of Manitoba

El-Sabh MI, Koutitonsky VG (1977) An oceanographic study of James Bay before the completion of the La Grande hydroelectric complex. Arctic 30:133–196. https://doi.org/10.14430/arctic2697

Ferguson SH, Stirling I, McLoughlin P (2005) Climate change and ringed seal (Phoca hispida) recruitment in western Hudson Bay. Mar Mammal Sci 21:121–135. https://doi.org/10.1111/j.1748-7692.2005.tb01212.x

Ferguson SH, Higdon JW, Chmelnitsky EG (2009) The rise of killer whales as a major Arctic predator. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay, 1st edn. Springer, pp 117–176

Ferguson SH, Dueck L, Loseto LL, Luque SÁP (2010) Bowhead whale Balaena mysticetus seasonal selection of sea ice. Mar Ecol Prog Ser 411:285–297. https://doi.org/10.3354/meps08652

Ferland J, Gosselin M, Starr M (2011) Environmental control of summer primary production in the Hudson Bay system: The role of stratification. J Mar Syst 88:385–400. https://doi.org/10.1016/j.jmarsys.2011.03.015

Fortier L (2012) The Arctic cod (Boreogadus saida) ecosystem under the double pressure of climate change and industrialization. In: ArcticNet Annual Research Compendium (2011-2012). ArcticNet, p 15

Friesen TM, Stewart A (2004) Variation in subsistence among inland Inuit: zooarcheology of two sites on the Kazan River, Nunavut

Galicia MP, Thiemann GW, Dyck MG, et al (2016) Dietary habits of polar bears in Foxe Basin, Canada: possible evidence of a trophic regime shift mediated by a new top predator. Ecol Evol 6:6005–6018. https://doi.org/10.1002/ece3.2173

Gagnon AS, Gough WA (2002) Hydro-Climatic Trends in the Hudson Bay Region, Canada. Can Water Resour J 27:245–262. https://doi.org/10.4296/cwrj2703245

Gagnon AS, Gough WA (2006) East-west asymmetry in long-term trends of landfast ice thickness in the Hudson Bay region, Canada. Clim Res 32:177–186. https://doi.org/10.3354/cr032177

Garibaldi A, Turner N (2004) Cultural Keystone Species: Implications for Ecological Conservation and Restoration

Gaston AJ, Elliott KH (2014) Seabird diet changes in northern Hudson Bay, 1981-2013, reflect the availability of schooling prey. Mar Ecol Prog Ser 513:211–223. https://doi.org/10.3354/meps10945

Gilchrist HG, Robertson GJ (2000) Observations of marine birds and mammals wintering at polynyas and ice edges in the Belcher Islands, Nunavut, Canada. Arct Inst North Am 53:61–68. https://doi.org/10.14430/arctic835

Glooschenko WA, Martini IP (1983) Wetlands of the Attawapiskat River mouth, James Bay, Ontario, Canada. Wetlands 3:64–76. https://doi.org/10.1007/BF03160731

Godin P, Macdonald RW, Kuzyk ZZA, et al (2017) Organic Matter Compositions of Rivers draining into Hudson Bay: Present Day Trends and Potential as Recorders of Future Climate Change: Lignins in Hudson Bay Rivers. J Geophys Res Biogeosciences 122:1848–1869. https://doi.org/10.1002/2016JG003569

Gormezano LJ, Rockwell RF (2013) What to eat now? Shifts in polar bear diet during the ice-free season in western Hudson Bay. Ecol Evol 3:3509–3523. https://doi.org/10.1002/ece3.740

Gosselin M, Legendre L, Therriault J-C, Demers S (1990) Light and nutrient limitation of sea-ice microalgae (Hudson Bay, Canadian Arctic). J Phycol 26:220–232

Government of Canada (2020) Canadian Protected and Conserved Areas Database. https://www.canada.ca/en/environment-climate-change/services/national-wildlife-areas/protected-conserved-areas-database.html

Grainger EH (1960) Some Physical Oceanographic features of southeast Hudson Bay and James Bay. Montreal

Grainger EH, McSween S (1976) Marine zooplankton and some physical-chemical features of James Bay related to La Grande hydro-electric development. Ste. Anne de Bellevue

Granskog MA, Kuzyk ZZA, Azetsu-Scott K, Macdonald RW (2011) Distributions of runoff, sea-ice melt and brine using δ 18O and salinity data — A new view on freshwater cycling in Hudson Bay. J Mar Syst 88:362–374. https://doi.org/10.1016/j.jmarsys.2011.03.011

Greendale RG, Hunter JG (1978) Feeding of freshwater fishes in estuarine and coastal waters. Ste. Anne de Bellevue

Grimwood BSR, Doubleday NC (2013) From river trails to adaptive co-management: Learning and relating with Inuit inhabitant of the Thelon River, Canada. Indig Policy J 23:1–18

Gulliksen B, Lønne OJ (1991) Sea ice macrofauna in the Antarctic and the Arctic. J Mar Syst 2:53–61. https://doi.org/10.1016/0924-7963(91)90013-K

Guéguen C, Mokhtar M, Perroud A, et al (2016) Mixing and photoreactivity of dissolved organic matter in the Nelson/Hayes estuarine system (Hudson Bay, Canada). J Mar Syst 161:42–48. https://doi.org/10.1016/j.jmarsys.2016.05.005

Gunn G (2014) Polynya formation in Hudson Bay During the Winter Period. University of Manitoba

Gutekunst K (2018) Hypothesis on the synchronistic evolution of autotrophy and heterotrophy. Trends Biochem Sci 43:402-411

Hammill MO (2013) Effects of Climate Warming on Arctic Marine Mammals in Hudson Bay: Living on the Edge? In: Mueter FJ, Dickson DMS, Huntington HP, et al. (eds) Responses of Arctic Marine Ecosystems to Climate Change. Alaska Sea Grant, University of Alaska Fairbanks, pp 21–38

Hannah CG, Dupont F, Dunphy M (2009) Polynyas and Tidal Currents in the Canadian Arctic Archipelago. Arctic 62:83–95

Harris LN, Yurkowski DJ, Gilbert MJH, Else BGT, Duke PJ, Ahmed MMM et al. (2020) Depth and temperature preference of anadromous Arctic char Salvelinus alpinus in the Kitikmeot Sea, a shallow and low-salinity area of the Canadian Arctic. Marine Ecology Progress Series 634:175–197.

Harrison WG, Cota GF (1991) Primary production in polar waters: relation to nutrient availability. Polar Res 10:87–104. https://doi.org/10.3402/polar.v10i1.6730

Harter B, Elliott KH, Divoky GJ, Davoren GK (2013) Arctic cod (Boreogadus saida) as prey: Fish length-energetics relationships in the Beaufort sea and Hudson Bay. Arctic 66:191–196. https://doi.org/10.14430/arctic4290

Heikkilä M, Pospelova V, Hochheim KP, et al (2014) Surface sediment dinoflagellate cysts from the Hudson Bay system and their relation to freshwater and nutrient cycling. Mar Micropaleontol 106:79–109. https://doi.org/10.1016/j.marmicro.2013.12.002

Hernández-Henríquez MA, Mlynowski TJ, Déry SJ (2010) Reconstructing the natural streamflow of a regulated river: A case study of La Grande Rivière, Québec, Canada. Can Water Resour J 35:301–316. https://doi.org/10.4296/cwrj3503301

Higdon JW, Ferguson SH (2010) Past, present, and future of bowhead whales (Balaena mysticetus) in Northwest Hudson Bay. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World’s Largest Northern Inland Sea, Hudson Bay, 1st edn. Springer, pp 159–177

Hochheim KP, Barber DG (2010) Atmospheric forcing of sea ice in Hudson Bay during the fall period, 1980-2005. J Geophys Res Ocean 115:1–20. https://doi.org/10.1029/2009JC005334

Hochheim K, Barber DG, Lukovich JV (2010) Changing Sea Ice Conditions in Hudson Bay, 1980-2005. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay, 1st edn. Springer, pp 39–52

Hochheim K, Barber D (2014) An update on the ice climatology of the Hudson Bay system. Arctic, Antarct Alp Res 46:66–83. https://doi.org/10.1657/1938-4246-46.1.66

Horner R, Ackley SF, Dieckmann GS, et al (1992) Ecology of sea ice biota 1. Habitat, terminology, and methodology. Polar Biol 12:417–427

Hudon C, Morin R, Bunch J, Harland R (1996) Carbon and nutrient output from the Great Whale River (Hudson Bay) and a comparison with other rivers around Quebec. Can J Fish Aquat Sci 53:1513–1525. https://doi.org/10.1139/f96-080

Imrie DD (2009) Inuit Knowledge and adaptations to sea ice changes in the Belcher Islands, Nunavut. University of Manitoba.

Ingram RG, Wang J, Legendre L, Fortier L (1996) Impact of freshwater on a subarctic coastal ecosystem under seasonal sea ice (southeastern Hudson Bay, Canada). I. Interannual variability and predicted global warming influence on river plume dynamics and sea ice. J Mar Syst 7:221–231

Irwin B, Harris L, Hodgson M, et al (1983) Primary Productivity and Nutrient measurements in Northern Foxe Basin, N.W.T., from 27 August to 7 September, 1981

Jolivel M, Allard M, St-Onge G (2015) Climate change and recent sedimentation in Nastapoka Sound, eastern coast of Hudson Bay. Can J Earth Sci 52:322–337. https://doi.org/10.1139/cjes-2014-0132

Jones EP, Anderson LG (1994) Northern hudson bay and foxe basin: Water masses, circulation and productivity. Atmos - Ocean 32:361–374. https://doi.org/10.1080/07055900.1994.9649502

Jørgensen LL, Archambault P, Blicher M, et al (2017) State of the Arctic Marine Biodiversity Report: Benthos

Kazmiruk Z (2018) Potential for Microbial Degradation of Terrestrial Dissolved Organic Carbon in Coastal Hudson Bay. University of Manitoba

Kelly TC, Loseto LL, Stewart REA, et al (2010) Importance of eating Capelin: Unique Dietary Habits of Hudson Bay Beluga. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay, 1st edn.

Springer, pp 53–69

Kelley, Tritsya C (2014) Linking Feeding and Reproductive Ecology in Beluga (Delphinapterus leucas) and Narwhal (Monodon monoceros). University of Manitoba

Kenchington EL, Link H, Roy V, et al (2011) Identification of Mega- and Macrobenthic Ecologically and Biologically Significant Areas (EBSAs) in the Hudson Bay Complex, the Western and Eastern Canadian Arctic. Dartmouth, Québec, Winnipeg, St.John's

Kenchington E, Siferd T, Lirette C (2012) Arctic Marine Biodiversity: Indicators for Monitoring Coral and Sponge Megafauna in the Eastern Arctic. Dartmouth; Winnipeg

Kerbes RH, Kotanen PM, Jefferies RL (1990) Destruction of Wetland Habitats by Lesser Snow Geese: A Keystone Species on the West Coast of Hudson Bay. J Appl Ecol 27:242–258

Kirk JL, St. Louis VL (2009) Multiyear Total and Methyl Mercury Exports from Two Major Sub-Arctic Rivers Draining into Hudson Bay, Canada. Environ Sci Technol 43:2254–2261. https://doi.org/10.1021/es803138z

Kuzyk ZAZA, Macdonald RWW, Granskog MA, et al (2008) Sea ice, hydrological, and biological processes in the Churchill River estuary region, Hudson Bay. Estuar Coast Shelf Sci 77:369–384. https://doi.org/10.1016/j.ecss.2007.09.030

Kuzyk ZZA, Macdonald RW, Johannessen SC, et al (2009) Towards a sediment and organic carbon budget for Hudson Bay. Mar Geol 264:190–208. https://doi.org/10.1016/j.margeo.2009.05.006

Kuzyk ZZA, Macdonald RW, Tremblay J-ÉÉ, Stern GA (2010) Elemental and stable isotopic constraints on river influence and patterns of nitrogen cycling and biological productivity in Hudson Bay. Cont Shelf Res 30:163–176. https://doi.org/10.1016/j.csr.2009.10.014

Kuzyk ZZA, Candlish LM. (2019) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. ArcticNet, Québec City, 424 pp.

Laidler GJ (2007) Ice, through Inuit eyes: Characterizing the importance of sea ice processes, use and change around three Nunavut Communities. University of Toronto

Landy JC, Ehn JK, Babb DG, Thériault N, Barber DG (2017) Sea ice thickness in the Eastern Canadian Arctic: Hudson Bay Complex and Baffin Bay. Remote Sens Environ 200:281-294. https://doi.org/10.1016/j.rse.2017.08.019

Lapoussière A, Michel C, Gosselin M, Poulin M (2009) Spatial variability in organic material sinking export in the Hudson Bay system, Canada, during fall. Cont Shelf Res 29:1276–1288.

https://doi.org/10.1016/j.csr.2009.02.004

Lapoussière A, Michel C, Gosselin M, et al (2013) Primary production and sinking export during fall in the Hudson Bay system, Canada. Cont Shelf Res 52:62–72. https://doi.org/10.1016/j.csr.2012.10.013

Labun P, Debicki C. (2018) Western Hudson Bay and its beluga estuaries: Protecting abundance for a sustainable future. Oceans North: Ottawa.

Legendre L, Demers S, Gosselin M (1987) Chlorophyll and photosynthetic efficiency of size-fractionated sea-ice microalgae (Hudson Bay, Canadian Arctic). Mar Ecol Prog Ser 40:199–203. https://doi.org/10.3354/meps040199

Lepage S, Ingram RG (1986) Salinity intrusion in the Eastmain River Estuary following a major reduction of freshwater input. J Geophys Res 91:909–915. https://doi.org/10.1029/JC091iC01p00909

Luque SP, Ferguson SH, Breed GA (2014) Spatial behaviour of a keystone Arctic marine predator and implications of climate warming in Hudson Bay. J Exp Mar Bio Ecol 461:504–515. https://doi.org/10.1016/j.jembe.2014.10.002

MacDonald M, Arraqutainaq L, Novalinga Z, et al. (1997) Voices from the Bay: Traditional Ecological Knowledge of Inuit and Cree in the Hudson Bay Bioregion. Canadian Arctic Resources Committee, Environmental Committee of Municipality of Sanikiluaq, Ottawa, Ontario

Macdonald RW, Kuzyk ZZA (2011) The Hudson Bay system: A northern inland sea in transition. J Mar Syst 88:337–340. https://doi.org/10.1016/j.jmarsys.2011.06.003

Mallory ML, Gaston AJ, Provencher JF, et al (2019) Identifying key marine habitat sites for seabirds and sea ducks in the Canadian Arctic. Environ Rev 27:215–240. https://doi.org/10.1139/er-2018-0067

Manson GK, Couture NJ, James TS (2019) CanCoast 2.0: Data and indices to describe the sensitivity of Canada’s marine coasts to changing climate

Marshall TR, Jones NE (2011) Aquatic Ecosystems of the Far North of Ontario: State of Knowledge

Martini IP, Morrison RIG, Glooschenko WA, Protz R (1980) Coastal studies in James Bay, Ontario. Geosci Canada 7:11–21. https://doi.org/10.12789/gs.v7i1.3199

Mathieson AC, Moore GE, Short FT (2010) A Floristic Comparison of Seaweeds from James Bay and Three Contiguous Northeastern Canadian Arctic Sites. Rhodora 112:396–434.

https://doi.org/10.3119/09-12.1

Matthews CJD, Watt CA, Asselin NC, et al (2017) Estimated abundance of the Western Hudson Bay beluga stock from the 2015 visual and photographic aerial survey. Ottawa

McCrea RC, Kwiatkowskie RE, Campbell DE, et al (1984) An investigation of contaminants and benthic communities in the major rivers of the Hudson Bay Lowland, Ontario. Burlington

McGeehan T, Maslowski W (2012) Evaluation and control mechanisms of volume and freshwater export through the Canadian Arctic Archipelago in a high-resolution pan-Arctic ice-ocean model. J Geophys Res Ocean 117:1–25. https://doi.org/10.1029/2011JC007261

Michel C, Legendre L, Therriault JC, et al (1993) Springtime coupling between ice algal and phytoplankton assemblages in southeastern Hudson Bay, Canadian Arctic. Polar Biol 13:441–449. https://doi.org/10.1007/BF00233135

Mikhail MY, Welch HE (1989) Biology of Greenland cod, Gadus ogac, at Saqvaqjuac, northwest coast of Hudson Bay. Environ Biol Fishes 26:49–62

Moline MA, Karnovsky NJ, Brown Z, et al (2008) High latitude changes in ice dynamics and their impact on polar marine ecosystems. Ann N Y Acad Sci 1134:267–319. https://doi.org/10.1196/annals.1439.010

Mussells O, Dawson J, Howell S (2016) Using RADARSAT to identify sea ice ridges and their implications for shipping in Canada's Hudson strait. Arctic 69:421–433. https://doi.org/10.14430/arctic4604

Ontario Ministry of Natural Resources (2009) The Lake Sturgeon in Ontario

Poulin M, Cardinal A (1982) Sea ice diatoms from Manitounuk Sound, southeastern Hudson Bay (Quebec, Canada). I. Family Naviculaceae. Can J Bot 60:1263–1278. https://doi.org/10.1139/b82-160

Prinsenberg SJ (1978) Analytical study of the circulation of James Bay. Burlington

Prinsenberg SJ (1980) Man-made changes in freshwater input rates of Hudson and James Bays. Can J Fish Aquat Sci 37:1101–1110. https://doi.org/10.1139/f80-143

Prinsenberg SJ (1987) Seasonal current variations observed in western Hudson Bay. J Geophys Res Ocean 92:756–766. https://doi.org/10.1029/JC092iC10p10756

Reeves R. Distribution, abundance and biology of ringed seals (Phoca hispida): an overview

Reist JD, Wrona FJ, Prowse TD, et al (2006) General Features of the Arctic Relevant to Climate

Change in Freshwater Ecosystems. Ambio A J Hum Environ 35:330–338. https://doi.org/10.1579/0044-7447(2006)35

Ridenour NA, Hu X, Sydor K, et al (2019) Revisiting the circulation of Hudson Bay: Evidence for a seasonal pattern. Geophys Res Lett 46:3891–3899. https://doi.org/10.1029/2019GL082344

Roff, J.C., Legendre L (1986) Physio-Chemical and Biological Oceanography of Hudson Bay. In: Martini IP (ed) Canadian Inland Seas, 1st edn. Elsevier Science, pp 265–292

Roger J, Duchesne MJ, Lajeunesse P, et al (2011) Imaging pockmarks and ring-like features in Hudson Bay from multibeam bathymetry data. Québec

Runge JA, Therriault J-C, Legendre L., et al (1991) Coupling between ice microalgal productivity and the pelagic, metazoan food web in southeastern Hudson Bay: a synthesis of results. Polar Res 10:325–338. https://doi.org/10.1111/j.1751-8369.1991.tb00657.x

Russell RH (1975) The Food Habits of Polar Bears of James Bay and Southwest Hudson Bay in Summer and Autumn. Arctic 28:1–13. https://doi.org/10.14430/arctic2823

Saucier FJ, Senneville S, Prinsenberg S, et al (2004) Modelling the sea ice-ocean seasonal cycle in Hudson Bay, Foxe Basin and Hudson Strait, Canada. Clim Dyn 23:303–326. https://doi.org/10.1007/s00382-004-0445-6

Schneider-Vieira F, Baker R, Lawrence M (1994) The Estuaries of Hudson Bay: A Case Study of the Physical and Biological Characteristics of Selected Sites. Winnipeg

Schuback N, Hoppe CJM, Tremblay JÉ, et al (2017) Primary productivity and the coupling of photosynthetic electron transport and carbon fixation in the Arctic Ocean. Limnol Oceanogr 62:898–921. https://doi.org/10.1002/lno.10475

Sergeant DE (1973) Biology of White Whales (Delphinapterus leucas) in Western Hudson Bay. J Fish Res Board Can 30:1065–1090

Shaverdo HV, Giberson DJ (2004) Predaceous Water Beetles (Coleoptera: Adephaga: Dytiscidae, Gyrinidae) Collected Along the Horton and Thelon Rivers in the Arctic Central Barrens of Canada. Can Field-Naturalist 118:425–433

Sibert V, Zakardjian B, Saucier F, et al (2010) Spatial and temporal variability of ice algal production in a 3D ice–ocean model of the Hudson Bay, Hudson Strait and Foxe Basin system. Polar Res 29:353–378. https://doi.org/10.1111/j.1751-8369.2010.00184.x

Sibert V, Zakardjian B, Gosselin M, et al (2011) 3D bio-physical model of the sympagic and planktonic productions in the Hudson Bay system. J Mar Syst 88:401–422. https://doi.org/10.1016/j.jmarsys.2011.03.014

Smith A, Higdon J, Richard P, et al (2017) Beluga whale summer habitat associations in the Nelson River estuary, western Hudson Bay, Canada. PLoS One 12:1–19. https://doi.org/10.1371/journal.pone.0181045

Stephenson SA, Hartwig L (2010) The Arctic Marine Workshop: Freshwater Institute Winnipeg, Manitoba, February 16-17, 2010. Can Manuscript Rep Fish Aquat Sci 2934

Stewart DB, Barber D (2010) The Ocean-Sea Ice-Atmosphere System of the Hudson Bay Complex. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay, 1st edn. Springer, New York, pp 1–38

Stewart DB, Howland KL (2009) An Ecological and Oceanographical Assessment of the Alternate Ballast Water Exchange Zone in the Hudson Strait Region. Winnipeg

Stewart DB, Lockhart WL. (2005). An Overview of the Hudson Bay Marine Ecosystem. Canadian Technical Report of Fisheries and Aquatic Sciences. 2586.

Stirling I, Cleator H (1981) Polynyas in the Canadlan Arctic. Edmonton

Straneo F, Saucier F (2008a) The outflow from Hudson Strait and its contribution to the Labrador Current. Deep Sea Res Part 1 Oceanogr Res Pap 55:926–946. https://doi.org/10.1016/j.dsr.2008.03.012

Straneo F, Saucier FJ (2008b) The Arctic–Subarctic Exchange Through Hudson Strait. In: Dickson RR, Meincke J, Rhines P (eds) Arctic-Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate, 1st edn. Springer Netherlands, pp 249–261

Sutherland DA, Straneo F, Lentz SJ, Saint-Laurent P (2011) Observations of fresh, anticyclonic eddies in the Hudson Strait outflow. J Mar Syst 88:375–384. https://doi.org/10.1016/j.jmarsys.2010.12.004

Taha W, Bonneau-Lefebvre M, Cueto Bergner A, Tremblay A (2019) Evolution From Past to Future Conditions of Fast Ice Coverage in James Bay. Front Earth Sci 7:1–20. https://doi.org/10.3389/feart.2019.00254

Tan FC, Strain PM (1996) Sea ice and oxygen isotopes in Foxe Basin, Hudson Bay, and Hudson Strait, Canada. J Geophys Res C Ocean 101:20,869-20,876. https://doi.org/10.1029/96JC01557

Traving SJ, Rowe O, Jakobsen NM, Sørensen H, Dinasquet J, Stedmon CA, Andersson A, Riemann L (2017) The Effect of Increased Loads of Dissolved Organic Matter on Estuarine Microbial Community Composition and Function. Front Microbiol. 9:351.

Tremblay C, Runge J, Legendre L (1989) Grazing and sedimentation of ice algae during and immediately after a bloom at the ice-water interface. Mar Ecol Prog Ser 56:291–300. https://doi.org/10.3354/meps056291

Wang J, Mysak LA, Grant Ingram R (1994) Interannual variability of sea-ice cover in Hudson Bay, Baffin Bay and the Labrador Sea. Atmos - Ocean 32:421–447. https://doi.org/10.1080/07055900.1994.9649505

Watt CA, Heide-Jørgensen MP, Ferguson SH (2013) How adaptable are narwhal? A comparison of foraging patterns among the world's three narwhal populations. Ecosphere 4:1–15. https://doi.org/10.1890/ES13-00137.1

Webb DJ (2014) On the tides and resonances of Hudson Bay and Hudson Strait. Ocean Sci 10:411–426. https://doi.org/10.5194/os-10-411-2014

Welch HE, Bergmann A, Siferd TD, Amarualik PS (1991) Seasonal Development of Ice Algae Near Chesterfield Inlet, N.W.T., Canada. Can J Fish Aquat Sci 48:2395–2402

Wenegrat JO, LN Thomas (2017) Ekman transport in balanced currents with curvature. J Phys Oceanogr 47:1189-1203

White D, Hinzman L, Alessa L, et al (2007) The arctic freshwater system: Changes and impacts. J Geophys Res 112:1–22. https://doi.org/10.1029/2006JGO00353

Wiken EB, Gauthier D, Marshall I, et al (1996) A Perspective on Canada's Ecosystems

Williams WJ, Carmack EC, Ingram RG (2007) Physical Oceanography of Polynyas. In: Smith, Walker O, Barber, David G (eds) Polynyas: Windows to the World, 1st edn. Elsevier, pp 55–85

Yurkowski DJ, Ferguson SH, Semeniuk CAD, et al (2016) Spatial and temporal variation of an ice-adapted predator's feeding ecology in a changing Arctic marine ecosystem. Oecologia 180:631–644. https://doi.org/10.1007/s00442-015-3384-5

5 IMPLICATIONS OF CLIMATE FORCING

5.1 ICE LOSS

> *The polar regions are losing ice, and their oceans are changing rapidly. The consequences of this polar transition extend to the whole planet, and are affecting people in multiple ways. (Meredith et al. 2018)*

As stated in the Intergovernmental Panel on Climate Change (IPCC)'s recently released *Special Report on the Ocean and Cryosphere in a Changing Climate* (2018), change in the ice and oceans of the polar regions is occurring rapidly, with significant and far-reaching consequences (Meredith et al. 2018). Since the IPCC's last assessment report was released in 2014 (Fifth Assessment Report or AR5), Arctic systems have experienced new extremes. Annual Arctic surface air temperature for each of the past five years since AR5 have exceeded that of any year since 1900. All Arctic winter sea ice maxima for four of the five years since the AR5 were at record low levels relative to 1979–2014 (Meredith et al. 2018).

Sea ice undergoes abrupt transitions from liquid to solid phases based on temperature. As a result, increases in surface air temperature in the Arctic have driven accelerated changes in sea ice, characterized by losses in extent and thickness (Barber et al. 2012). Increased surface air temperatures have been observed throughout the HBME in recent decades (Hochheim and Barber 2010), causing reduced sea ice extent (area of ocean covered in ice) as well as freeze-ups that occur later in the year and breakups that occur earlier in the spring (Hochheim and Barber 2014). Future projections predict a loss of 50% winter sea ice in James Bay as sea ice loss moves in a southeast-northwest gradient through the HBME (Joly et al. 2011). The HBME has been noted as one of the regions within the circumpolar Arctic for which sea ice reductions have been greatest (Tivy et al. 2011). The far-reaching impacts of reductions in sea ice in the HBME are noted throughout the rest of this chapter in sections 5.2, 5.4, 5.5, 5.6, 5.7 and 5.8.

While surface air temperature is the key driver of Arctic ice loss, knowledge is still being obtained about mechanisms that amplify this loss. Some of the mechanisms that have been identified include: (1) reduced summer albedo due to lower levels of multiyear sea ice and snow cover over ice, (2) an increase of total water vapour content in the Arctic atmosphere resulting from elevated evaporation rates that have been linked to the loss of sea-ice and warming sea surface temperatures (Boisvert et al. 2015), (3) changes in total cloudiness in summer, (4) additional heat generated by newly formed sea ice across more extensive open water areas in autumn, (5) northward transport of heat and moisture, and (6) the lower rate of heat loss to space from the Arctic relative to the subtropics (Meredith et al. 2018). Spatially inhomogeneous ice loss across the northern hemisphere has also been tied to the dynamic variability of ice export. An increasingly brittle ice pack due to disproportionate losses of multiyear ice enables advection to move sea ice more rapidly, causing observable declines in sea ice extent. (Barber et al. 2012).

It is in this context that changes in ice in the HBME are examined. Surface air temperature has been warming around Hudson Bay over the last several decades (Hochheim and Barber 2010). Hochheim and Barber (2010) report surface air temperature anomalies (deviation from the mean) increasing from October (0.6–0.8°C per decade) to December (1.1–1.6°C per decade) from 1980 to 2005, with the most significant warming trend within Hudson Bay having occurred in its northern and eastern extents. Between 1980 and 2010, increases in fall temperatures in the HBME were the highest in the northern reaches of Hudson Bay and Foxe Basin, at +0.8 to 1.1°C per decade (Andrews et al. 2017). Further, spring surface air temperature anomalies surrounding Hudson Bay have increased by 0.26 to 0.30°C per decade during 1960–2005 (Hochheim et al. 2011). Between 1980 and 2010, the highest surface air temperature anomalies within the HBME were in Foxe Basin and the northern and eastern regions of Hudson Bay, at +0.5 to 0.9°C per decade (Andrews et al. 2017).

For every 1°C increase in surface air temperature, Hochheim and Barber (2014) found that sea ice extent decreases by 14% and freeze-up is delayed by 0.7 to 0.9 weeks on average within the Hudson Bay, James Bay, Hudson Strait and Foxe Basin system. Breakup dates in spring were also observed to be highly correlated to winds (dynamic forcing that drives sea ice circulation) as well the surface air temperatures of the current spring and the previous fall. Based on Canadian Ice Service (CIS) and passive microwave-based (PMW) data for this area, the authors also showed that mean ice extents have decreased by 105,000 to 117,000 km^2 for every 1°C increase in late November (Hochheim and Barber 2010). Hochheim and Barber (2014) suggest that changes in the Hudson Bay, James Bay, Hudson Strait and Foxe Basin system have been occurring more rapidly, in particular in eastern Hudson Bay and are more strongly associated with atmospheric forcing relative to other Canadian Arctic regions, while Tivy et al. (2011) suggest that reductions in sea ice cover in the Hudson Bay region are among the greatest in the circumpolar Arctic. Communities in the Arctic have been observing changes in ice conditions for some time. Inuit in communities in eastern Hudson Bay (Nunavik's western coast) have reported changes in ice conditions including later freeze-up, earlier breakup and ice that is thinner (Nickels et al. 2006; Tremblay et al. 2006). Onarheim et al. (2018) describe how the northern regions characterized by the largest sea ice extent variability and trend occurring during the summer months will eventually enter into a 'transition mode'. This transition mode is typified by seasonal ice cover, rather than perennial, as well as more pronounced changes to sea ice extent during the winter. Hudson Bay is currently approaching the transition mode, with nearly no summer sea ice remaining. Figure 5.1 is a depiction of seasonal sea-ice concentrations under the current climate scenario versus a predicted warmer climate scenario.

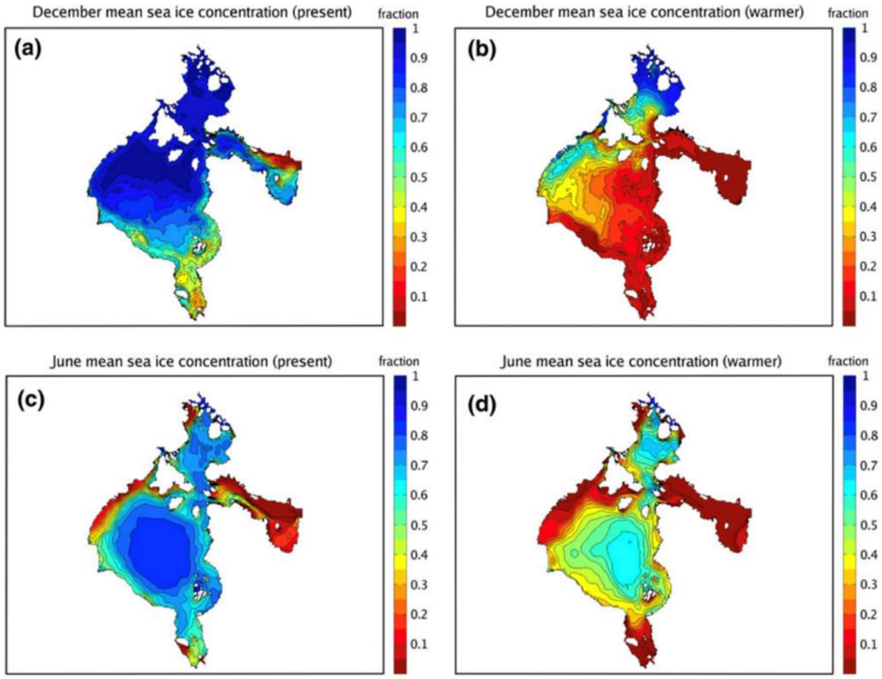


Figure 5.1. December (a,b) and June (c,d) mean sea ice concentration for the present climate simulation (a, c) and the warmer climate scenario (b, d) (Joly et al. 2011, p. 1845)

A summary of knowledge of changes in sea ice extent—or sea ice concentration used as an indicator of sea ice extent—in the HBME is provided in Table 5.1. Recent sea ice extent reductions have been pronounced in the fall, for example, Hochheim and Barber (2014) found reductions of approximately one third in fall sea ice extent in Foxe Basin and Hudson Bay (including James Bay) when comparing 1996–2010 to 1980–1995. Tivy et al. (2011) found that reductions in summer sea ice extent over four decades starting in the late 1960s were more substantial in northwestern Hudson Bay and the Hudson Bay Narrows (area between Southhampton Island, Coats Island, Mansel Island, and around Cape Dorset) compared to the rest of the Hudson Bay-James Bay system. The authors do not discuss the causes regarding changes to sea ice extent at a regional scale within the HBME. However, they do note that the strongest relationship between summer all ice coverage (AIC) and surface air temperatures in their study was found in the Hudson Bay and Foxe Basin regions with 30% of the summer AIC variance explained by spring surface air temperatures.

There are very limited observational studies of trends in sea ice thickness in the HBME, as most ice thickness measuring sites in northern Canada were closed in the early 2000s (Landy et al. 2017). As a result, published information does not include data on the recent warming trend. Gagnon and Gough (2006) found an east-west asymmetry in the long-term trends in ice thickness between about 1960 to 2000, with ice thinning on the eastern side of Hudson Bay but thickening on the western side (Table 5.2). This asymmetry is related to the variability of air temperature, snow depth, and the dates of ice freeze-up and breakup.

Table 5.1. Summary of changes in sea ice extent or concentration in Foxe Basin, Hudson Bay and James Bay

Source	Data type and years	Mean change in sea ice extent (SIE) or concentration (SIC) (km^2)	Mean change in SIE or SIC (%)
Foxe Basin			
Tivy et al. (2011)	Canadian Ice Service (CIS) charts for 1968–2008	*Overall:* 7.4 ± 1.9 × 10^2 km^2 reduction in summer SIE over total time period	*Overall:* 8.9 ± 2.3% reduction in summer SIE per decade
Hochheim and Barber (2014)	Passive microwave-based (PMW) data for 1980–2010	*Overall:* 6.06 ±1.66 × 10^4 km^2 reduction in fall SIE for 1996–2010 compared to 1980–1995	*Overall:* 29.2 ± 8.0% reduction in fall SIE for 1996–2010 compared to 1980–1995
Hudson Bay			
Tivy et al. (2011)	CIS charts for 1968–2008	*Overall including James Bay:* 16.5 ± 5.0 × 10^2 km^2 reduction in summer SIE *Hudson Bay Narrows:* 2.4 ± 0.77 × 10^2 km^2 reduction in summer SIE *Northwest Hudson Bay:* 6.7 ± 2.1 × 10^2 km^2 reduction in summer SIE	*Overall including James Bay:* 10.4 ± 3.1% reduction in summer SIE per decade *Hudson Bay Narrows:* 13.2 ± 4.4% reduction in summer SIE per decade *Northwest Hudson Bay:* 13.6 ± 4.3% reduction in summer SIE per decade
Cavalieri and Parkinson (2012)	PMW data for 1979–2010	*Overall including James Bay and Foxe Basin:* 4.4 ± 0.7 × 10^3 km^2 reduction per year in annual sea ice extent; 8.6 ± 1.6 × 10^3 km^2 reduction in fall SIE	*Overall including James Bay and Foxe Basin:* 5.1 ± 0.9% reduction per decade in annual sea ice extent; 12.9 ± 2.4% reduction per decade in fall SIE
Hochheim and Barber (2010)	CIS and PMW data for 1980–2005		*Overall including James Bay:* 14.3–16.8 reduction for fall SIC per decade (PMW data) *Marginal ice zone:* 23.3–26.9% reduction November SIC per decade (CIS charts)
Hochheim et al. (2011)	CIS and PMW data for 1960–2005		*Western and south-western Hudson Bay:* 15.1–20.4% reduction in spring SIC per decade
Hochheim and Barber (2014)	PMW data for 1980–2010	*Overall including James Bay:* 2.83 ± 0.61× 10^5 km^2 reduction in fall SIE for 1996-2010 compared to 1980-1995	*Overall including James Bay:* 30.5 ±6.6% reduction in fall SIE for 1996-2010 compared to 1980-1995

Table 5.2. Summary of changes in sea ice thickness in Foxe Basin, Hudson Bay and James Bay and projections of future changes

Source	Data type and years	Mean change in ice thickness
Foxe Basin		
Gagnon and Gough (2006)	Drill hole measurements for 1959–2003	*Hall Beach:* 0.10 cm increase per year in maximum sea ice thickness
Hudson Bay		
Gagnon and Gough (2006)	Drill hole measurements for 1958–2003 (Coral Harbour); 1960–1987 (Churchill); 1959–1990 (Inukjuak); 1972–1991 (Kuujjuarapik)	*Coral Harbour:* 0.50 cm increase per year in maximum sea ice thickness *Churchill:* 0.90 cm increase per year in maximum sea ice thickness *Inukjuak:* 0.45 cm decrease per year in maximum sea ice thickness *Kuujjuarapik:* 0.80 cm decrease per year in maximum sea ice thickness
Hochheim and Barber (2010)	CIS ice thickness data for 2002–2007 compared to 1980–1989	*Coral Harbour:* 19.4 cm reduction in November
Lavoie et al. (2013)	Model projection for 2050 driven by Representative Concentration Pathway (RCP) 4.5 and 8.5 compared to 1960–2005 data	*Overall*: 6.2 cm reduction in April sea ice thickness per decade for RCP 4.5; 8.3 cm reduction in April sea ice thickness per decade for RCP 8.5
Joly et al. (2011)	Model projection for years 2041–2070 driven by CGCM3.1/T47 (IPCC SRES A2 scenario) compared to 2001–2005 data	*Central Hudson Bay:* 40–55% reduction in winter sea ice thickness *Northwest Hudson Bay:* 30% reduction in winter sea ice thickness
James Bay		
Gagnon and Gough (2006)	Drill hole measurements for 1959–1993	*Moosonee:* 0.82 cm increase per year in maximum sea ice thickness
Joly et al. (2011)	Model projection for years 2041–2070 driven by CGCM3.1/T47 (IPCC SRES A2 scenario) compared to 2001–2005 data	*Overall*: >50% reduction in winter sea ice thickness

A summary of changes in timing of freeze-up and breakup, and thus ice season length, is shown in Table 5.3. While different studies present slight differences in magnitude of changes, all studies show that freeze-up has been occurring later and breakup has been occurring earlier in recent decades in the HBME. For example, Galbraith and Larouche (2011) found that over the 1970s and

80s, breakup was advancing by approximately 5 days per decade in Foxe Basin, and that in the following two decades the rate nearly doubled, at 9 days advance per decade. Anomalous freeze-up timing in Foxe Basin in 2006 and its implications was also explored by Ford et al. (2009). Changes in freeze-up and breakup timing are not homogenous across the HBME: Gagnon and Gough (2005a) found a significant trend towards an earlier breakup in James Bay, along the southern shore of Hudson Bay, and in the western half of Hudson Bay, and a significant trend towards later freeze-up in Hudson Bay's northern and northeastern extents (Table 5.3).

Table 5.3. Summary of changes in timing of ice freeze-up and breakup in Foxe Basin, Hudson Bay and James Bay and projections of future changes

Source	Data type and years	Mean change in freeze-up	Mean change in breakup
Foxe Basin			
Galbraith and Larouche (2011)	CIS charts for 1971–2009		*Overall:* 4.9 days advance per decade (1971–1989) *Overall:* 9.0 days advance per decade (1990–2009)
Hochheim and Barber (2014)	PMW data for 1980–2010	*Overall:* 2.0 ±0.51 weeks delay between 1996-2010 compared to 1980-1995	*Overall:* 1.48 ± 0.42 weeks advance between 1996-2010 compared to 1980-1995
Joly et al. (2011)	Model projection for years 2041–2070 driven by CGCM3.1/T47 (IPCC SRES A2 scenario) compared to 2001–2005 data	*Overall:* 31 days delay	*Overall:* 22 days advance
Hudson Bay			
Kowal et al. (2017)	CIS charts for 1971–2003	*Overall including James Bay:* 0.46 days delay per year	*Overall including James Bay:* 0.49 days advance per year
Gagnon and Gough (2005a)	CIS charts for 1971–2003	*Northern and northeastern Hudson Bay:* 0.32 to 0.55 days delay per year	*South shore and western half of Hudson Bay:* 0.49–1.25 days advance per year
Galbraith and Larouche (2011)	CIS charts for 1971–2009		*Overall including James Bay:* 3.2 days advance per decade (1971–2009)
Hochheim and Barber (2014)	PMW data for 1980–2010	*Overall including James Bay:* 1.6 ± 0.32 weeks delay between 1996-2010 compared to 1980-1995	*Overall including James Bay:* 1.53 ±0.39 weeks advance between 1996-2010 compared to 1980-1995
Andrews et al. (2017)	PMW data for 1980–2014	*Overall including James Bay:* 0.47 days delay per year	*Overall including James Bay:* 0.51 days advance per year
Lavoie et al. (2013)	Model projection for 2050 driven by RCP	*Overall including James Bay:* 1-month delay for RCP 8.5	*Overall including James Bay:* 1 month advance for RCP

Source	Data type and years	Mean change in freeze-up	Mean change in breakup
	4.5 and 8.5 compared to 1960–2005 data		4.5; 2-month advance for RCP 8.5
Joly et al. (2011)	Model projection for years 2041–2070 driven by CGCM3.1/T47 (IPCC SRES A2 scenario) compared to 2001–2005 data	*Overall:* 25 days delay	*Overall:* 24 days advance
James Bay			
Gagnon and Gough (2005a)	CIS charts for 1971–2003		*Overall:* 0.49 to 1.25 days advance per year
Taha et al. (2019)	Projection for 2050 compared to 1998–2016 data	*Overall:* 1–3 weeks delay	*Overall:* 2–10 days advance
Joly et al. (2011)	Model projection for years 2041–2070 driven by CGCM3.1/T47 (IPCC SRES A2 scenario) compared to 2001–2005 data	*Overall:* 26 days delay	*Overall:* 39 days advance

Tables 5.2 and 5.3 include not only measures of ice thickness and ice season timing, but projections of future changes. Joly et al. developed a regional sea ice-ocean model to investigate impacts of a climate warming scenario on sea ice and oceanic heat storage in Hudson Bay, Foxe Basin and James Bay in 2041–2070 (Figure 5.1). Within the HBME, the reduction in sea ice follows a southeast–northwest gradient and is greatest in James Bay, with a greater than 50% reduction in winter sea ice projected. Outside of the HBME, but significantly affecting it, the Hudson Strait is projected to be nearly ice-free in June, under the warmer future scenario. The authors find that the maximum volume of sea ice is reduced by almost one third, while the difference in maximum cover is much lower at 2.6% (32,350 km^2).

Gagnon and Gough (2005b) describe the average projected warming around Hudson Bay to be 4.8˚ to 8.0˚C higher in 2070–99 compared to 1961–90, with implications for less ice cover, reduced thickness and earlier freeze-up and delayed breakup.

Lavoie et al. (2013) compared outputs of five global climate models using two different scenarios—Representative Concentration Pathway (RCP) 4.5 (stabilization scenario) and 8.5 (high greenhouse gas emissions scenario), and found future trends that are consistent with Joly et al. (2011), projecting freeze-up to be delayed by one month in the RCP 8.5 scenario and breakup to advance by one to two months, for RCP 4.5 and 8.5 respectively. For an overview of RCPs, their development and characteristics, see Box 5.1 below and van Vuuren et al. (2011).

Box 5.1. Representative Concentration Pathways

There are four Representative Concentration Pathways (RCPs) that describe different 21st century climate warming outcomes based upon greenhouse gas (GHG) emissions and atmospheric concentrations, land use and air pollutant emissions. The primary drivers of GHG emissions are the economy, population size, energy use, land use, technology and climate policy. RCP2.6 is considered a strict GHG mitigation scenario, RCP4.5 and RCP6.0 are intermediate scenarios and RCP8.5 is a high GHG emissions scenario. If substantial efforts to reduce GHG emissions are not made, the RCP6.0 or RCP8.5 are the likely pathways. RCP2.6 requires substantial mitigation, however, may maintain global warming below 2ºC above pre-industrial temperatures (IPCC 2020).
Special Report on Emission Scenarios (SRES) were used prior to the development of RCPs by the Intergovernmental Panel on Climate Change (IPCC). These were also scenarios

In addition to temperature, Joly et al. (2011) describe the influence of changing freshwater inputs on ice formation. A lower amount of spring meltwater weakens the halocline (vertical salinity gradient) and enhances downward mixing of heat during summer and fall. Haline (saltwater) convection at the beginning of winter takes place within a deeper mixed layer, which delays surface freezing.

Additional information about recent changes in ice conditions in the HBME can be found in (Candlish et al. 2019c), and a summary of climate change projections can be found in (Candlish et al. 2019b).

5.2 STORMINESS

Communities across the Arctic and Subarctic, including in Nunavut and Nunavik, have been reporting observations of weather changes that include increased thunderstorms and extreme weather events (Ford et al. 2016). On Hudson Bay’s east coast, residents of Puvirnituq reported observing stronger winds or more frequent windy days, thunderstorms and lightning are occurring less often but at different times of the year, the sky is more hazy, and the weather is increasingly variable and unpredictable (Nickels et al. 2006). In Fort Albany, on the western coast of James Bay, residents reported observing rain, thunder, and lightning storms occurring in December, something they had not witnessed in the past, and an increase in the variability, unpredictability and severity of weather (Tam et al. 2013). These observations accord with evidence about increasing intensity and frequency of storms in the circumpolar Arctic (IPCC 2013; Akperov et al. 2014). In a summary of climate change implications for northern coastal areas, Ford et al. (2017) describe evidence for the positive correlation between the amount of open water and cyclonic intensity in the Arctic, and the likelihood of increasing storm activity as sea ice extents continue to decrease. Cyclonic intensity is typically measured by estimations of mean sea level pressure, although maximum wind speed is sometimes used (Day et al. 2018).

Separating the influence of natural internal climate variability and anthropogenic climate change on storms is challenging, because they are dynamic, short-lived events (Greenan et al. 2019). Limitations in long-term monitoring, data and observations affect the strength of conclusions regarding storminess trends (Greenan et al. 2019). Further, sea ice impacts on storm surges (wind modifications in the marginal ice zone) in the Arctic are not well modelled (Steiner et al. 2015). Nonetheless, there are some studies that model projected future changes in storminess of relevance to the HBME. Increased wind speeds have been observed throughout areas of the HBME along with directional shifts to warmer south and easterly winds (Cheng 2014; Fazel-Rastgar 2019). Projections of increased wind speeds in the HBME will have impacts on the wave climate as well as sea ice extent. Little information can be found on changes to waves within the HBME, although increased wave heights are predicted in the latter part of the century within Foxe Basin (Khon et al. (2014).

Savard et al. (2014) used the IPCC's SRES A2 scenario to project storm characteristics for the Hudson Bay area in 2041–2070 compared to 1961–2000. The number of cyclonic centres (centres of low pressure systems) was projected to increase by one quarter under the A2 scenario in winter as a result of increasing open water, with no changes in the average number of cyclonic centres on an annual basis (see Candlish et al. 2019b; Candlish et al. 2019a). Francis et al. (2018) found that warming Arctic air temperatures, including over the Hudson Bay region, are associated with a pattern of increasing weather-regime persistence, where persistent weather can lead to destructive extreme events (e.g. prolonged cold spells, heat waves, flooding). Leung and Gough (2016) assessed changes in air mass distribution and temperature trends from 1971 to 2010 in the HBME, and linked statistically significant temperature increases with statistically significant changes in air mass frequency at the same locations, particularly the declining frequency of dry polar air. The authors conclude that a fundamental shift in the concurrent air mass frequency, paired with changes in radiative forcing due to anthropogenic climate change, are influencing the heterogeneity of the climate warming signal in the HBME.

Analysis of winds over the HBME from 1998–2015 in comparison to the 'normal' period of 1981–2010 showed increases in wind speeds around James Bay and eastern and northwestern Hudson Bay (Fazel-Rastgar 2019). Shifts in wind direction from the colder northwesterly to the relatively warmer south and easterlies were found. Further, an anti-cyclonic anomaly pattern, which has been linked to sea ice decreases in summer and fall, was identified over most parts of Hudson Bay. These findings accord with research findings for Canada and the circumpolar Arctic. Cheng (2014) found that over the last five decades, wind gust speeds over Canada increased significantly as the daily temperature anomaly increased and the daily pressure anomaly decreased. For every 1 hectopascal (hPa) decrease in daily pressure anomaly, the speed of wind gust events ≥ 50 km per hour increased by more than 0.2 km per hour over most regions and by 0.4 km per hour over the Hudson Bay Complex (HBC; includes Foxe Basin, Hudson Strait, Ungava Bay, Hudson Bay and James Bay). As a result, future temperature and pressure anomalies can be expected to further increase wind gust events over the HBME. Mioduszewski et al. (2018) analyzed near-surface winds over the Arctic Ocean for 1971–2000 to project changes in 2071–2100. The authors project the most substantial increases in winds over the central Arctic Ocean, but their model also projects an increase in wind speed in eastern Hudson Bay and Foxe Basin in winter and in eastern and south-central Hudson Bay in spring. Increasing wind frequency and strength amplified changes by increasing wave heights, coastal erosion, and further breakup of vulnerable sea ice (Mioduszewski et al. 2018).

Little information is available on the wave climate of Hudson Bay (Steiner et al. 2013). An analysis of current and projected future wave activity for the northern hemisphere by Khon et al. (2014) indicate increases in significant wave heights in the northern regions of the HBME (Foxe Basin) of about 95% in 2046–2065 relative to 1980–1999. Changes to wind speed, sea ice loss and longer fetches all appreciably contribute to increased wave height-response.

5.3 RIVER INPUTS

Recent studies on river discharge into the HBME indicate that there is a recent upward trend in overall discharge (Déry et al. 2011) This is consistent with global climate models which project increasing rates of river discharge in the circumpolar Arctic throughout this century (Steiner et al. 2015). Increased riverine output, resulting in part from increased temperature and precipitation, will have impacts upon sea ice, water column stratification as well as biological productivity (MacDonald et al. 2018).

Recent changes in river inputs into the HBME have been documented. Déry et al. (2005) examined discharge data for 42 rivers flowing into the Hudson Bay Complex, and found a decline of 2.6 km^3 of freshwater inputs per year for 1964–2000, equivalent to a 13% decline in annual streamflow per year for the system. Over this period, the authors found that 36 out of 42 rivers showed decreasing discharge, including 33 rivers that are not affected by dams, diversions, and/or reservoirs. Large and significant declines in freshwater discharge in the Churchill and Koksoak rivers are attributed to their partial diversions into the Nelson and La Grande Rivière river systems. When the impacts of these diversions are removed, the Nelson and La Grande Rivière systems still show negative trends. In the Nelson River, low rates of precipitation and high evaporation rates coupled with increased reservoir retention are responsible for the observed declining discharge. Additionally, the authors found that the annual spring peak discharge associated with snowmelt advanced by eight days over the four-decade period and diminished by 0.036 km^3 per day in intensity. In a more recent study focused on 23 rivers flowing into the HBME over 1964–2008, Déry et al. (2011) did not find annual changes in total discharge but did identify decadal trends: a downward trend from the mid-1960s to the mid-1980s then relatively high flows in the mid-1980s; and then an upward trend starting in the early 1990s, marked by a record annual discharge in 2005.

Global climate models consistently project increasing rates of pan-Arctic river discharge for the 21st century (see Steiner et al. 2015). A review by Steiner et al. (2013) discusses how the recent trend of increasing streamflow into the HBME may be a result of the intensification of the hydrological cycle, consistent with other regions of the Arctic. It has been proposed that rising air temperatures in the Arctic will enable moisture loading in the atmosphere and in turn increase precipitation levels. Thus, changes in HBME river inputs since the 1990s may be related to impacts of anthropogenic climate change but could also be a result of changing precipitation patterns driven by the Arctic Oscillation (AO). The AO is an atmospheric circulation pattern which influences the weather and climate of the Northern Hemisphere as it fluctuates between negative and positive oscillations. Changes in oscillations also manifest as variability in the stratospheric polar vortex, a low-pressure air mass which constrains and affects the location of the jet stream (Dahlman 2009; Steiner et al. 2013).

MacDonald et al. (2018) and Arnell (2005) project future river discharge into to the HBME. MacDonald et al. (2018) drive their model using CMIP5 to investigate impacts of global mean temperature warming of 1.5 and 2.0 °C on the Hudson Bay Complex, and consider values from the RCP 4.5 and 8.5 scenarios to span the range of projected changes (see Box 5.1 for more information on RCPs). The authors found that discharge in 2070 compared to 1986–2005 is projected to increase in all seasons except summer, due to projected precipitation increases of 2% in summer to 19% in winter. Northern Hudson Bay and Foxe Basin, as well as Hudson Strait outside of the HBME, are expected to experience the greatest rise in discharge, exceeding 10% above historical annual means. Extreme daily high flows are also projected to exceed historical levels. These projections are consistent with river discharge projections for the HBME developed by Arnell (2005). Driving their model using HadCM3 A2 and B2 emissions scenarios, Arnell (2005) found that in 2080 compared to a 1961–1990 mean, the average river discharge into Hudson and James Bays will increase by approximately 4%, while the average discharge into Foxe Basin will increase by 31%. Additionally, Chassé et al. (2013) assess precipitation, evaporation and freshwater flux over Canada for 1986–2005 to project changes for 2066–2085. The authors find that for the Hudson Bay watershed, precipitation is expected to increase 15% (RCP 8.5), while evaporation is expected to increase by 17%. Overall, they project an increase of 11% of precipitation less evaporation (P-E) over the baseline for 2066–2085. Modelling also suggests an earlier occurrence of the freshwater pulse in the Hudson Bay watershed in the future, by approximately 12 days per century.

Increased river discharge into the HBME has numerous implications. Elevated freshwater flux impacts sea ice (lower salinity and increased sea ice thickness), water column stratification and biological productivity (MacDonald et al. 2018). Increased temperature and precipitation are also expected to enhance contaminant influxes to aquatic systems via accelerating rates of deposition and transfer. The increased contaminant mobility resulting from permafrost melt is an example of this. This enhanced influx results in the increased vulnerability of aquatic organisms to contaminant exposure and effects, leading to higher contaminant loads and biomagnification (Wrona et al. 2006). For example, atmospheric deposition of polychlorinated biphenyls (PCBs) to the surface of Hudson Bay has been found to be extremely low, likely related to the Bay's low productivity and vertical carbon fluxes (Kuzyk et al. 2010). Thus, if loss of sea ice or changes in river input increase marine production and vertical flux of carbon, PCB deposition would also increase (Kuzyk et al. 2010).

5.4 ACIDITY

Oceans absorb a large portion of anthropogenic CO_2 emissions. While this reduces global warming as a result of greenhouse gases, it also alters ocean chemistry in a process termed ocean acidification (for a detailed description of see Lavoie et al. 2013; Steiner et al. 2014; Azetsu-Scott 2018). When CO_2 enters the ocean, it dissolves in the surface water to form carbonic acid (H_2Co_3), which dissociates to form hydrogen ions (H^+). This dissociation decreases pH (increases acidity) as well as the concentration of the carbonate ion (CO_3^{2-}), a building block of calcium carbonate ($CaCO_3$) shells and skeletons. Two forms of $CaCO_3$ commonly produced by marine organisms are aragonite and calcite, with the former being more vulnerable to undersaturation in marine waters. Ocean acidification reduces the aragonite saturation (Ω_{arg}) and calcite saturation (Ω_{cal}) of seawater, and negatively impacts marine organisms that build calcium carbonate ($CaCO_3$) shells and skeletons. These include coccolithophores, a group of calcite-plated marine phytoplankton that are the basis of some marine food chains; pteropods, which are a food source for a variety of northern fish; and cold-water corals, which provide important habitats for other organisms, in addition to a wide variety of species that are important for subsistence and commercial harvests. $CaCO_3$ shells start to dissolve when marine waters become undersaturated with respect to $CaCO_3$. The solubility of CO_2 in seawater increases with decreasing temperatures, which means that cold Arctic waters have naturally low saturation states for aragonite and calcite and are vulnerable to further decline (Steiner et al. 2014). In the Arctic, ocean acidification driven by rising CO_2 levels is intensified by increasing river runoff, multiyear sea ice melt, and the oxidation of methane from thawing subsea permafrost (AMAP 2018).

Steiner et al. (2015) determined that the Hudson Bay region is one of the most vulnerable to ocean acidification in the Canadian Arctic. This is due to (1) the large freshwater input from rivers, typically resulting in a reduction of the buffering capacity of marine waters (Azetsu-Scott et al. 2014), and (2) projected changes in ice cover, which allows for greater exchange of atmospheric CO_2 across the air-water interface, and is discussed in more detail below. There are only limited, seasonal observations of biogeochemical variables in the Arctic, leading to gaps in baseline data that include the HBME (Steiner et al. 2014). No data on acidification are available for the HBME between 1990 and 1999, however, data for 2000 to 2011 show that the aragonite saturation state and pH were low (Steiner et al. 2015). Calcite saturation states have also been found to be low throughout the HBME with river runoff and loss of sea ice having a significant influence upon the reduced $CaCO_3$ saturation states (Azetsu-Scott et al. (2014). River runoff impacts saturation states by diluting carbonate and calcium concentrations and reduced sea ice enables greater uptake of CO_2, which can result in $CaCO_3$ under-saturation. Projections of surface water pH in the HBME show declining trends as well as a shallowing of the aragonite saturation horizon depth, as described below (Lavoie et al. 2013).

Further, Azetsu-Scott et al. (2014) measured biogeochemical variables in Hudson Bay, James Bay and Hudson Strait in 2015 to investigate ocean acidification in these waters. The authors found very low $CaCO_3$ saturation states throughout the HBME. Over 67% and 22% of the bottom water of Hudson Bay was undersaturated with respect to aragonite and calcite respectively.

Freshwater inputs generally reduce the saturation state of seawater because they dilute carbonate and calcium concentrations, leading to increased partial pressure of CO_2 and greater CO_2 uptake (Azetsu-Scott et al. 2014). The authors found the calcium carbonate saturation state of seawater in the surface waters of the HBME to be strongly influenced by river runoff. Specifically, there was an aragonite under-saturation in the surface waters of southeastern Hudson Bay, where river runoff is proportionately higher. Heterogeneity in watershed characteristics were also found to influence the alkalinity of freshwater inputs, which contributed some variation. For example, in southwestern Hudson Bay where the watershed is dominated by limestone, the calcium carbonate saturation state of seawater was higher than in eastern Hudson Bay, where the watershed consists of an igneous rock formation. The aragonite saturation horizon (defined as Ω_{arg}= 1; water under the saturation horizon is undersaturated, and water over the horizon is supersaturated) in the central Hudson Bay was shallow, at around 50 m.

Retreating sea ice is a major driver of increasing acidification in the Arctic. This is related to the addition of melt water from multiyear ice and the increase in open water areas allowing for enhanced air-sea exchange (Steiner et al. 2014), with the latter being an important factor for HBME. Reductions in seasonal ice cover mean that the cold and relatively fresh surface water of Hudson Bay will take up more CO_2, likely leading to a totally under-saturation of $CaCO_3$ (Azetsu-Scott et al. 2014). Else et al. (2008) assessed baseline sea surface fugacity (partial pressure) of CO_2 in Hudson Bay, and found that nearshore outer-estuary systems act as a source of CO_2 (supersaturated with respect to atmospheric CO_2) while offshore regions act as a sink (undersaturated with respect to atmospheric CO_2). Implications for acidification are not clearly stated by the authors, but presumably this may influence heterogenous CO_2 absorption and thus acidification across HBME in the future.

Lavoie et al. (2013) project future physical and biogeochemical conditions in Hudson Bay, James Bay and Hudson Strait by comparing outputs of five models for 2050 compared to 1960–2005 data. All models show decreasing trends for pH in surface waters, and the multi-model mean trend represents a pH decrease of 0.11 and 0.20 units over the next 50 years for RCP 4.5 and 8.5, respectively (see Box 5.1 for more information on RCPs). The authors also analyze the aragonite saturation horizon for one of the models (CanESM2) for the period of 2012 to 2062, projecting it to decrease at a rate of -69.5 cm and -116 cm per decade to reach the surface around 2065 and 2055 for RCP 4.5 and RCP 8.5, respectively. However, the authors also note that initial saturation horizon depths modelled are too shallow, so the saturation horizon may not reach the surface as early as projected.

5.5 PRIMARY PRODUCTIVITY

Phytoplankton, ice algae, benthic (micro and macro) algae and benthic vascular plants (e.g. eelgrass) together contribute to total primary production of the HBME (Niemi et al. 2010). Models have indicated that primary production in Arctic waters has been increasing in recent years as a result of sea ice decline as well as a longer growing season (Arrigo et al. 2008). This increasing trend is also apparent within the HBME with primary productivity increasing by 27% in Hudson

Bay over 15 years (Frey et al. 2018). Predicting the outcomes of climate change upon primary productivity within the HBME is difficult as changes in the timing of the ice algal and phytoplankton blooms are expected (Moline et al. 2008). There is evidence that the warming waters and altered bloom times may change the species composition of the algal community, possibly displacing larger plankton species such as diatoms with smaller picoplankton (Lovejoy 2014; Steiner et al. 2015). Projections do indicate a probable continued increase in primary productivity within the HBME, primarily within the subsurface chlorophyll maximum (Lavoie et al. 2013).

Ice algae and phytoplankton transform dissolved inorganic carbon into organic material in the Arctic marine ecosystem. As a result, they provide a critical ecosystem service, transferring energy up the food web (Frey et al. 2018). Changes in sea ice have contributed substantially to shifts in primary productivity in the Arctic in recent years, including in the HBME (Frey et al. 2018). Environmental forcing of nutrient supply to the surface, specifically nitrogen, has been proposed as the main driver of primary productivity in seasonally ice-free marine waters (Tremblay and Gagnon 2009). Arrigo et al. (2008) used a primary production algorithm (as a function of diurnal changes in spectral downwelling irradiance, sea surface temperature and chlorophyll *a* concentration) to calculate that annual primary production in the Arctic has increased yearly by an average of 27.5 teragrams of carbon (Tg C = 1 million metric tons of carbon) per year since 2003 and by 35 Tg C per year between 2006 and 2007. The authors found that 30% of this increase was attributable to decreasing minimum summer ice extent and 70% to a longer phytoplankton growing season. Frey et al. (2018) calculated primary production based on algal chlorophyll-*a* (Chl-*a*) estimates from satellite-based data during ice-free periods (not including sea ice algae or under-ice phytoplankton blooms). The authors found widespread positive (increasing) primary productivity anomalies for all regions in the Arctic in 2017 compared to the 2003–2016 mean, with Hudson Bay among the areas with the highest anomalies. The oligotrophic conditions of the HBME mean that Chl-*a* and primary productivity are generally low. In this context, over 2003 to 2017, primary productivity increased in Hudson Bay by 27%. Steiner et al. (2015) report on unpublished satellite-derived phytoplankton biomass and primary productivity data for 1998 to 2010 for Hudson Bay (P. Larouche, Maurice-Lamontagne Institute, unpublished data). Satellite results showed a 20–25% increase in Chl-*a* biomass per decade and a 15–20% increase in primary productivity per decade. At the same time, a study of dinocyst assemblages in the sedimentary record of Hudson Bay found a differing trend (Ladouceur 2007). Dinocysts or dinoflagellate cysts are a dormant stage in the lifecycle of dinoflagellates, a marine plankton (Zonneveld and Pospelova 2015). Findings suggest that a shift in the algal community occurred from heterotrophic dinoflagellates, associated with a diatom-dominated community, to autotrophic dinoflagellates. These autotrophic taxa are characteristic of warmer temperatures and higher productivity, indicating that primary productivity was higher in the 1980s than in the 2000s (Ladouceur 2007).

Implications of climate forcing on primary productivity in Arctic marine waters are complex. There are concerns that across the Arctic, loss of sea ice and subsequent increases in water column stratification and light availability may alter microbial community structure and the degree of pelagic-benthic coupling (Arrigo et al. 2008; Lovejoy 2014). The spring phytoplankton bloom has been described as a band of production following the receding ice-edge. Changes in breakup timing are expected to lead to earlier timing of the phytoplankton bloom, changes in the timing and extent of ice edge blooms, and decreased time-lag between the phytoplankton bloom and ice algal bloom (Lovejoy 2014; Barber et al. 2015). The timing and rate of sea ice loss affects physiological stress in ice algae and mortality in zooplankton related to the nutritional status of ice algae, with consequences for higher trophic levels (Moline et al. 2008). Thinner ice is expected to allow increased light intensity to reach the ice algal layer, causing algae to slough off from the ice earlier in the season (Barber et al. 2015). Blooms of phytoplankton adjacent to the marginal ice zone could also result in a more sporadic occurrence of ice-edge blooms and limit the access of seabirds and marine mammals to secondary production associated with under-ice phytoplankton blooms (Barber et al. 2015). In the Canadian Arctic, warming and freshening of the surface layer is leading to a displacement of large nanophytoplankton species by small picophytoplankton cells in the offshore, with potentially significant marine food web impacts (Steiner et al. 2015). Earlier blooms mean changes in day length during bloom time, which can influence species composition. Adding to this selection pressure on microbial communities are the impacts of ocean acidification (Lovejoy 2014). Changing wind and storm patterns will also influence stratification, mixing and upwelling, and thus nutrient distribution and primary productivity (Niemi et al. 2010).

Atmospheric forcing is also leading to other changes that affect primary productivity. Bélanger et al. (2013) assessed photosynthetically active radiation (PAR) above and below the Arctic sea surface, which is an important limitation for marine photosynthesis at northern latitudes. The authors found that while primary productivity has been rising at a rate of 14% per decade in the circumpolar Arctic and more, when considering subarctic seas, PAR above the sea surface significantly decreased over the whole Arctic and subarctic seas because of increased cloudiness in the summer (except in areas of the Arctic Ocean with full-year ice coverage). The largest decreases were found between 55° and 70°, in the latitudes where the HBME lies. For the HBME, PAR under the sea surface was also found to have decreased despite primary productivity increasing, related to the optical properties of the water (nutrients depleted surface waters limited by haline stratification). Over 1998–2009, the trend in reduction in primary productivity due to increasing cloudiness in the HBME was 0.19% per year.

Eelgrass (*Zostera marina*) beds in the James Bay region and the salt marshes of coastal southwestern Hudson Bay are also a contributor to primary productivity and form the base of major food chains in these coastal marine ecosystems (Stewart and Lockhart 2005). Despite their importance, there is limited data on benthic primary production by eelgrass (Capelle et al. 2019). Water depth, ice thickness, local currents, amount of runoff, spring tides or storm surges, and the timing and speed of breakup can all interact to affect the eelgrass beds, in ways that can promote or inhibit growth (Stewart and Lockhart 2005). Current threats to eelgrass include nutrient pollution, an overabundance of nutrients that is a precursor to eutrophication, and suspended sediments, both of which reduce water clarity and impact photosynthesis and growth (Tremblay et al. 2019). A recently initiated study overseen by Niskamoon Corporation (formed to facilitate the agreements between James Bay Cree and Hydro-Québec) focused on the changing ecology and oceanography of the coastal region of Eeyou Istchee where eelgrass is a key environmental feature. The Coastal Habitat Comprehensive Research Program will run from 2017 to 2020 and updates are documented in Niskamoon Corporation's newsletters and annual reports. This study may increase our limited knowledge of potential impacts of atmospheric forcing on eelgrass and their coastal habitat.

In the HBME, Ferland et al. (2011) found there to be a high degree of complexity in primary production, biomass, and in the relationships between these properties and the water column structure. This study suggests this will complicate predictions of how the system will respond to global warming. Lavoie et al. (2013) projected biogeochemical conditions in HBME in 2050 for a suite of models compared to 1960–2005 data. Primary productivity is projected to increase by 9.5% over the next 50 years (RCP 8.5; see Box for more information on RCPs), with most models showing a greater increase in the southern part of the region. Chl-*a* trends in the surface layer are divergent for different models. While no conclusions can be drawn for Chl-*a* at the surface, subsurface Chl-*a* is predicted to increase marginally. Nitrogen is a limiting factor of primary production in the HBME and the transport of nutrients from the bottom to the surface is limited by strong haline stratification. Most models show decreasing nitrate concentrations at the surface. All models show decreasing dissolved oxygen concentration at the surface, but trends in deeper layers are low and variable. Dissolved inorganic carbon concentration trends are weak and variable in all layers, so no conclusions can be drawn at this time.

5.6 FOOD WEBS

Changes in ice, weather, freshwater inputs, ocean acidity, atmospheric forcing and the resulting changes in primary productivity are already affecting food webs in the HBME in complex ways. Moline et al. (2008) describe how reductions in sea ice extent lead to habitat loss for sympagic species such as amphipods, copepods, hyperiids, Arctic cod, and seals. Further implications of climate warming include introduction of new species, leading to possible competition and displacement of Arctic species, and disruption of spatially- and temporally dependent trophic interactions between predators and prey, in addition to changes to primary production. This resulting trophic mismatch could have substantial consequences for species in the HBME such as nutritional stress as well as reduced abundance and reproductive success. The growing body of research on food web implications of global warming in the HBME is distributed unevenly among species and food web interactions, with more studies on marine mammals than other wildlife groups. Among these, most studies relate to polar bears and ringed seals. Studies related to key wildlife groups and trophic interactions are summarized below.

In addition to food web changes in the HBME described below, climate warming is expected to have direct impacts on the susceptibility of organisms to contaminant exposure. In particular, mid- and higher trophic level species are vulnerable to exposure via bioaccumulation and biomagnification. Increased contaminant exposure results from indirect impacts brought about by ecosystem changes such as the loss of sea ice, altered hydrology and increased productivity (Barber et al. 2012). For example, reduced sea ice extent increases the surface area of the ocean available for particulate mercury to settle upon, allowing higher concentrations to become integrated into Arctic marine food webs and bioaccumulate within higher trophic levels (AMAP

2011). Contaminants in freshwater food webs (which may also have implications for marine food webs in the HBME due to high levels of freshwater input into the region) are expected to be affected by changes in temperature, water chemistry and the hydrological regime. Increased methylmercury (MeHg) concentrations released into freshwater systems are expected as temperatures increase and permafrost soils thaw. Dissolved organic matter (DOM) input into freshwater systems is also expected to increase with climate warming, in part due to increased precipitation. Higher DOM concentrations in lakes reduces the penetration of visible and UV light, a key factor involved in the decomposition of MeHg, into the water column. Furthermore, research into *Daphnia* species in Arctic lakes indicates higher levels of MeHg than observed in other freshwater zooplankton. The distribution of *Daphnia* is linked to productivity, therefore, subsequent increases in productivity occurring from elevated temperatures could cause an expansion in their distribution throughout the Arctic. Fish taking advantage of this increased food resource would be consuming higher levels of mercury, resulting in bioaccumulation and subsequent biomagnification within the food web. Nonetheless, there are still major gaps in knowledge related to implications of climate warming for Arctic freshwater food webs (AMAP 2011). For a detailed explanation of the interactions between climate change and mercury in aquatic systems of the Arctic, see the AMAP's *Assessment 2011: Mercury in the Arctic*.

Invertebrates and fish

A review by Steiner et al. (2015) discusses how limitations in data and direct observations about zooplankton in the HBME preclude a trend analysis, but find evidence in the literature for zooplankton distribution being affected by environmental changes. Zooplankton distribution has been found to be strongly correlated with water column stratification, therefore any major alterations to stratification from changes such as increased freshwater input from rivers or sea ice melt would also result in impacts on distribution.

To assess changes in fish, shellfish and invertebrates in the HBME, the diets of seabirds have been studied. Based on the diets of thick-billed murres, Provencher et al. (2012) found that the proportion of cold-water hyperiid amphipods has decreased at Digges Sound compared to levels in the 1970s and 1980s, as had Arctic cod. Meanwhile, the proportion of two subarctic fish—capelin and sandlance—and mysids in thick-billed murres has increased, indicating a northward expansion of these subarctic fish species. Despite these changes, the authors also found that invertebrate species characteristic of southern waters have not yet moved northward (from southern Hudson Bay to Davis Strait). Gaston et al. (2003) found similar trends based on observations of food delivered to nestlings of thick-billed murres at Coats Island and Digges Island. The authors found that the incidence of Arctic cod, sculpins, and benthic zoarcids decreased and the incidence of capelin and sandlance increased over 1980 to 2002. Specifically, Arctic cod fell from an average of 43% of deliveries in the mid-1980s to 15% in the late 1990s, while in the same period benthic species (zoarcids and sculpins) fell from 36% to 15%, and capelin increased from 15% to 50%. Similarly, Gaston and Elliott (2014) found that between 1981 and 2013, the proportion of Arctic cod in thick-billed murre diets at Coats Island decreased, and the proportion of capelin increased, even when effects of changing ice conditions were taken into account. The authors link these changes to implications of atmospheric forcing, and specifically declines in ice cover, in the HBME (Gaston et al. 2003; Gaston et al. 2012). Arctic cod is strongly associated with sea ice throughout its range as it uses the underside of the ice for foraging and to avoid predation, therefore loss of sea ice cover increases the vulnerability of this species.

An unusual and large number of small jellyfish (*Aglantha digitale*) were unintentionally collected in sediment traps in the HBME in 2006/2007, potentially an early indication of ecosystem changes in the region brought on by climate warming (Lalande and Fortier 2011). The biomass of *A. digitale* has been found to be positively correlated with temperature and the large number collected may indicate an elevated frequency of jellyfish blooms. However, the lack of data impedes identification of any positive trend as interannual variability in this species's abundance has been documented. Recent anomalous extreme warm temperatures were linked to fish die-offs in the Albany River in western James Bay (Hori et al. 2012).

Poesch et al. (2016) synthesize key ongoing and projected environmental changes in Canadian freshwater fishes, which generally apply to fishes in the coastal inland areas around the HBME, including changes in contaminant bioaccumulation, quantity and access to critical habitat as well as community composition and relative abundance. These changes are driven by a combination of climate change impacts as well as impacts of development activities and human population increases. For more details on some key environmental changes (ongoing and anticipated) in Canadian freshwater ecosystems and potential consequences to their fish communities resulting from climate change refer to Poesch et al. (2016, p. 387).

Birds

As indicated, changes in fish species in the HBME driven by changes in environmental conditions have already had implications for seabirds. Research has shown that breeding biology of thick-billed murres in northern HBME is associated with ecosystem alterations driven by climate change (Gaston et al. 2005; Gaston et al. 2012). For instance, timing of thick-billed murre egg laying on Coats Island is positively correlated with higher summer ice cover when greater than 50%, therefore, reductions in ice cover will likely lead to earlier laying.

Simultaneous to the decrease in ice surrounding Coats Island and the switch from Arctic cod-dominated diet to a capelin-dominated diet, the date of murre egg-laying at Coats Island occurred earlier in the year and chick growth rates and adult body mass had decreased (Gaston et al. 2005; Gaston et al. 2012). Gaston and Elliott (2014) found that thick-billed murre diets at Coats Island had an increasing portion of benthic fish (stichaeids, zoarcids, pholids and sculpins) and invertebrates (squid, amphipods and crustaceans), secondary prey items with lower comparative nutritional value, when ice cover was low and hatching was late relative to ice breakup. Further, chick growth rates were low when the proportion of benthic fish were high, demonstrating impacts of diet composition on growth.

Changing mosquito emergence timing relative to murre hatching time, driven by environmental changes, is also affecting murre reproductive success (Mallory et al. 2010). Gaston et al. (2005) predicted that, based on current trends, continued climate warming is expected to adversely affect reproduction of thick-billed murres, likely resulting in an eventual northward displacement of the population. As Mallory et al. (2010) explained, for the piscivorous murres, earlier ice breakup is creating a mismatch between the timing of breeding and the peak in food availability. However, delayed freeze-up dates are also being observed, meaning that the birds can remain in the HBME longer into the fall, although current research indicates this does not have a substantial effect on reproductive success (Gaston and Elliott 2014).

Changes in murre diet are also leading to changes in contaminant exposure. Braune et al. (2014) show that thick-billed murres breeding at Coats Island lowered their trophic position as a result of dietary change. After adjusting mercury concentration in murre eggs for trophic position, the trend over time of mercury in murre eggs increased from nonsignificant to significantly increasing. As a lower mercury concentration is typically associated with lower trophic levels, these results provide support for increasing mercury bioavailability in the HBME.

While changing environmental conditions are leading to primarily negative impacts on thick-billed murre, they are also leading to expansion of razorbills into the HBME. Razorbills were first documented at Coats Island in 1998, a site that is 300 km from their previous most westerly site and 2,000 km from their nearest largest colony (Gaston and Woo 2008). Their appearance at Coats Island is correlated with the increases in numbers of sandlance in the HBME, a preferred prey for the species. For non-migratory common eider in southern HBME, more open water (larger and more numerous polynyas and floe edges) are generally expected to increase gathering of prey necessary for overwinter survival (Mallory et al. 2010).

Predation on birds is also being affected by changing climatic conditions (Smith et al. 2010; Iverson et al. 2014). Iverson et al. (2014) show that polar bear incursions on common eider and thick-billed murre in the HBME (around Digges Island and the intersection between Foxe Basin and Hudson Strait) as well as nearby areas (in Hudson Strait and Ungava Bay) increased sevenfold since the 1980s. Polar bear visits to nesting areas increased as the length of the ice season decreased. During years of low ice coverage, the authors found bears or bear signs on more than one third of eider ccolonies and estimated that egg losses caused by bear predation exceeded that of typical nest predators (foxes and gulls).

Research centred on the Hudson Bay Lowland has shown changes in goose habitat and reduced abundance in the last 30 to 40 years, with more significant change in more recent decades. For example, Cree hunters from James Bay described how they were no longer able to find snow geese to hunt and they have observed altered migrations such as flying further inland when the migration route used to be more coastal (Peloquin and Berkes 2009; Robus 2012; Tam et al. 2013). These changes are linked to environmental changes as a result of climate warming. As ice breakup becomes more rapid, many geese are spending less time in the James Bay area as they migrate northwards, which reduces hunting opportunities.

Seals and whales

Changing ice conditions have differing implications for marine mammals, depending on a variety of factors. Ringed seals have been a focus of study in the HBME in relation to changing environmental conditions, as they use snow-covered sea ice for reproduction and survival (Chambellant 2010). Based on aerial surveys, Ferguson et al. (2017) found a gradual decline in ringed seal density in the HBME from 1995 to 2013. The authors also found that body condition decreased and stress (cortisol levels) increased over time, in relation to shorter duration of ice cover. Luque et al. (2014) found that ringed seal adults in the HBME restricted movement more than juveniles during the winter ice-covered period, and suggested that as a result, reduced stable fast ice and less predictable ice conditions should have a disproportionately larger effect on adults by reducing the ability to gather resources for reproduction or produce milk for pups.

Chambellant (2010) found that in the HBME, sandlance is a major component of the ringed seal diet in the fall and Arctic cod is a minor proportion of the diet. This contrasts with other Arctic locations where Arctic cod is a major component of the seal fall diet. Young and Ferguson (2014) found that seals in northwestern Hudson Bay appeared to have a greater reliance on capelin than those in southeastern Hudson Bay, demonstrating the foraging plasticity of ringed seals and potential adaptations to changing food availability. It has been hypothesized that a reduction in sea ice cover in the HBME may be shifting the habitat suitability towards harbour seals. Increases in harbour seal abundance were observed at the Churchill River estuary between 1996 and 2016, potentially indicating a trend that may be seen in other locations in the HBME (Florko et al. 2018).

Further, observations of killer whales in the HBME in recent decades have risen exponentially, associated with changes in ice cover and access, leading to concerns about increased killer whale predation on bowhead whales in Foxe Basin, narwhal in northwest Hudson Bay, and beluga in southwest Hudson Bay (Ferguson et al. 2009).

Implications of climate forcing on the bowhead whale use and its use of the HBME is uncertain (Higdon and Ferguson 2010; Pomerleau et al. 2012). Higdon and Ferguson (2010) describe bowhead use of the northern extent of the HBME, including a spring nursery in northern Foxe Basin and late summer and fall feeding locations in northwest Hudson Bay. The authors describe how loss of sea ice and warming are expected to influence bowhead distribution and abundance in general, and specifically may increase killer whales access to nursery areas in Foxe Basin. Increased shipping due to reduced ice may have negative impacts on bowheads. There is also the potential that increases in primary production and zooplankton abundance may also increase feeding opportunities. Dietary changes for the North Hudson Bay narwhal population have been identified for the last three decades, with shifts from Arctic species such as Arctic cod to Subarctic species such as capelin, and are associated with changes in sea ice patterns and resulting changes in migratory pathways (Watt 2013). The North Hudson Bay narwhal population forages more on benthos compared to the two other global populations of narwhals, and differences in primary prey of narwhal populations demonstrate the potential adaptability of narwhals to foraging strategies in response to changing environmental conditions (Watt 2013; Watt et al. 2013).

Further, for wildlife that depends on ice such as belugas and seals, ice extent-related changes in habitat selection and feeding behaviour have been identified as affecting dietary exposure to contaminants such as mercury (AMAP 2011). Gaden et al. (2009) found that as the ice-free season in the western Canadian Arctic was elongated, higher mercury concentrations were found in ringed seals. These increases were related to increased marine productivity and therefore, higher rates of Arctic cod consumption by the seals which led to greater mercury accumulation.

Polar bears

A large number of studies has been conducted on polar bears in the HBME, with particular attention on the Southern and Western Hudson Bay subpopulations (Regehr et al. 2007; Rockwell and Gormezano 2009; Castro de la Guardia et al. 2013; Gormezano and Rockwell 2013; Hammill 2013; Galicia et al. 2016; Lunn et al. 2016). Kuzyk and Barber (2019) explain that scientific assessments show that polar bear subpopulations are stable, with the exception of the Southern Hudson Bay subpopulation. The editors of the third Integrated Regional Impact Study (IRIS-3) also note that variability in scope and methods, including in relation to approaches that use scientific methods and approaches that focus on Indigenous Knowledge, have led to differing perceptions or assessments of subpopulation trends.

Several studies have shown associations between changes in polar bear diet and/or bear survival and spring break up timing (Regehr et al. 2007; Lunn et al. 2016; Johnson et al. 2019). Hammill (2013) describes how climate warming is expected to impact polar bears feeding on ringed seals in the HBME in two primary ways: by shortening the period where there is sufficient ice to enable bears to access seals, and by affecting ringed seal abundance. Johnson et al. (2019) assessed polar bear hair isotopic values from the Western Hudson Bay subpopulation, and found that values were significantly correlated with the length of the open water period, indicating that changing ice conditions impact polar bear diet. Lunn et al. (2016) modeled future population rates of the Western Hudson Bay polar bear subpopulation based on environmental variables, and estimated long-term growth rates, through the use of survival and reproduction rates in matrix projection models, at approximately 1.02 and 0.97 under hypothetical high and low sea ice conditions. Castro de la Guardia et al. (2013) modeled changes in sea ice conditions in spring forced with IPCC greenhouse gas emission scenarios to assess potential future changes to Western Hudson Bay polar bear habitat. The authors found that under medium and high emissions scenarios sea ice, which provides critical polar bear habitat, deteriorated rapidly after 2050.

However, recent studies have also shown the prey switching abilities of polar bears and general plasticity in foraging, indicating that the bears are opportunistic omnivores that may adapt foraging strategies as environmental conditions change (Gormezano and Rockwell 2013; Iverson et al. 2014; Galicia et al. 2016). Gormezano and Rockwell (2013) assessed Western Hudson Bay polar bear scat and found an increasing proportion of caribou and snow geese in the bear's diet compared to a similar study four decades ago. They also noted previous observations of polar bears seeking eggs onshore even when seals were available on the ice. Fatty acid analysis of polar bears harvested in Foxe Basin in 2010–2012 was used to examine feeding habits (Galicia et al. 2016). The authors found that the ringed seal was the primary prey in Foxe Basin, and that walruses also contributed to polar bears' diets. Significantly, the authors found that bowheads were also present in the diets of polar bears in all areas and age and sex classes, although it represented a greater proportion of the diets of subadult bears. Opportunistic scavenging of bowhead is the result of stranding, killer whale predation, or anthropogenic mortality. The authors suggest that increasing abundance of killer whales and bowhead whales in the region could be indirectly contributing to polar bears foraging successes despite reductions in sea ice, at least in the short-term.

Changes in polar bear feeding ecology may also have implications for contaminant exposure. Changes in feeding in the Western Hudson Bay subpopulation over 1991–2007 resulted in increases in the tissue concentrations of several bioaccumulative chlorinated and brominated contaminants (McKinney et al. 2009). This change was associated with an increase in the consumption of open water-associated species (harbour and harp seals) and a decrease in the proportion of ice-associated species (bearded seals) in years of earlier ice breakup.

5.7 EFFECTS ON SUBSISTENCE HARVESTING AND ECOSYSTEM SERVICES

The implications of climate forcing on subsistence harvesting and ecosystem services in the HBME are complex and wide-ranging. While Inuit and Cree communities that live along the coast of the HBME are experiencing impacts of changing environmental conditions, they are also adapting to these changes. Numerous studies have been published on the human dimensions of climate change in the Arctic of relevance to the HBME (Nickels et al. 2006; Furgal 2008; Ford et al. 2012b; Ford et al. 2016; Ford et al. 2017).

The Millennium Ecosystem Assessment framework for ecosystem services identifies four main categories (Alcamo et al. 2003).

- *Provisioning services* are “products obtained from ecosystems”, such as food, freshwater and firewood;
- *Regulating services* are “benefits obtained from regulation of ecosystem processes” such as climate regulation, disease regulation, water regulation, water purification and pollination;
- *Cultural services* are “nonmaterial benefits obtained from ecosystems” such as cultural heritage, spiritual and religious, recreation and ecotourism, aesthetic, inspirational, educational and sense of place; and,
- *Supporting services* are “services necessary for the production of all other ecosystem services” such as stable ice cover, soil formation, nutrient cycling and primary production.

Ecosystem services accessed through subsistence harvesting relate to all four categories (provisioning, regulating, cultural and supporting services). As a result, these services and the implications of climate change for communities that depend on these services will be discussed holistically.

As described in detail in Chapter 3, a key motivation and benefit for land use by Inuit and Cree residents of communities along the coast of the HBME is subsistence harvesting. Wildlife resources are critically important for diets and livelihoods (provisioning services), as well as providing a range of nonmaterial benefits that span cultural identity; social, mental, emotional, spiritual and physical health and wellbeing; and sense of place and other place-based connections security in northern regions in relation to wild or country foods as it influences animal availability, human ability to access wildlife, and the safety and quality of wildlife for consumption. Past and likely future changes in abundance, distribution, timing of presence, and health of wildlife as a result of changes in the environment driven by climate warming are described in sections 5.2 to 5.6. To assess the potential nutritional impacts of the loss of country foods due to climate change in the Canadian Arctic, Rosol et al. (2016) collected data from participants in Arctic communities, including in the HBME. The authors show that while fish contributed less than 2% of all calories in the Kivalliq region, it provided almost one fifth of vitamin D, while whale also supplied approximately one fifth of vitamin D and zinc. A simulated 50% reduction in consumption of fish, whales, ringed seals and birds—all country food sources that were reported by communities to have declining abundance over the last year—resulted in a significant decrease in essential nutrients intake, even when considering the nutritional contributions of substitute foods. Thus, reductions in country food availability, access, and quality as a result of environmental changes have direct implications for nutritional intake.

Environmental changes are also bringing new species into HBME waters, with food web effects and potential effects on land use and harvesting. For example, Hammill (2013) describes the possible future implications of killer whales becoming a dominant apex predator in the HBME, and polar bears having a reduced presence. Polar bear harvesting has economic and food security benefits, while killer whales are not a traditionally hunted species and are a direct competitor for marine mammals. Thus, an increasing killer whale presence may have complex impacts that extend beyond food web changes and harvesting implications.

Sea ice is a critical element of the Arctic environment for Inuit, forming a continuous platform for travel that facilitates access to wildlife resources, movement between communities and across the vast Inuit homeland (ICC 2008; Aporta 2009). As a result, sea ice is considered critical infrastructure across Inuit Nunangat (i.e. it is a supporting service), at the same time as using sea ice provides a myriad of non-material benefits for mental, emotional, spiritual, physical and cultural health and wellbeing and place connections (cultural services) (Durkalec et al. 2015). Sea ice provides habitat to species that are depended on for subsistence harvesting, as described in Chapter 3, and also provides supporting services that extend outside of the Arctic region through the cooling effect of its high albedo (Ford et al. 2016). Changes in ice duration, extent and thickness in the HBME as a result of climate forcing are described in detail in section 5.1, and implications of these changes for other supporting services such as primary productivity and well as biophysical and oceanographic factors in the HBME that have implications for food webs and thus availability of species are described in sections 5.2 to 5.6.

Further, as in the rest of the Arctic, communities along the HBME coast have been reporting changes in ice and weather conditions that are leading to changes in travel safety and the timing and extent of access, increased travel costs, increased frequency and severity of injuries while hunting and travelling on the land, reduced opportunities for younger generations to engage in land activities, and impacts on intergenerational transmission of Indigenous Knowledge, among other changes (Nickels et al. 2006; Ford et al. 2006; Ford et al. 2008a; Ford et al. 2008b; Ford et al. 2009; Laidler et al. 2009). In climate change workshops that took place in Nunavik and Nunavut, including in Puvirnituq, Ivujivik and Naujaat along the HBME coast, participants identified complex implications of environmental change (Nickels et al. 2006). Themes common to Nunavut and Nunavik included hesitancy of Elders in providing weather predictions because of increasing unpredictability and variability in both weather and ice conditions; stronger winds leading to decreased travelling and hunting; earlier breakup and freeze-up making travel more unpredictable and dangerous; more occurrences of meat being discarded; less snow making travel by snowmobile more difficult and causing igloos to no longer be built; increasing frequency of sunburns; and increased spending on store-bought food; among other changes. These changes accord with those reported by residents of Igloolik (Ford et al. 2006; Ford et al. 2008b; Ford et al. 2009), who also reported some additional changes and changes specific to harvesting practices in Foxe Basin. For example, sudden and rapid changes in the wind were reported to cause walrus hunters to become stranded on moving pack-ice, and resulted in the loss of hunting equipment (Ford et al. 2006). In James Bay, residents of Fort Albany First Nation reported negative impacts on their traditional hunting lifestyle from shorter winters, earlier spring melt, less snowfall, differences in snow texture, thinner ice on frozen lakes, dry or increasingly shallow rivers, warmer seasons, unpredictable weather, and increases in severe weather conditions (Tam et al. 2013). Impacts and threats associated with various environmental changes that have been reported by communities across northern Canada are identified in Table 5.4.

Environmental changes and their resulting human impacts vary across the HBME, depending on a range of factors including how the climate signal interacts with existing biophysical conditions, human relationships with the environment, and existing vulnerabilities and capacities to adapt to change. For example, in Igloolik, Nunavut, located on the coast of Foxe Basin, ringed seals and walruses are important components of diets and the procurement, consumption and sharing of these country foods provides a range of cultural and social benefits (Laidler et al. 2009). Residents of Igloolik have reported earlier sea ice breakup, later freeze-up and more dynamic winter sea ice, resulting in numerous impacts on ringed seal and walrus hunting, such as delayed seal hunting, difficulty locating seals, walrus being further away in winter and increased break-off events at the floe edge causing hunters to become stranded (Laidler et al. 2009).

During 2006, ice conditions around Igloolik were anomalous as summer sea ice was absent, and freeze-up was delayed about 3-4 weeks (Ford et al. 2009). The absence of floating ice in summer had significant implications for walrus hunting in Foxe Basin:

> *'For the walrus hunt this year there [was] no ice at all, that was the problem. July and August there's no ice at all. ….. [Rowley Island] is walrus area, it always has ice, but this year there was none, no ice.' (L. Uttak, Dec 2006)* (Ford et al. 2009)

Table 5.4. Environmental changes and threats to health and wellbeing in northern Canada related to land use (after Furgal 2008, p. 342)

Environmental changes	Impacts and threats to health and well-being
Precipitation extremes and natural disasters	• Property damage, injuries and death, increased travel risks
Unpredictability of weather	• Limitations on hunting and travelling • Increased travel risks and injuries • Increased damage to equipment • Decreased access to traditional foods
Temperature-related injuries	• Changes in incidence of cold-related injuries • Increased heat stress
Warming temperatures and changing ice conditions	• Increased injuries and deaths (e.g. drowning) associated with uncharacteristic and dangerous ice conditions • Impacts to equipment and household economies • Decreased access to traditional food • Disruption of traditional cycles and impacts on social cohesion and mental well-being
Increased exposure to UV radiation	• Increased incidence of sun burns, rashes and blisters
Environmental changes and food security	• Decreases in traditional food availability (wildlife health and numbers), accessibility (changes in ice and snow conditions impacting routes to hunting grounds) and quality (safety of meat for consumption) • Appearance of new species
Water security	• Decrease in availability and accessibility to safe natural drinking water sources

In addition to travel risks and impacts on food security, changes in environmental conditions resulted in time-consuming and costly detours, limiting harvesting access for those with limited time and/or financial resources (Ford et al. 2009). Studies have documented the high level of adaptability among Igloolik residents to climate-related risks and changes resulting from traditional Inuit Knowledge, resource use flexibility and diversity, group mobility, and strong social and food-sharing networks (Ford et al. 2006; Ford et al. 2009; Laidler et al. 2009). However, increasing climate extremes and related-risks have also overwhelmed the adaptive capacity of some individuals and groups. Those with greater dependence on country food and those with limited financial resources were identified as being particularly vulnerable to impacts on food security related to climate risks (Ford 2009).

In James Bay, on the opposite southern extent of the HBME, Cree hunters have also been reporting environmental changes, impacts on harvesting, and individual and community adaptations to respond to changing conditions. In Fort Albany First Nation in western James Bay, residents have reported observing reductions in size, changes in taste, and flight pattern and migration timing changes for Canada geese and snow geese (Tam et al. 2013). In eastern James Bay in the Cree Nation of Wemindji, Cree hunters have been reporting declines in the number of geese harvested during spring and fall hunts for several decades related to a variety of factors, including hydroelectric development impacts, changes in hunting practices and environmental changes such as warmer temperatures and reduced ice thickness (Peloquin and Berkes 2009). The authors document how hunters employ Cree Knowledge, values and skills to respond to a wide variety of changing variables that affect goose harvesting. Sayles and Mulrennan (2010) document long-term Cree modification and enhancement of the landscape to retain and enhance desirable conditions for goose hunting, including the construction of mud dykes and cutting of corridors in the coastal forest, as an example of social-ecological resilience practices that are adaptive to changing environmental conditions as a result of climate warming.

Other cultural services are accessed through recreation and tourism (sport fishing, cruise tourism, adventure tourism, cultural and heritage experiences), and are becoming an increasingly important aspect of northern economies (Ford et al. 2016). Changing environmental conditions have the potential to affect tourism in positive and negative ways in the HBME, sometimes simultaneously, depending on the type and location. For example, while reductions in sea ice may increase access to cruise ships, reductions in sightings of ice-supported wildlife may bring long-term decline to cruise tourism in the HBME (Stewart et al. 2010). Polar bear wildlife viewing in Churchill, Manitoba by tourists appears resilient in the face of potential environmental impacts on bear populations, with the majority of tourists indicating a willingness to return even if they see only a fraction of the bears sighted previously (Hall and Saarinen 2010).

5.8 EFFECTS ON COMMERCIAL HARVESTS

Current commercial harvests within the boundaries of the HBME are mostly limited to anadromous fish species (Arctic char), eider down, kelp, mussels, and other macroinvertebrate species (clams, scallops, amphipods) occurring at various times within last few decades (see Section 3.5 for an overview of past and current commercial harvests in the HBME). Nearby in the Hudson Strait, commercial harvests focus on shrimp (see section 3.5). Despite the current limited scope of commercial harvests in the HBME, climate forcing may have complex implications on sea ice, food webs, and thus potential commercial fisheries development in the HBME.

Cheung et al. (2011) projected future commercial fish and invertebrate species change in the Hudson Bay Complex by 2050 using an algorithm which predicts the probability of a species occurrence within this larger region. The authors found that based on an estimate of 100 species, future species loss was projected at a loss of 0 to 1 for most of the HBC, and species gain was projected as 2 to 10 species under the SRES A1B climate scenario, totalling just under a 0.1 species turnover (gain + loss relative to current number) per 100 km^2. However, the authors note that given the relatively low species richness in regions such as the HBC, the gain or loss of relatively small numbers of species may lead to large changes in the overall species community structure. Arctic species are likely to move further north following sea ice retraction, with southern species moving into the HBC to replace them.

As reviewed in section 5.5, research has already shown declining abundance of some fish and invertebrate species in the HBME such as cold-water hyperiid amphipods (largely *Themisto* *libellula*), benthic fishes such as zoarcids, sculpins and cod, while capelin, sandlance, and mysids are increasing in abundance (Gaston et al. 2003; Provencher et al. 2012; Gaston and Elliott 2014). These changes are linked to impacts of atmospheric forcing on sea ice cover and the consequent impacts on food webs. Capelin are sensitive to changes in oceanographic conditions, particularly variability in water temperature, and Arctic cod habitat is associated with the underside of the sea ice surface (Gaston et al. 2003; Gaston et al. 2012). Decreases in sea ice cover contributing to substantial shifts in primary productivity in the HBME and across the Arctic, with recent primary productivity increases of 15–20% per decade in the HBME (Arrigo et al. 2008; Steiner et al. 2015; Frey et al. 2018). While a high degree of complexity in the HBME complicates future projections under climate warming scenarios (Ferland et al. 2011), models suggest that primary productivity will continue to increase in the HBME over the next several decades (Lavoie et al. 2013). Implications of this increasing primary productivity for commercial fisheries potential in the HBME is difficult to predict. The Arctic Council's *Arctic Resilience Report* discusses potential effects of global warming on Arctic ecosystems and ecosystem services, including the potential impacts of food web regime shifts on ecosystem services such as commercial fishing (Arctic Council 2016). The report suggests that it is unclear, given climatic and biological uncertainties, whether increasing primary productivity in the Arctic will increase the productivity of higher trophic levels (e.g. commercially attractive fish stocks) or be locked into lower trophic levels (e.g. plankton and jellyfish). Nonetheless, some projections have been made in future fisheries change that are relevant to the HBME based on other environmental variables and habitat suitability changes. A model projection by Tai et al. (2019) shows that based on projected changes in sea ice, temperature, and other environmental variables in the HBC, fisheries catch potential in this region may increase.

Tai et al. (2019) project the current total fisheries catch potential (commercial and subsistence) in the HBC to be 3.22 (± 2.36) million tonnes and valued at $3.41 (± 3.21) billion USD annually (see section 3.5). These figures are much higher than current actual fisheries harvests. The authors note that a significant proportion of current catch potential is from capelin and European conger. Under the RCP 8.5 climate scenario (high climate change), annual catch potential in the HBC increases to 4.8 (± 3.8) million tonnes and landed value to $6.0 (± 5.8) billion USD by 2100 (Figure 5.2). Under the RCP 2.6 scenario (low climate change), catch potential remains at similar levels as modelled for today, which is still significantly higher than actual catches (for information on RCPs, see Box 5.1). Within the Canadian Arctic, the HBC and the Eastern Arctic-West Greenland LMEs show the largest potential increases in marine capture fisheries. In the model projection, the authors limit future ocean acidification effects to invertebrate species and most of the increase in potential catches is due to expected increases in abundance of European conger and capelin.

Lam et al. (2014) project changes in fisheries in the Arctic under climate change and ocean acidification scenarios. While not geographically specific to the HBME, this research provides general insights into commercial fisheries changes. The authors find that for the Canadian Arctic, there is a 20–25% reduction in landed value of fisheries as a result of projected impacts of ocean acidification (comparing the scenario of ocean acidification plus climate warming to the scenario of only climate warming). Nonetheless, under both climate warming and combined climate

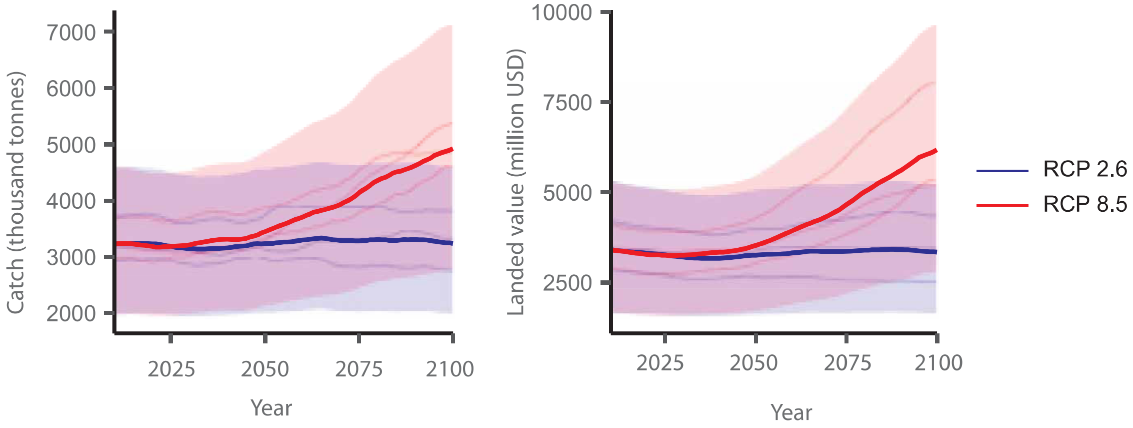


Figure 5.2. Projected annual maximum sustainable catch and landed value potential (no discounting) in the HBC. Thin lines represent each model simulation using the different earth systems models, while bold lines are multi-models means. Shaded ribbons are the upper and lower standard error estimates from parameter uncertainty (to estimate maximum potential catch biomass). Blue lines are projections of the low climate change scenario (RCP 2.6) and red lines are the high climate change scenario (RCP 8.5). Data are smoothed using a 10-year running mean. (Tai et al. 2019, p. 6)

warming and ocean acidification scenarios, the total landed value of marine capture commercial fishing for the Canadian Arctic is expected to increase by about 20 to 25% over current estimated landed value of approximately 30 million USD by 2050. Species that are expected to become more important for Canadian Arctic harvests under the dual drivers of climate change and ocean acidification are Atlantic cod, Atlantic mackerel, blue mussel, Pacific herring, capelin, Atlantic halibut, Atlantic rainbow smelt, while species that become less important are *Pandalus* shrimps, crustaceans, queen crab, marine crab and scallops. With regard to species that are currently commercially important around the HBME, projections by Tai et al. (2019) and Lam et al. (2014) suggest that the current shrimp fishery in Hudson Strait and beyond may decline, while commercial fisheries for capelin and other fin fish have the potential to develop.

These studies highlight uncertainty in future fisheries projections for the Canadian Arctic, as species distribution and abundance may be affected by ecological interactions, such as invasions and extinctions, which can drastically affect food web dynamics and community structure. Changes in Arctic cod abundance in the HBME due to ice loss may have significant implications for marine mammals, which will need to replace this lipid-rich species with subarctic and boreal forage fish with smaller fat stores (Schembri et al. 2019). Rainbow smelts were illegally introduced into the Hudson Bay drainage lakes in northern Ontario, and by the early 2000s had expanded to the Churchill and Nelson River estuaries (Stewart and Lockhart 2005). As Stewart and Lockhart (2005) explain, this small, predatory anadromous fish is a concern for commercial fisheries as they are voracious predators of invertebrates; compete directly for food with various commercially harvested species, and prey upon the eggs and larvae of commercially harvested species. Further, reductions in ice cover in the HBME may make the marine region more accessible to activities that impact fish populations by harming fish health, damaging habitats or introducing non-native species (Schembri et al. 2019).

There are possible benefits of expected changes in environmental conditions for some species that are, or have been recently, harvested commercially. More open water (larger and more numerous polynyas and floe edges) are generally expected to increase gathering of food supplies necessary for overwinter survival for common eider in the southern HBME (Mallory et al. 2010). This may prove beneficial for eider down abundance and developing eider down commercial harvesting efforts (see section 3.5). Increased productivity of HBME marine waters (see section 5.5) may also increase aquatic plant growth, and create an opportunity for commercial harvesting of kelp and other plant species (Krause-Jensen and Duarte 2014).

5.9 CLIMATE CHANGE 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).* (Candlish et al. 2019b, p. 98)

The IRIS-3 for the Greater Hudson Bay Marine Region provides the statement above regarding climate models and projections. Climate scenarios, a number of which have been presented in this chapter related to biophysical variables in the HBME such as ice cover, timing of ice freeze-up and breakup and primary productivity, describe how the future may develop based on a set of assumptions about driving forces. As Candlish et al. (2019b) explained, most published projections use model ensembles, to provide insights into agreement between models and uncertainties. In section 5.1, Tables 5.1 to 5.3 show a range of projections related to ice conditions in the HBME to aid readers in assessing uncertainty in projections. While rates of change differ, general trends are for the most part consistent.

Steiner et al. (2015) provide a detailed discussion of uncertainty in climate and ice models of relevance to the HBME, discussing how observational data sets often contain spatial, temporal and seasonal gaps, and spot measurements are used to represent larger areas and periods. Further, the authors describe how global climate models lack the resolution that is needed to adequately represent the complexity of the Canadian Arctic, so can provide a general tendency and range of expected future changes but lack accuracy in local details. There are major complexities in disentangling the effects of natural variability and anthropogenic-driven change on shorter time scales.

Ford et al. (2017) summarized that while climate and ice models are advancing in precision at regional scales, knowledge gaps and model disagreements remain related to uncertainty about greenhouse gas emissions, parameterization of physical processes and model structure variance, made more complicated by high temporal and spatial variability across regions. For example, in their study of baseline parameters for primary productivity related to the HBME, Ferland et al. (2011) identify a high degree of complexity in primary production and biomass, the relationships between these properties, and water column structure, concluding that this complicates predictions of how the system will respond to climate change. Kuzyk et al. (2009), in developing sediment and organic carbon budgets related to the HBME, identify the likely influence of isostatic rebound on changing sediment and organic carbon supply and burial within the HBME, and suggest that this will significantly complicate the task of predicting and measuring the additional consequences of river diversions and climate change on the system.

Broader changes within food webs and on subsistence harvesting and other ecosystem services are extremely complex. Uncertainty is increased because of knowledge gaps in a number of areas. As described in section 5.6, research on food web implications of global warming in the HBME is distributed unevenly among species and food web interactions, with more studies on marine mammals than other wildlife groups. Among these, the majority of studies are related to polar bears and ringed seals. Further, many gaps in knowledge related to human dimensions of climate change have been identified in recent reviews (Furgal 2008; Ford et al. 2012b; Ford and Pearce 2012; Ford et al. 2012a; Ford et al. 2017). For example, while potential direct impacts of climate change on subsistence harvesting in communities in northern Canada have been explored, there are gaps in knowledge about the potential indirect effects of environmental change on various aspects of culture, economies and individual and community health.

In general, there was more literature identified on human dimensions of climate change relating to Inuit communities and regions around the HBME compared with Cree communities and regions, with even less literature on interactions between environmental change and subsistence harvesting for First Nations along Ontario’s Hudson Bay coastline (Lemelin et al. 2010; Robus 2012) and the western coast of James Bay (Hori et al. 2012; Tam et al. 2013; Khalafzai et al. 2019). In particular, there was a relatively higher concentration of research on human dimensions of climate change related to the community of Igloolik (Ford et al. 2006; Ford et al. 2008a; Ford et al. 2009; Ford 2009; Laidler et al. 2009; Karpala 2010). Community-based research that addresses key parameters of importance to communities could help address a number of these information gaps in a way that also strengthens adaptation to impacts of environmental change.

5.10 REFERENCES

Akperov M, Mokhov I, Rinke A, et al. (2014) Cyclones and their possible changes in the Arctic by the end of the twenty first century from regional climate model simulations. Theoretical and Applied Climatology 12 p. doi: oi:10.1007/s00704-014-1272-2

Alcamo J, Bennett E, Millennium Ecosystem Assessment (2003) Ecosystems and Their Service. Ecosystems and human well-being: A framework for assessment. Island Press, Washington, D.C., pp 49–70

AMAP (2018) AMAP Assessment 2018 : Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme, Tromsø, Norway

AMAP (2011) How Does Climate Change Influence Arctic Mercury? AMAP Assessment 2011: Mercury in the Arctic, 1st ed. Arctic Monitoring and Assessment Programme (AMAP), Oslo, pp 67–83

Andrews JS, Babb D, Barber DG (2017) Climate change and sea ice: marine shipping access in Hudson Bay and Hudson Strait (1980 – 2014). Elem Sci Anth 5:15. doi: 10.1525/elementa.130

Aporta C (2009) The trail as home: Inuit and their pan-Arctic network of routes. Human Ecology 37:131–146. doi: 10.1007/s10745-009-9213-x

Arctic Council (2016) Arctic Resilience Report. Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm

Arnell NW (2005) Implications of climate change for freshwater inflows to the Arctic Ocean. Journal of Geophysical Research Atmospheres 110:1–9. doi: 10.1029/2004JD005348

Arrigo KR, van Dijken G, Pabi S (2008) Impact of a shrinking Arctic ice cover on marine primary production. Geophysical Research Letters 35:1–6. doi: 10.1029/2008GL035028

Azetsu-Scott K (2018) Ocean Acidification in Canadian Waters. In: International Ocean Institute-Canada (ed) The Future of Ocean Governance and Capacity Development: Essays in Honor of Elisabeth Mann Borgese (1918-2002). Brill/Nijhoff, pp 227–231

Azetsu-Scott K, Starr M, Mei Z-P, Granskog M (2014) Low calcium carbonate saturation state in an Arctic inland sea having large and varying fluvial inputs: The Hudson Bay system. Journal of Geophysical Research: Oceans 119:6210–6220. doi: 10.1038/175238c0

Barber DG, Asplin MG, Raddatz RL, et al. (2012) Change and variability in sea ice during the 2007-2008 Canadian International Polar Year program. Climatic Change 115:115–133. doi: 10.1007/s10584-012-0477-6

Barber DG, Hop H, Mundy CJ, et al. (2015) Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone. Progress in Oceanography 139:122–150. doi: 10.1016/j.pocean.2015.09.003

Bélanger S, Babin M, Tremblay J-É (2013) Increasing cloudiness in Arctic damps the increase in phytoplankton primary production due to sea ice receding. Biogeosciences 10:4087–4101. doi: 10.5194/bg-10-4087-2013

Boisvert LN, Wu DL, Shie CL (2015) Increasing evaporation amounts seen in the Arctic between 2003 and 2013 from AIRS data. Journal of Geophysical Research 120:6865–6881.

Braune BM, Gaston AJ, Hobson KA, et al. (2014) Changes in food web structure alter trends of mercury uptake at two seabird colonies in the Canadian Arctic. Environmental Science & Technology 48:1346–1352. doi: 10.1021/es5036249

Candlish L, Andrews J, Babb D (2019a) Climate and weather in the Greater Hudson Bay Marine Region. In: Kuzyk ZZ, Candlish L (eds) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. Arctic Research Consortium of the United States, Arctic Studies Centre, Smithsonian Institution, Quebec City, pp 59–77

Candlish L, Babb D, Andrews J (2019b) Climate change projections. In: Kuzyk ZZ, Candlish L (eds) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. ArcticNet, Quebec City, pp 97–111

Candlish LM, Babb DG, Andrews J, et al. (2019c) Characteristics of the Seasonal Sea Ice Cover. In: Kuzyk ZZ, Candlish L (eds) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. ArcticNet, Quebec City, pp 79–95

Capelle DW, Kuzyk ZZA, Guéguen C, et al. (2019) Carbon Cycling in the Greater Hudson Bay Marine System. In: Kuzyk ZZ, Barber D (eds) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. Synthesis and Recommendations. ArcticNet, Quebec, pp 203–222

Castro de la Guardia L, Derocher AE, Myers PG, et al. (2013) Future sea ice conditions in Western Hudson Bay and consequences for polar bears in the 21st century. Global Change Biology 19:2675–2687.

Cavalieri DJ, Parkinson CL (2012) Arctic sea ice variability and trends, 1979-2010. Cryosphere 6:881–889. doi: 10.5194/tc-6-881-2012

Chambellant M (2010) Hudson Bay ringed seal: Ecology in a warming climate. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World's Largest

Northern Inland Sea, Hudson Bay, 1st ed. Springer, pp 137–157

Chassé J, Lambert N, Lavoie D (2013) Precipitation, evaporation and freshwater flux over Canada from six Global Climate Models. Moncton

Cheng CS (2014) Evidence from the historical record to support projection of future wind regimes: An application to Canada. Atmosphere - Ocean 52:232–241. doi: 10.1080/07055900.2014.902803

Cheung WWL, Zeller D, Pauly D (2011) Projected species shifts due to climate change in the Canadian Marine Ecoregions. Vancouver, BC

Dahlman L (2009) Climate Variability: Arctic Oscillation. National Oceanic and Atmospheric Administration

Déry SJ, Mlynowski TJ, Hernández-Henríquez MA, Straneo F (2011) Interannual variability and interdecadal trends in Hudson Bay streamflow. Journal of Marine Systems 88:341–351. doi: 10.1016/j.jmarsys.2010.12.002

Déry SJ, Stieglitz M, McKenna EC, Wood EF (2005) Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964-2000. Journal of Climate 18:2540–2557. doi: 10.1175/JCLI3440.1

Donaldson SG, Van Oostdam J, Tikhonov C, et al. (2010) Environmental contaminants and human health in the Canadian Arctic. The Science of the total environment 408:5165–5234. doi: 10.1016/j.scitotenv.2010.04.059

Durkalec A, Furgal C, Skinner MW, Sheldon T (2015) Climate change influences on environment as a determinant of Indigenous health: Relationships to place, sea ice, and health in an Inuit community. Social Science & Medicine 136–137:17–26. doi: 10.1016/j.socscimed.2015.04.026

Else BGT, Papakyriakou TN, Granskog MA, Yackel JJ (2008) Observations of sea surface fCO2 distributions and estimated air-sea CO2 fluxes in the Hudson Bay region (Canada) during the open water season. Journal of Geophysical Research 113:C08026 (1-12). doi: 10.1029/2007JC004389

Elliott JM, Elliott JA (2010) Temperature requirements of Atlantic salmon Salmo salar, brown trout Salmo trutta and Arctic charr Salvelinus alpinus: Predicting the effects of climate change. Journal of Fish Biology 77:1793–1817. doi: 10.1111/j.1095-8649.2010.02762.x

Fazel-Rastgar F (2019) Hudson Bay Climate Change and Local Winter Wind Circulation. American Journal of Climate Change 8:544–560. doi: 10.4236/ajcc.2019.84029

Ferguson SH, Higdon JW, Chmelnitsky EG (2009) The rise of killer whales as a major Arctic predator. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay, 1st ed. Springer, pp 117–176

Ferguson SH, Young BG, Yurkowski DJ, et al. (2017) Demographic, ecological, and physiological responses of ringed seals to an abrupt decline in sea ice availability. PeerJ 1–17. doi: 10.7717/peerj.2957

Ferland J, Gosselin M, Starr M (2011) Environmental control of summer primary production in the hudson bay system: The role of stratification. Journal of Marine Systems 88:385–400. doi: 10.1016/j.jmarsys.2011.03.015

Florko KRN, Bernhardt W, Breiter, C-Jae C, et al. (2018) Decreasing sea ice conditions in western Hudson Bay and an increase in abundance of harbour seals (Phoca vitulina) in the Churchill River. Polar Biology 41:1187–1195. doi: 10.1007/s00300-018-2277-6

Ford, J., Bell, T., Couture N (2016) Perspectives on Canada's North Coast Region. In: Lemmen DS, Warren FJ, James TS, Mercer Clarke CSL (eds) Canada's Marine Coasts in a Changing Climate, 1st ed. Government of Canada, Ottawa, pp 153–206

Ford JD (2009) Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. Regional Environmental Change 9:83–100. doi: 10.1007/s10113-008-0060-x

Ford JD, Bell T, Couture NJ (2016) Perspectives on Canada's North Coast Region. In: Lemmen DS, Warren FJ, James TS, Mercer Clarke CSL (eds) Canada's Marine Coasts in a Changing Climate, 1st ed. Government of Canada, Ottawa, pp 153–206

Ford JD, Berrang-Ford L (2009) Food security in Igloolik, Nunavut: an exploratory study. Polar Record 45:225. doi: 10.1017/S0032247408008048

Ford JD, Bolton K, Shirley J, et al. (2012a) Mapping human dimensions of climate change research in the Canadian Arctic. Ambio A Journal of the Human Environment 41:808–822. doi: 10.1007/s13280-012-0336-8

Ford JD, Bolton KC, Shirley J, et al. (2012b) Research on the human dimensions of climate change in Nunavut, Nunavik, and Nunatsiavut: A literature review and gap analysis. Arctic 65:289–304. doi: 10.2307/41758936

Ford JD, Couture N, Bell T, Clark DG (2017) Climate change and Canada's north coast: Research trends, progress, and future directions. Environmental Reviews 26:82–92. doi: 10.1139/er-2017-0027

Ford JD, Gough WA, Laidler GJ, et al. (2009) Sea ice, climate change, and community vulnerability in northern Foxe Basin, Canada. Climate Research 38:137–154. doi: 10.3354/cr00777

Ford JD, Pearce T (2012) Climate change vulnerability and adaptation research focusing on the

Inuit subsistence sector in Canada: Directions for future research. The Canadian Geographer 56:275–287. doi: 10.1111/j.1541-0064.2012.00418.x

Ford JD, Pearce T, Gilligan J, et al. (2008a) Climate change and hazards associated with ice use in Northern Canada. Arctic, Antarctic, and Alpine Research 40:647–659. doi: 10.1657/1523-0430(07-040)[FORD]2.0.CO;2

Ford JD, Smit B, Wandel J, et al. (2008b) Climate change in the Arctic: Current and future vulnerability in two Inuit communities in Canada. The Geographical Journal 174:45–62. doi: 10.1111/j.1475-4959.2007.00249.x

Ford JD, Smit B, Wandel J, MacDonald J (2006) Vulnerability to climate change in Igloolik, Nunavut: what we can learn from the past and present. Polar Record 42:127–138.

Francis JA, Skific N, Vavrus SJ (2018) North American Weather Regimes Are Becoming More Persistent: Is Arctic Amplification a Factor? Geophysical Research Letters 45:11,414-11,422. doi: 10.1029/2018GL080252

Frey KE, Comiso JC, Cooper LW, et al. (2018) Arctic Ocean Primary Productivity: The Response of Marine Algae to Climate Warming and Sea Ice Decline.

Furgal C (2008) Health impacts of climate change in Canada’s North. In: Seguin J (ed) Human health in a changing climate: A Canadian assessment of vulnerabilities and adaptive capacity. Health Canada, Ottawa, pp 303–366

Gaden A, Ferguson SH, Harwood L, Melling H, Stern GA. (2009) Mercury Trends in Ringed Seals (*Phoca hispida*) from the Western Canadian Arctic since 1973: Associations with Length of Ice-Free Season. Environmental Science & Technology 43:3646-3651

Gagnon AS, Gough WA (2006) East-west asymmetry in long-term trends of landfast ice thickness in the Hudson Bay region, Canada. Climate Research 32:177–186. doi: 10.3354/cr032177

Gagnon AS, Gough WA (2005a) Trends in the dates of ice freeze-up and breakup over Hudson Bay, Canada. Arctic 58:370–382. doi: 10.14430/arctic451

Gagnon AS, Gough WA (2005b) Climate change scenarios for the Hudson Bay region: An intermodel comparison. Climatic Change 69:269–297. doi: 10.1007/s10584-005-1815-8

Galbraith PS, Larouche P (2011) Sea-surface temperature in Hudson Bay and Hudson Strait in relation to air temperature and ice cover breakup, 1985-2009. Journal of Marine Systems 87:66–78. doi: 10.1016/j.jmarsys.2011.03.002

Galicia MP, Thiemann GW, Dyck MG, et al. (2016) Dietary habits of polar bears in Foxe Basin, Canada: possible evidence of a trophic regime shift mediated by a new top predator. Ecology and Evolution 6:6005–6018. doi: 10.1002/ece3.2173

Gaston AJ, Elliott KH (2014) Seabird diet changes in northern Hudson Bay, 1981-2013, reflect the availability of schooling prey. Marine Ecology Progress Series 513:211–223. doi: 10.3354/meps10945

Gaston AJ, Gilchrist HG, Hipfner JM (2005) Climate change, ice conditions and reproduction in an Arctic nesting marine bird: Brunnich's guillemot (Uria lomvia L.). Journal of Animal Ecology 74:832–841. doi: 10.1111/j.1365-2656.2005.00982.x

Gaston AJ, Smith PA, Provencher JF (2012) Discontinuous change in ice cover in Hudson Bay in the 1990s and some consequences for marine birds and their prey. ICES Journal of Marine Science 69:1218–1225. doi: 10.1093/icesjms/fss040

Gaston AJ, Woo K (2008) Razorbills (Alca Torda) follow Subarctic prey into the Canadian Arctic: Colonization results from climate change? The Auk 125:939–942. doi: 10.1525/auk.2008.07195

Gaston AJ, Woo K, Hipfner JM (2003) Trends in Forage Fish Populations in Northern Hudson Bay since 1981, as Determined from the Diet of Nestling Thick-Billed Murres Uria lomvia. Arctic 56:227–233. doi: 10.14430/arctic618

Gormezano LJ, Rockwell RF (2013) What to eat now? Shifts in polar bear diet during the ice-free season in western Hudson Bay. Ecology and Evolution 3:3509–3523. doi: 10.1002/ece3.740

Greenan BJW, James TS, Loder JW, et al. (2019) Changes in Oceans Surrounding Canada. In: Bush E., Lemmen DS (eds) Canada's Changing Climate Report. Government of Canada, Ottawa, pp 345–408

Hall MiC, Saarinen J (2010) Tourism and change in polar regions: Climate, environments and experiences. Routledge, London and New York

Hammill MO (2013) Effects of Climate Warming on Arctic Marine Mammals in Hudson Bay: Living on the Edge? In: Mueter FJ, Dickson DMS, Huntington HP, et al. (eds) Responses of Arctic Marine Ecosystems to Climate Change. Alaska Sea Grant, University of Alaska Fairbanks, pp 21–38

Higdon JW, Ferguson SH (2010) Past, present, and future of bowhead whales (Balaena mysticetus) in Northwest Hudson Bay. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay, 1st ed. Springer, pp 159–177

Hochheim K, Barber D (2014) An update on the ice climatology of the Hudson Bay system. Arctic, Antarctic, and Alpine Research 46:66–83. doi: 10.1657/1938-4246-46.1.66

Hochheim K, DG B (2010) Atmospheric forcing of sea ice in Hudson Bay during the fall period, 1980-2005. Journal of Geophysical Research: Oceans 115:1–20. doi: 10.1029/2009JC005334

Hochheim KP, Barber DG (2010) Atmospheric forcing of sea ice in Hudson Bay during the fall period, 1980-2005. Journal of Geophysical Research: Oceans 115:1–20. doi: 10.1029/2009JC005334

Hochheim KP, Lukovich J V., Barber DG (2011) Atmospheric forcing of sea ice in Hudson Bay during the spring period, 1980-2005. Journal of Marine Systems 88:476–487. doi: 10.1016/j.jmarsys.2011.05.003

Hori Y, Tam B, Gough WA, et al. (2012) Use of traditional environmental knowledge to assess the impact of climate change on subsistence fishing in the James Bay Region of Northern Ontario, Canada. Rural and Remote Health 12:1–16.

ICC (2008) The sea ice is our highway: An Inuit perspective on transportation in the Arctic. A contribution to the Arctic Marine Shipping Assessement. Ottawa

Intergovernmental Panel on Climate Change (IPCC) (2000) Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York

Intergovernmental Panel on Climate Change (2013) Climate Change 2013: The physical science basis. Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York

Intergovernmental Panel on Climate Change (2020) Climate Change 2014 Synthesis Report Fifth Assessment Report. Cambridge University Press, Cambridge and New York

Iverson SA, Gilchrist HG, Smith PA, et al. (2014) Longer ice-free seasons increase the risk of nest depredation by polar bears for colonial breeding birds in the Canadian Arctic. Proceedings of the Royal Society B: Biological Sciences. doi: 10.1098/rspb.2013.3128

Johnson AC, Hobson KA, Lunn NJ, et al. (2019) Temporal and intra-population patterns in polar bear foraging ecology in western Hudson Bay. Marine Ecology Progress Series 619:187–199. doi: 10.3354/meps12933

Joly S, Senneville S, Caya D, Saucier FJ (2011) Sensitivity of Hudson Bay sea ice and ocean climate to atmospheric temperature forcing. Climate Dynamics 36:1835–1849.

Karpala KSE (2010) Adapting to a World of Change: Inuit Perspectives of Environmental Changes in Igloolik, Nunavut. Carelton University

Khalafzai MAK, McGee TK, Parlee B (2019) Flooding in the James Bay region of Northern Ontario, Canada: Learning from traditional knowledge of Kashechewan First Nation. International Journal of Disaster Risk Reduction 36:101100. doi: 10.1016/j.ijdrr.2019.101100

Khon VC, Mokhov II, Pogarskiy FA, et al. (2014) Wave heights in the 21st century Arctic Ocean simulated with a regional climate model. Geophysical Research Letters 41:2956–2961. doi: 10.1002/2014GL059847

Kowal S, Gough WA, Butler K (2017) Temporal evolution of Hudson Bay Sea Ice (1971-2011). Theoretical and Applied Climatology 127:753–760. doi: 10.1007/s00704-015-1666-9

Krause-Jensen D, Duarte CM (2014) Expansion of vegetated coastal ecosystems in the future Arctic. Frontiers in Marine Science 1:1–10. doi: 10.3389/fmars.2014.00077

Kuzyk ZZ, Barber D (2019) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. Synthesis and Recommendations. Quebec City

Kuzyk ZZA, Macdonald RW, Johannessen SC, et al. (2009) Towards a sediment and organic carbon budget for Hudson Bay. Marine Geology 264:190–208. doi: 10.1016/j.margeo.2009.05.006

Kuzyk ZZA, Macdonald RW, Johannessen SC, Stern GA (2010) Biogeochemical Controls on PCB Deposition in Hudson Bay. Environmental science & technology 44:3280–3285. doi: 10.1021/es903832t

Ladouceur S (2007) Évaluation des changements hydrographiques de la Baie d'Hudson et du Bassin de Foxe au cours des derniers siècles à partir de traceurs palynologiques et micropaléontologiques. Université du Québec à Montréal

Laidler GJ, Ford JD, Gough WA, et al. (2009) Travelling and hunting in a changing Arctic: Assessing Inuit vulnerability to sea ice change in Igloolik, Nunavut. Climatic Change 94:363–397. doi: 10.1007/s10584-008-9512-z

Lalande C, Fortier L (2011) Downward particulate organic carbon export and jellyfish blooms in southeastern Hudson Bay. Journal of Marine Systems 88:446–450. doi: 10.1016/j.jmarsys.2010.12.005

Lam VWY, Cheung WWL, Sumaila R, Sumaila UR (2014) Marine capture fisheries in the Arctic: Winners or losers under climate change and ocean acidification? Fish and Fisheries 17:335–357. doi: 10.1111/faf.12106

Landy J, Ehn J, Babb D, et al. (2017) Sea ice thickness in the Eastern Canadian Arctic: Hudson Bay Complex & Baffin Bay. Remote Sensing of Environment 200:281–294.

Lavoie D, Lambert N, Baaren A Van Der (2013) Projections of Future Physical and Biogeochemical Conditions in Hudson and Baffin Bays from CMIP5 Glocal Climate Models.

Lemelin H, Matthews D, Mattina C, et al. (2010) Climate change, wellbeing and resilience in the Weenusk First Nation at Peawanuck: the Moccasin Telegraph goes global. Rural and Remote Health 10:1333.

Leung A, Gough W (2016) Air mass distribution and the heterogeneity of the climate change signal in the Hudson Bay/Foxe Basin region, Canada. Theoretical and Applied Climatology 125:583–592. doi: 10.1007/s00704-015-1523-x

Lovejoy C (2014) Changing views of Arctic protists (marine microbial eukaryotes) in a changing Arctic. Acta Protozoologica 53:91–100. doi: 10.4467/16890027AP.14.009.1446

Lunn NJ, Servanty S, Regehr E V., et al. (2016) Demography of an apex predator at the edge of its range: impacts of changing sea ice on polar bears in Hudson Bay. Ecological Applications 26:1302–1320. doi: 10.1890/15-1256

Luque SP, Ferguson SH, Breed GA (2014) Spatial behaviour of a keystone Arctic marine predator and implications of climate warming in Hudson Bay. Journal of Experimental Marine Biology and Ecology 461:504–515. doi: 10.1016/j.jembe.2014.10.002

MacDonald MK, Stadnyk TA, Déry SJ, et al. (2018) Impacts of 1.5 and 2.0 °C Warming on Pan-Arctic River Discharge Into the Hudson Bay Complex Through 2070. Geophysical Research Letters 45:7561–7570. doi: 10.1029/2018GL079147

Mallory ML, Gaston AJ, Gilchrist HG, et al. (2010) Effects of Climate Change, Altered Sea-Ice Distribution and Seasonal Phenology on Marine Birds. In: Ferguson SH, Loseto LL, Mallory ML (eds) A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay, 1st ed. Springer, pp 179–195

McKinney M, Peacock E, Letcher RJ (2009) Sea Ice-associated diet change and brominated contaminants in polar bears. Environmental Science & Technology 43:4334–4339.

Meredith M, Sommerkorn M, Cassotta C, et al. (2018) Polar regions. In: Portner H-O, Roberts D, Masson-Delmotte V, et al. (eds) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change, pp 203–230

Mioduszewski J, Vavrus S, Wang M (2018) Diminishing Arctic sea ice promotes stronger surface winds. Journal of Climate 31:8101–8119. doi: 10.1175/JCLI-D-18-0109.1

Moline MA, Karnovsky NJ, Brown Z, et al. (2008) High latitude changes in ice dynamics and their impact on polar marine ecosystems. Annals of the New York Academy of Sciences 1134:267–319. doi: 10.1196/annals.1439.010

Nickels S, Furgal C, Buell M, Moquin H (2006) Unikkaagatigiit – Putting the human face on climate change: Perspectives from Inuit in Canada. Inuit Tapiriit Kanatami, Nasivvik Centre for Inuit Health and Changing Environments, and National Aboriginal Health Organization, Ottawa

Niemi A, Paulic J, Cobb D (2010) Ecosystems status and trends report: Arctic Marine Ecozones. Winnipeg, Manitoba

Onarheim IH, Eldevik T, Smedsrud LH, Stroeve JC (2018) Seasonal and regional manifestation of Arctic sea ice loss. Journal of Climate 31:4917–4932. doi: 10.1175/JCLI-D-17-0427.1

Van Oostdam J, Donaldson SG, Feeley M, et al. (2005) Human health implications of environmental contaminants in Arctic Canada: A review. The Science of the Total Environment 351–352:165–246. doi: 10.1016/j.scitotenv.2005.03.034

Peloquin C, Berkes F (2009) Local knowledge, subsistence harvests, and social-ecological complexity in James Bay. Human Ecology 37:533–545. doi: 10.1007/s10745-009-9255-0

Poesch MS, Chavarie L, Chu C, et al. (2016) Climate Change Impacts on Freshwater Fishes: A Canadian Perspective. Fisheries 41:385–391. doi: 10.1080/03632415.2016.1180285

Pomerleau C, Lesage V, Ferguson SH, et al. (2012) Prey assemblage isotopic variability as a tool for assessing diet and the spatial distribution of bowhead whale Balaena mysticetus foraging in the Canadian eastern Arctic. Marine Ecology Progress Series 469:161–174. doi: 10.3354/meps10004

Provencher JF, Gaston AJ, O’Hara PD, Gilchrist HG (2012) Seabird diet indicates changing Arctic marine communities in eastern Canada. Marine Ecology Progress Series 454:171–182.

Reist JD, Wrona FJ, Prowse TD, et al. (2006) An overview of effects of climate change on selected Arctic freshwater and anadromous fishes. Ambio 35:381–387. doi: 10.1579/0044-7447(2006)35[402:EOCCAU]2.0.CO;2

Regehr EV, Lunn NJ, Amstrup SC, Stirling I (2007) Effects of Earlier Sea Ice Breakup on Survival and Population Size of Polar Bears in Western Hudson Bay. Journal of Wildlife Management 71:2673–2683. doi: 10.2193/2006-180

Robus J (2012) Linking two ways of knowing to understand climate change impacts on geese and First Nations in the Hudson Bay Lowland. Trent University

Rockwell RF, Gormezano LJ (2009) The early bear gets the goose: Climate change, polar bears and lesser snow geese in western Hudson Bay. Polar Biology 32:539–547. doi: 10.1007/s00300-008-0548-3

Rosol R, Powell-Hellyer S, Chan LHM, Chan HM (2016) Impacts of decline harvest of country food on nutrient intake among Inuit in Arctic Canada: Impact of climate change and possible adaptation plan. International Journal of Circumpolar Health 75:1–8. doi: 10.3402/ijch.v75.31127

Sayles JS, Mulrennan ME (2010) Securing a Future: Cree Hunters’ Resistance and Flexibility to Environmental Changes, Wemindji, James Bay. Ecology and Society 15:22 p. doi: 10.5751/ES-03828-150422

Schembri S, Leblanc M, Bernatchez S, et al. (2019) Hudson Bay Fish and Fisheries. In: Kuzyk ZZ, Barber, David G (eds) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. ArcticNet, Quebec City, pp 255–274

Smith PA, Elliott KH, Gaston AJ, Gilchrist HG (2010) Has early ice clearance increased predation on breeding birds by polar bears? Polar Biology 33:1149–1153. doi: 10.1007/s00300-010-0791-2

Steiner N, Azetsu-Scott K, Galbraith P, et al. (2013) Climate Change Assessment in the Arctic Basin Part 1 : Trends and Projections - A Contribution to the Aquatic Climate Change Adaptation Services Program. Sidney

Steiner N, Azetsu-Scott K, Hamilton J, et al. (2015) Observed trends and climate projections affecting marine ecosystems in the Canadian Arctic. Environmental Reviews 23:191–239. doi: 10.1139/er-2014-0066

Steiner NS, Christian JR, Six KD, et al. (2014) Future ocean acidification in the Canada Basin and surrounding Arctic Ocean from CMIP5 earth system models. Journal of Geophysical Research: Oceans 119:332–347. doi: 10.1002/2013JC009069

Stewart DB, Lockhart WL (2005) An Overview of the Hudson Bay Marine Ecosystem. Canadian Technical Report of Fisheries and Aquatic Sciences. doi: 10.3109/10826084.2014.916521

Stewart EJ, Tiyy A, Howell SEL, et al. (2010) Cruise tourism and sea ice in Canada's Hudson bay Region. Arctic 63:57–66. doi: 10.14430/arctic647

Taha W, Bonneau-Lefebvre M, Cueto Bergner A, Tremblay A (2019) Evolution From Past to Future Conditions of Fast Ice Coverage in James Bay. Frontiers in Earth Science 7:1–20. doi: 10.3389/feart.2019.00254

Tai TC, Steiner NS, Hoover C, et al. (2019) Evaluating present and future potential of arctic fisheries in Canada. Marine Policy 108:11. doi: 10.1016/j.marpol.2019.103637

Tam BY, Gough WA, Edwards V, Tsuji LJS (2013) The impact of climate change on the well-being and lifestyle of a First Nation community in the western James Bay region. The Canadian Geographer / Le Géographe canadien 57:441–456. doi: 10.1111/j.1541-0064.2013.12033.x

Tivy A, Howell SEL, Alt B, et al. (2011) Trends and variability in summer sea ice cover in the Canadian Arctic based on the Canadian Ice Service Digital Archive, 1960-2008 and 1968-2008. Journal of Geophysical Research: Oceans. doi: 10.1029/2009JC005855

Tremblay J-É, Lee J, Gosselin M, Bélanger S (2019) Nutrient Dynamics and Marine Biological Productivity in the Greater Hudson Bay Marine Region. In: Kuzyk ZZA, Barber, David G (eds) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. Synthesis and Recommendations. ArcticNet, Quebec City, pp 225–243

Tremblay JE, Gagnon J (2009) The effects of irradiance and nutrient supply on the productivity of Arctic waters: A perspective on climate change. Influence of Climate Change on the Changing Arctic and Sub-Arctic Conditions. pp 73–89

Tremblay M, Furgal C, Larrivée C, et al. (2006) Climate change in Nunavik: Access to the territory and its resources. Kuujjuaq

van Vuuren DP, Edmonds J, Kainuma M et al. (2011) The representative concentration pathways: an overview. Climatic Change 109: 5 (2011)

Watt CA (2013) Narwhal (Monodon monoceros) diet and dive behaviour as an assessment of foraging adaptability with changing climate. doi: 10.2305/IUCN.UK.2017-3.RLTS.T13704A50367651.en

Watt CA, Heide-Jørgensen MP, Ferguson SH (2013) How adaptable are narwhal? A comparison of foraging patterns among the world’s three narwhal populations. Ecosphere 4:1–15. doi: 10.1890/ES13-00137.1

Wrona FJ, Prowse TD, Reist JD, et al. (2006) Effects of ultraviolet radiation and contaminant-related stressors on Arctic freshwater ecosystems. Ambio 35:388–401. doi: 10.1579/0044-7447(2006)35[388:EOURAC]2.0.CO;2

Young BG, Ferguson SH (2014) Using stable isotopes to understand changes in ringed seal foraging ecology as a response to a warming environment. Marine Mammal Science 30:706–725. doi: 10.1111/mms.12075

Zonneveld KAF, Pospelova V (2015) A determination key for modern dinoflagellate cysts. Palynology 39:387-409

6 UNCERTAINTY, PREDICTIVE TRENDS AND DISCUSSION

6.1 CUMULATIVE IMPACTS

Cumulative effects are the aggregate and often compounding changes to environment, social, economic, and health conditions and the positive and negative consequences of these changes. While cumulative effects can stem from natural changes, they are largely attributed to anthropogenic changes, particularly from development. The temporal and geographic scope of what is considered as contributing to cumulative change can range from the local and immediate (e.g. the construction of a wharf) to the global and long-term (e.g. climate change).

Three types of development with a significant footprint in the HBME are discussed here in the context of cumulative effects locally, regionally, and even globally. These include hydroelectric power generation, shipping, and mineral exploration and mining. Commercial fishing, oil and gas development, and historical changes are also discussed briefly. The interplay between these sources of environmental, social, and economic changes is also considered through a climate change lens. As the Arctic environment warms, becoming more accessible, and the national and international need for resources intensifies, the Canadian North will be of increasing interest for its development potential. Already, resource potential and transportation are shaping the HBME (Figure 6.1).

6.1.1 Hydroelectric development

Freshwater inputs from a number of larger rivers throughout Hudson and James Bays play a significant role in the ecology, chemistry, and oceanographic characteristics of the HBME (Kuzyk & Candlish 2019). Hydroelectric development along many of these river systems has shaped the terrestrial and marine environments of the southern parts of the region, as well as the legal, political, and socio-economic landscapes. In Québec, hydroelectric development was the trigger for the 1975 *James Bay and Northern Quebec Agreement* and eventually the *Paix des Braves Agreement* (2002), the *Agreement on Cree Nation Governance* (2017), and *Nunavik Inuit Land Claims Agreement* (2007), among others. Major hydroelectric developments within the HBME include the Nelson and Churchill rivers in Manitoba, the Moose River in Ontario, and La Grande Rivière (which diverts water from the Eastmain, Opinaca, and Caniapiscau Rivers), and the Grande rivière de la Baleine (which includes development on the Nottaway, Rupert and other rivers) in Québec. The Innavik Project in Inukjuak, Nunavik is a small hydroelectric project developed by

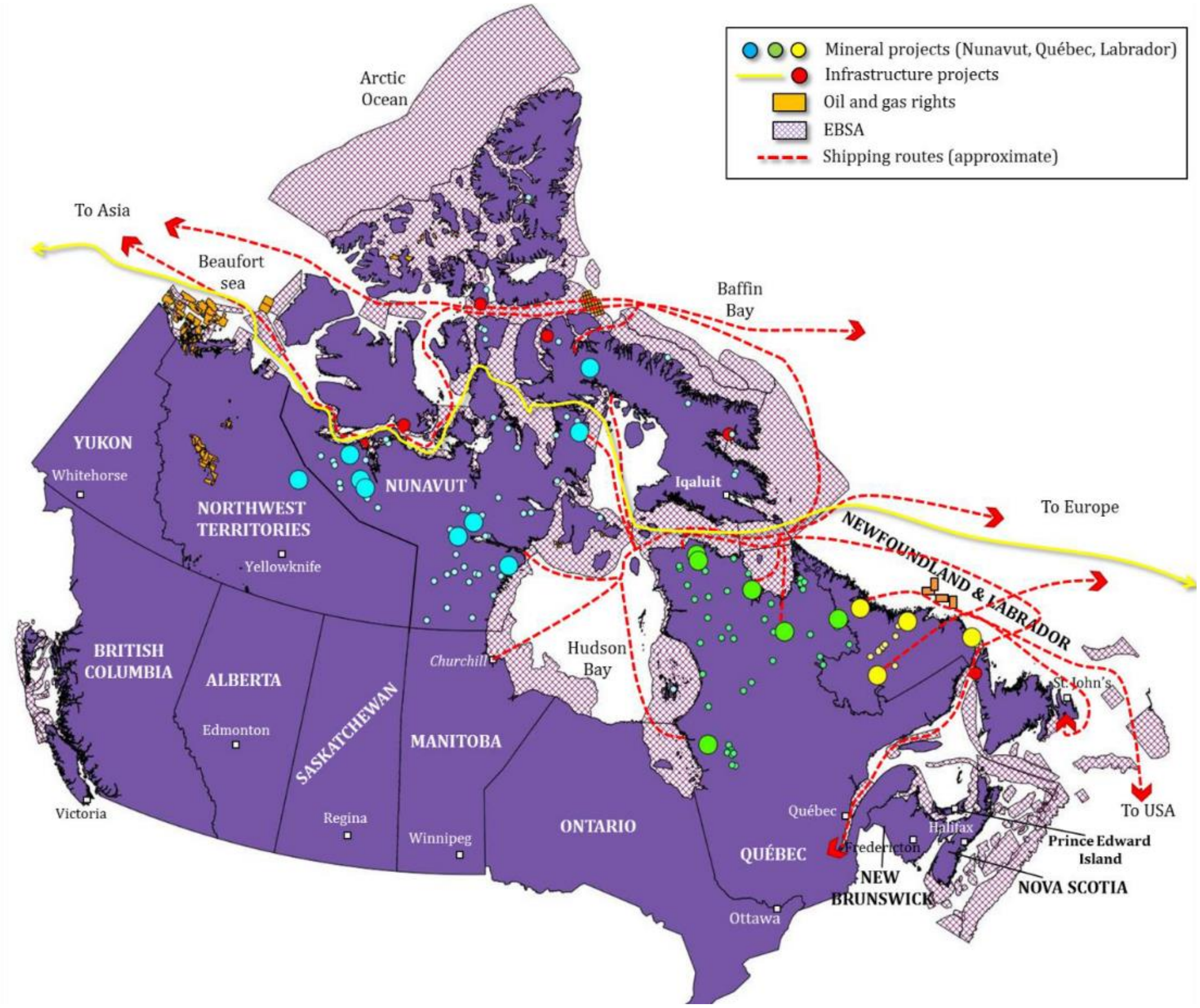


Figure 6.1. Summary of development projects with a marine component, throughout the HBME and beyond. Large circles represent mineral projects that are in-production or in a late-development stage, whereas small circles represent an early-development stage or exploration (Gavrilchuk & Lesage 2014, p. 10)

Pituvik Landholding Corporation that is currently under construction after approval by the community was confirmed through a referendum (Rodon 2017).

While hydroelectric power is often seen as cleaner than fossil fuel-derived energy, large-scale hydroelectric projects are not without considerable adverse environmental and social effects, particularly for the communities that live in the immediate vicinity of the development. Environmental effects include the flooding of land, increased sedimentation in downstream marine areas, movement of barriers for marine and anadromous fish species, methylmercury bioaccumulation in the food web, soil erosion, loss of wetlands, disruption of wildlife systems and patterns, emission of greenhouse gases from dam reservoirs, altered river flows, and altered food web structure (McDonald et al. 1997, Rosenberg et al. 1997, Whiteman 2004). For small communities that are highly dependent on the local food web, these combined effects can be significantly adverse.

Flooding of lakes and rivers to create dam reservoirs is associated with two related environmental concerns: the bioaccumulation of methylmercury and the release of methane and carbon dioxide, particularly if the lands being flooded are forested peatlands. Reservoir creation from hydroelectric projects influences mercury cycling as decomposition of submerged terrestrial organic matter causes elevated microbial activity and therefore greater methylmercury production (Hsu-Kim et al. 2018). For further discussion of mercury in the HBME, see sections 4.2 and 5.6. For the Grande rivière de la Baleine hydro complex (and others) there is a concern about the increased amount of mercury in the local food web, which bioaccumulates in a number of species, including fish (Bodaly & Johnston 1992). Predatory fish in the La Grande hydro complex exhibited the effects of bioaccumulation, with methylmercury levels six times that of background levels, well beyond what is considered safe for human consumption (Rosenberg et al. 1997). Mercury levels take decades to return to normal following the initial flooding event. While methylmercury levels in fish remain unsafe, local people must either choose not to harvest fish in affected areas, alienated from their own fisheries, or risk the dangers of mercury poisoning; both of these choices have significant physical and mental health implications (Rosenberg et al. 1997).

The same decomposition processes that result in methylmercury also produce greenhouse gases. The methane and carbon dioxide release from the sizeable dam reservoirs in Nunavik may last over a century, turning peatlands that are natural carbon sinks into sources (Rosenberg et al. 1997). While not historically considered in cumulative effects assessment, the greenhouse gas footprint of future projects will need to be considered in balance with the benefits derived from development, as Canada struggles to meet international climate change commitments.

Hydro-electric projects rely on altering the local hydrograph, or discharge pattern, to ensure consistent power generation. This practice can affect the neighbouring marine environment in a suite of undesirable ways: increased offshore salinity and upstream saltwater intrusions when flow is reduced, altered sedimentation patterns that damage natural levees and/or create new sediment deposits that inhibit human and wildlife movements and bury benthic species, and reduced seasonal nutrient input into estuaries reducing biological productivity and diversity (Rosenberg et al. 1997). Some of these issues can be mitigated by a more thoughtful discharge pattern, although power needs of cities far removed from the region often win out over local ecological concerns.

Several negative effects to local marine and anadromous wildlife populations are often associated with hydroelectric development: habitat destruction/alteration, introduction of non-native species, blocked migration routes, fragmented river systems, and habitat simplification represent several common issues (Rosenberg et al. 1997). Dam complexes can keep marine and anadromous species from habitat important for life history requirements. For example, physical barriers and changes in water flows can keep Arctic char from moving upstream to spawn, expose spawning ground to the air, and alter the temperature profile. Concern about the loss of waterfowl habitat has been expressed by community members Nunavik (McDonald et al. 1997).

A notable outcome of the Québec hydroelectric projects is the high volume of all-season and winter roads that now cut through the region. While the direct impact is a terrestrial one, these roads open up new land to additional development, like mining (Whiteman 2004), that can have a marine component if resources are shipped instead of driven to market (see section 6.1.2 below).

Hydroelectric development has contributed to the unraveling of traditional Cree and Inuit lifestyles in the communities adjacent to these large projects (Niezen 1993, MacDonald et al. 1997, Rosenberg et al. 1997, Hornig 1999, Whiteman 2004). However, the small population in the James and Hudson Bay area lead some to the conclusion that the consequences of these massive developments are limited (Roy & Messier 1989); on the contrary, the consequences have been life-changing, multifaceted, and long-lasting for many people in the region. For example, the Cree community of Fort George Island was relocated entirely—to present day Chisasibi—due to dam-related erosion risk from the La Grande hydroelectric project (Niezen 1993). Fort George Island is remembered as a largely crime-free, healthy community. The years following the relocation in 1980 were marked by a rise in suicides, substance abuse, and crime, illustrating the severe mental and social consequences of the large development project (Niezen 1993). A similar sequence of events unfolded when the Churchill River was diverted into the Nelson River; the community of South Indian River was relocated shortly before their settlement was flooded. A slew of social issues ensued, eroding family and cultural cohesion (Rosenberg et al. 1997). While the relocations of Fort George Island and South Indian Lake represent extreme examples, the communities of Hudson and James Bays have collectively expressed their concerns on a range of social and environmental effects of hydroelectric development in the region in *Voices from the Bay* (McDonald et al. 1997). Cumulative effects of these specific hydroelectric projects are also detailed and examined in *Social and Environmental Impacts of the James Bay Hydroelectric Project* (Hornig 1999), as well as in *The Impact of Economic Development in James Bay, Canada: The Cree Tallymen Speak Out* (Whiteman 2004).

New phases over the course of the development of the James Bay project brought influxes of workers to the communities of James Bay. Development also drew more local Indigenous peoples into the wage-economy and increased the amount of expendable income, which had positive and negative consequences (MacDonald et al. 1997, Hornig 1999). The significant socio-economic repercussions of the various large hydroelectric projects throughout the southern HBME on the local and largely Indigenous communities are examined further in Chapter 3, particularly in the context of land use and harvesting practices. These effects at the community level are compounded by change brought on by several other commercial sectors (discussed below). For Cree and Inuit throughout the region, these effects are also couched in the significant and relatively recent impact of colonial practices and centralization in year-round communities.

6.1.2 Shipping

Shipping through the Northern Sea Route (through Alaska, Russia, and Canada, including the Northwest Passage) is expected to increase 20% per year over the next 25 years, influenced by trade relations, sea ice patterns and predictability, and extractive opportunities (Miller & Ruiz

2014). Ship traffic throughout the Canadian Arctic nearly tripled in the last decade (Dawson et al. 2020), with traffic in Hudson Strait and Hudson Bay (to and from Churchill) showing an increase in recent years (Andrews et al. 2017). In the HBME, it is projected that the average ice-free season (over the years 2041-2070) will lengthen by 49 days in Hudson Bay, 53 days in Foxe Basin, and 65 days in James Bay (Kuzyk & Candlish 2019), increasing the safe shipping window and the feasibility of new northern ports.

While the majority of Arctic shipping in Canadian waters will travel through the various legs of the Northwest Passage, access to the Passage via Foxe Basin and Hudson Bay will likely be important in connecting Canadian goods with international markets (Liu et al. 2017), as will be the Arctic Bridge Gateway through Hudson Strait (Figure 6.2). The port at Churchill, Manitoba is Canada's only international port not connected to the road system. Activity at the port is currently limited by a short seasonal window of July to mid-October (Gavrilchuk & Lesage 2014), although shipping has recently been pushed even further into the shoulders seasons (July–November) and winter shipping has already occurred just outside the region to service mining operations (Kuzyk & Candlish 2019). There will be a growing need for coastal infrastructure and accessible ports, as more ships use northern passages (Miller & Ruiz 2014). Enhanced shipping infrastructure in existing communities contributes to more efficient and safe transport (Kuzyk & Candlish 2019).

In response to this emerging pressure, the federal government has been collaborating with affected communities to create low-impact shipping corridors. Community engagements revealed a number of potential mitigation measures to minimize the negative effects of increased shipping, such as creating "no wake" zones, restricted access during key harvesting seasons, and avoiding key wildlife areas (Dawson et al. 2020). The suggested mitigation measures have been synthesized into proposed corridors (Figure 6.3). Regardless, the threats to sensitive areas in the region cannot be entirely removed, as Ecologically and Biologically Significant Areas skirt the coast line of most of Hudson Bay and cover the entirety of James Bay (Kuzyk & Candlish 2019). See section 4.1.7 for more information on Ecologically and Biologically Significant Areas.

Marine shipping falls into a handful of categories: community re-supply, bulk transport, fishing, passenger vessels and tourism, research, and icebreakers and government operations (e.g., coast guard vessels). These shipping categories carry their own specific types of potential environmental impacts (Table 6.1); however, release of grey water, sewage, ballast and bilge water, air pollution, fuel/oil discharge, noise, sonar, and strikes on wildlife are common issues among all ship types (Arctic Council 2008).

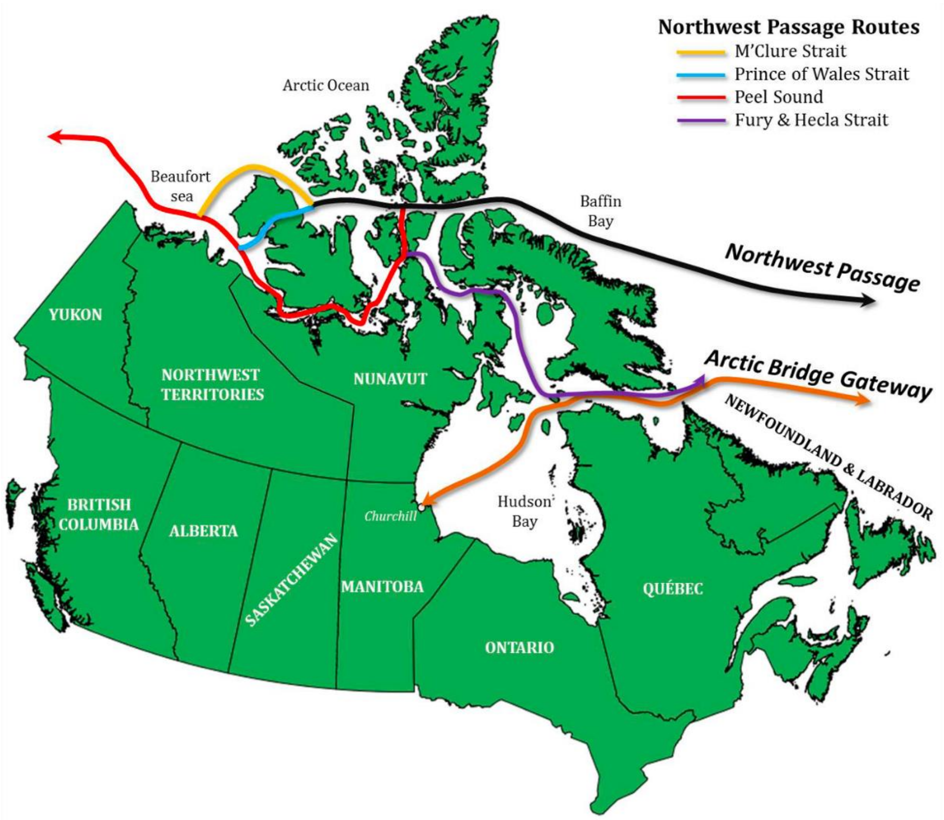


Figure 6.2. Major Canadian Arctic shipping routes (Gavrilchuk & Lesage 2014, p. 8)

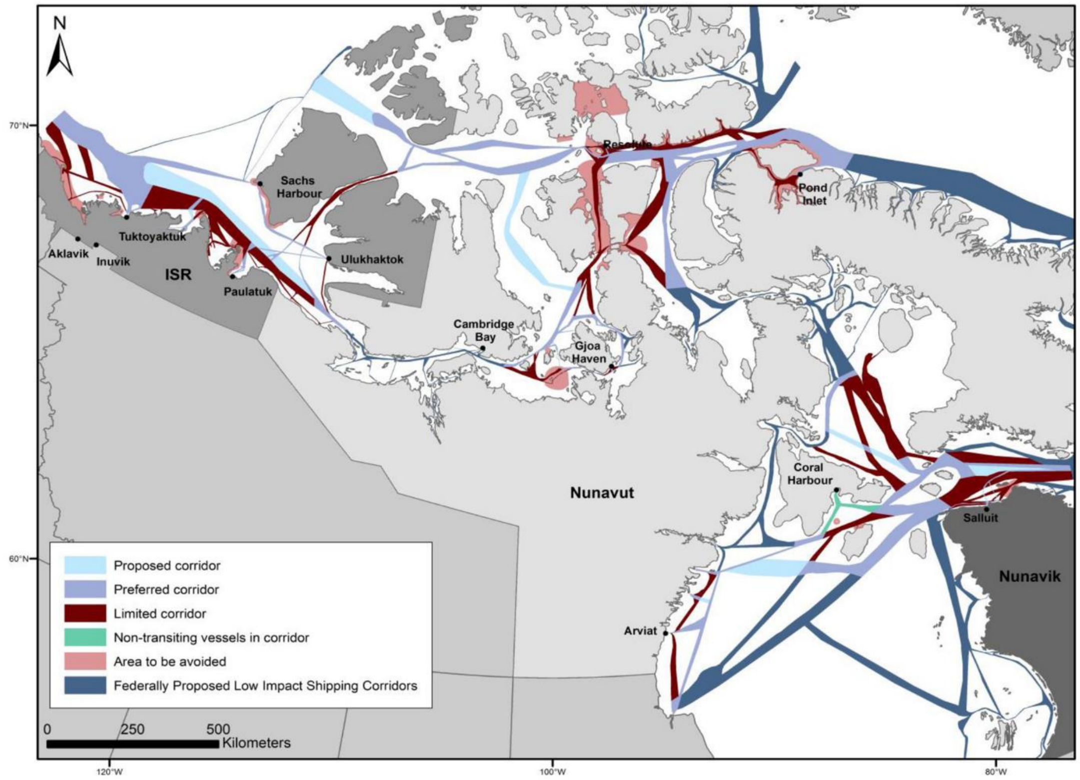


Figure 6.3. Community-informed shipping corridors (Dawson et al. 2020, p. 24)

Table 6.1. Potential environmental impacts linked to ship types operating in the Arctic, from *Arctic Marine Shipping Assessment* (Arctic Council 2008)

Ship Category	Ship Sub-category/Use	Ship Type-Specific Pollution Sources
Government Vessels and Icebreakers	Coast guard vessels, research icebreakers, private icebreakers, government icebreakers, other research vessels	Accident/Incident recovery-produced contaminants, emergency dumping oil/fuel, nuclear icebreaker raditation contamination, explosives/munitions, impacts due to icebreaking activity (disruption of ice formation, marine mammals, etc).
Container Ships	Cargo transport	Hazardous goods in transit, convoy collision hazard, grounding hazard (uncharted waters, lack of experienced ice navigation).
General Cargo	Community re-supply vessels, roll on/off cargo	Hazardous goods in transit, accidental cargo release, contaminated cargo.
Bulk Carriers	Timber, merchant, oil, ore, automobile carriers	Release of metal contaminants, radtiation contamination from cargo, hazardous goods in transit.
Tanker Ships	Oil tankers, natural gas tankers, chemical tankers	Liquid Nitrogen Gas contamination, chemicals and hazardous goods in transit, spills from oil transfer.
Passenger Ships	Cruise ships, ocean liners, ferries	Large volumes of black and grew water release, garbage disposal, cleaning contaminants, disturbance of wildlife through viewing activities, automotive contaminants w/ vehicle ferries
Tug/Barge	Re-supply vessels Bulk cargo transport	Increased accident hazard (non-proppelled), hazardous goods in transit, spills during oil transfer, heavy emitters of air contaminants (black carbon).
Fishing Vessels	Small fishing boats, trawlers, whaling boats, fish processing boats	Increased fire hazard, introduction of new pathogens and other contaminants from released fish offal, accidental release of invasive species/related biological contaminants, release of plastics, ghost nets and other fishing debris, seafloor damage from bottom trawlers, depletion of marine species (if not managed), accidental release of refrigerant contaminants.
Oil and Gas Exploration/Exploitation Vessels	Seismic exploratory vessels, oceanic and hydrographic survey vessels, oil drilling vessels, oil and gas storage vessels, offshore re-supply, portable oil platform vessels, other oil and gas support vessels	Hazardous cargo, explosives, acoustic impacts from seismic activities, oil/hydrocarbon contamination, contamination from extraction chemicals, accidental loading/offloading spillage, fire hazards.

Collisions, groundings, and mechanical failure are all risks that can result in local or even regional environmental damage if the cargo is lost or a vessel is submerged. Shipping in Arctic waters carries its own specific set of risks, too. Unfortunately, there are already examples of the effects of shipping accidents involving oil spills that have resulted in disastrous environmental damages and loss of life (Arctic Council 2008). Seasonal and multiyear ice and ocean currents add a high degree of complexity to mitigating the risk of oil spills – there is much to be learned about the potential effects of oil spills in the Arctic (Kuzyk & Candlish 2019). There is currently insufficient infrastructure and emergency preparedness to manage the risks that come with the growth in Arctic shipping (Arctic Council 2008).

The increase in circumpolar Arctic shipping is strongly tied to the extraction of non-renewable resources (Miller & Ruiz 2014). The transportation of oil, gas, and mineral ore has constituted a significant portion of Arctic marine traffic in recent years (Arctic Council 2008). Thus, the effects of minerals or oil and gas development cannot be considered without understanding the current and likely future shipping pressures. The future of Arctic shipping is examined in detail in the Arctic Council's *Arctic Marine Shipping Assessment* (Arctic Council 2008).

The vast majority of ship traffic occurs in the ice-free months. As that window is still fairly short (July to mid-October in Hudson Bay (Gavrilchuk & Lesage 2014)), ship traffic can be heavy to maximize the limited season (Arctic Council 2008). These periods of intense use mean that risks to marine wildlife, like migrating cetaceans, are concentrated and intensified within a few months. Planning temporal and geographic corridors informed by local wildlife patterns and needs will be essential in maintaining the ecological integrity of the region. The government-led, community-informed low impact shipping corridor project mentioned above is a step in this direction (Dawson et al. 2020). Planning will also need to be adaptive as the climate changes. It is possible that the migration patterns of various species will change as the marine environment warms.

Increased ship traffic escalates the potential for collisions with marine mammals. This direct effect on wildlife is not limited to actual ship strikes either. Increased ship traffic is expected to have an effect on the acoustic environment of marine wildlife (Arctic Council 2008). In Foxe Basin and Hudson Strait, for example, the underwater soundscape is largely pristine at present, with occasional discrete ship noise. Given current shipping predictions, the soundscape of these areas are expected to be transformed, with ship noise becoming a more continuous sound (Aulanier et al. 2017). It is clear that ship noise adversely affects marine mammals, but the effects at the population level are poorly established across species (Kuzyk & Candlish 2019). Research into the effects of ship noise on a range of marine species is ongoing.

With the rise in Arctic shipping comes the increased likelihood of non-native and potentially invasive marine species being introduced into the HBME. Non-native species are transported in ballast water and on the hulls of ships. However, as the Arctic tourism sector expands, humans may also become vehicles for the transport of non-native species (Miller & Ruiz 2014). Northern waters have had a relatively low exposure to non-native species, but that is now changing. Already, 34 unique non-native species and 54 introduction events in Arctic waters have been confirmed, with species coming from mainly from the Northeast Atlantic and Northwest Pacific, but also the Northeast Pacific and the Northwest Atlantic (Chan et al. 2019). Shipping vessels were the main pathway for these introductions. Several non-native species have been found in the vicinity of the Churchill port (Goldsmit et al. 2014). An Alternative Ballast Water Exchange Zone in eastern Hudson Strait has been recommended for use by Canadian ships coming from southern temperate waters, which are normally exempt from having to exchange their ballast water. The strong currents moving towards the Atlantic Ocean would ideally act as a natural barrier to potential invasive marine species and reduce the possibility of their establishment in warmer waters of Hudson Bay and James Bay (Stewart and Howland 2009).

While cruise ships and other passenger vessels are not a large source of ship traffic in the HBME, they are worth noting as they contribute to the larger shipping footprint and tourism-based ship traffic in the Arctic more generally has been increasing (Arctic Council 2008). Like other ship traffic, tourist vessel traffic is concentrated in the ice-free months. These ships use the marine environment in a different way compared to bulk transport shipping. For example, a tourist vessel may spend more time in areas rich in marine wildlife for sightseeing purposes. Depending on the timing, location, and nature of the tourist activity, this could interfere with local Indigenous harvesting activities and/or with the life history requirements of the wildlife involved. The nature of potential effects is, therefore, somewhat different from a barge or coast guard ship. With the average cruise ship producing between 532,000 and 798,000 litres of sewage and 3.8 million litres of wastewater a day, these ships also represent an additional source of marine pollution (Arctic Council 2008).

Growth in Arctic shipping brings the potential positive socio-economic effect of lower costs for the communities in the HBME that rely on goods that are barged in (i.e. most communities in the region). Resource development associated with increased shipping is also noted as a positive socio-economic benefit, particularly via job creation (Arctic Council 2008). Of course, these must be weighed against the risks and considered in the context of who will carry the burden of any negative environmental or socio-economic effects.

6.1.3 Exploration and mining

While mining is terrestrially focused, there is a marine component to this type of development: shipping. There are at least five significant mineral developments that rely on shipping in the region, with ports at Baker Lake, Rankin Inlet, Roche Bay, and Steensby Inlet in Nunavut, and at Chisasibi in Québec (Gavrilchuk & Lesage 2014). There are also 40 proposed mines in Nunavik and 49 mines at various stages of exploration in Nunavut (Figure 6.4) (Kuzyk & Candlish 2019). Figure 6.4 was adapted by Kuzyk and Candlish (2019) from Gavrilchuk and Lesage (2014) and the mines noted in this figure rely on marine access through Hudson Bay and Hudson Strait, differing from Figure 6.1, which describes all mine projects in various stages of development in the HBME region. The driving force behind mineral exploration and extraction in the Canadian North are global markets and exploration and development priorities can change quickly. With climate change reducing the ice-on season, these new northern shipping routes result in reduced cost and increased feasibility of getting mined resources to market which is appealing to any resource extraction company.

As with large-scale hydroelectric projects, the construction and operation of major mine developments bring potential opportunities in the wage economy for community members. For example, the Raglan nickel mine in Nunavik (just outside the HBME) has employed up to 500 people, with about 15-16% of these employees identifying as Inuit (Koke 2008, Rodon & Lévesque 2015). These jobs represent an important source of employment in the region and facilitate participation in the subsistence economy, as the equipment required to practice these activities comes at a significant financial cost. Other benefits include: new roads that make subsistence harvest more accessible, new local businesses that support mining operations or employee needs, royalty distribution throughout the community via an Impact Benefit Agreement that can boost local infrastructure, and an increase in local employment that can have a positive effect on community morale (Koke 2008, Rodon & Lévesque 2015).

However, these large projects can also usher in a suite of troubling socio-cultural changes: loss or reduction of key harvested species, disruption of the traditional harvesting calendar, increased presence of outside influences including subsistence use, substance abuse-related social issues, municipal services disruptions associated with royalty payouts, disruptions in school attendance, and fear of eating traditional foods due to contamination are all risks that need consideration and mitigation (Rodon & Lévesque 2015). Many of these issues are mirrored in the effects of the large hydroelectric projects in the region (Niezen 1993, Whiteman 2004). In terms of cumulative effects, beyond shipping, there may be minimal overlap in the environmental effects of mine development and other marine-based development, but there is certainly an accumulation of socio-economic effects.

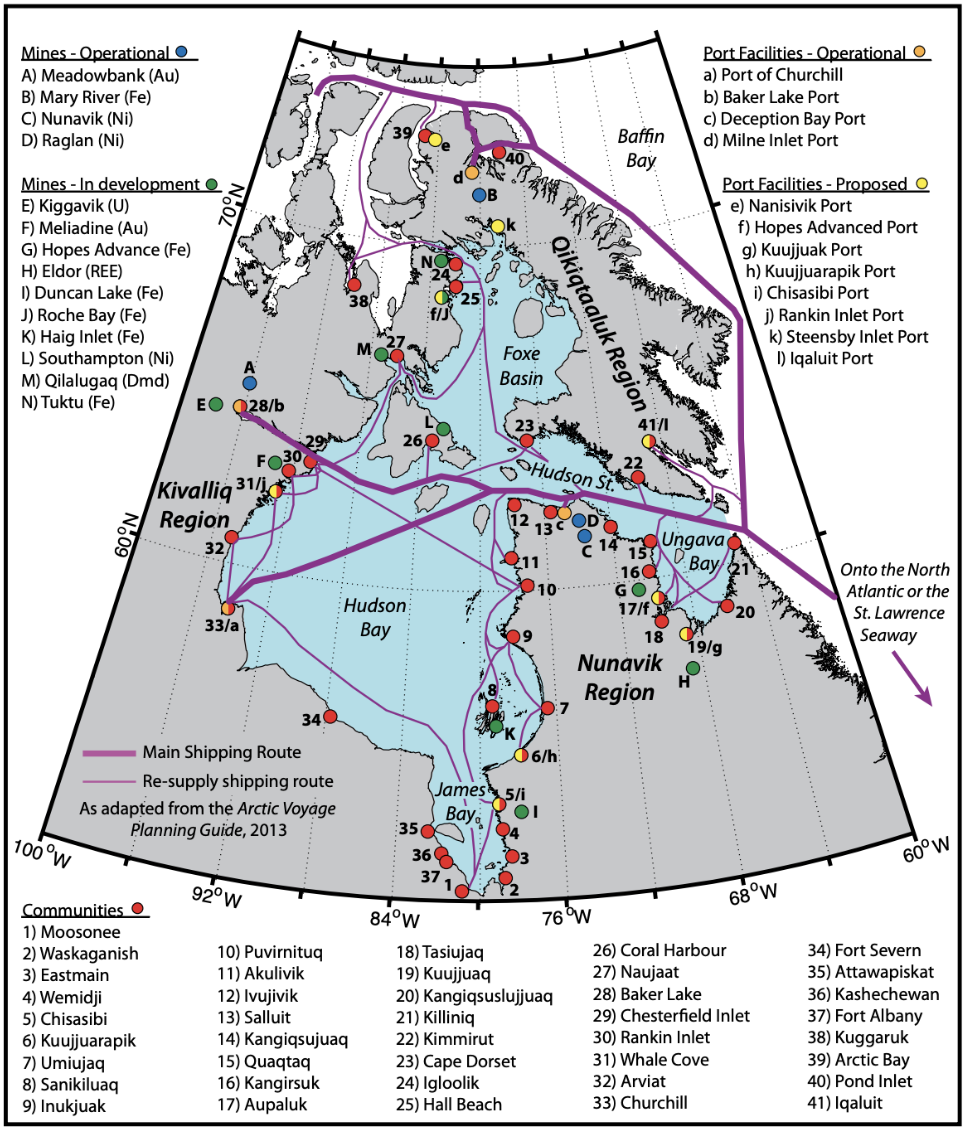


Figure 6.4. Proposed, developing, and operational mines in the Greater HBME that are, to some extent, reliant upon marine and port access. Mined resources are provided for each mine (Au – Gold, Fe – Iron, Ni – Nickel, U – Uranium, REE – Rare Earth Elements, Dmd – Diamonds) (Kuzyk & Candlish 2019, adapted from Gavrilchuk and Lesage (2014) – see Figure 6.1)

6.1.4 A climate change lens

When considering cumulative effects in the coming decades, it will not be possible to simply rely on how ecosystems have operated in the past. Climate change has made past experience a poor predictor of future outcomes. Warmer air temperatures, longer ice-free seasons, increased wind speeds and precipitation, reduced extent of seas, melting permafrost, increased coastal erosion, increased freshwater inputs to marine systems, and ocean acidification are just a handful of the physical changes already observed in the Arctic marine environment (AMAP 2011, Kuzyk & Candlish 2019). While the effects of climate change on a diverse suite of biophysical and socio-economic factors are currently the focus of research around the world, the interplay between many of these individual changes is complex and not always well-understood. Modeling likely scenarios under various possible climates and with a range of development-related effects is a valuable activity, but still operates without a complete picture.

There are a multitude of ways in which the cumulative effects of current and potential development in the HBME are already, or may be in the future, affected by climate change. Some examples are provided below.

First, the introduction of non-native and potentially invasive species to Arctic marine systems illustrates the complexity of cumulative effects coupled with a changing climate. Not only will a climate change-induced reduction in sea ice result in greater ship traffic, bringing more opportunities for the introduction of non-native species, but a warmer Arctic climate may also result in a more hospitable environment for these non-native species (Chan et al. 2019). Further, passage between the Atlantic and Pacific oceans through the Arctic Archipelago requires less time. Many non-native and potentially invasive species that might have perished on the longer journey through the Panama Canal could have a greater chance of survival on ships traveling through the north (Miller & Ruiz 2014). Thus, climate change removes multiple barriers for the disruption of local and regional food webs in the HBME.

Second, it is predicted that human interactions with marine mammals will change as the extent and timing of sea ice coverage decrease. Loss of sea ice may limit where Inuit harvesters are able to travel for important species like seals or narwhal as the ice-on season becomes shorter, the region becomes windier, and travel routes are less predictable (Hovelsrud et al. 2008, Kuzyk & Candlish 2019). This is not the only climate-related threat to harvest, though. Reduction in sea ice coverage, differences in prey species availability, and new southern species moving into warming waters are adversely affecting marine mammal species in the region (Kuzyk & Candlish 2019). These evolving patterns in the food web will have implications for harvesters, particularly if preferred species become less abundant or less accessible. Harvesters will have to take these factors and others into consideration when planning hunting trips, perhaps shifting areas of use or timing of travel. This type of land use change in response to a warming climate needs to be considered in the context of other proposed developments, such as the planning of shipping routes and infrastructure, as increased ship traffic could further hamper harvesters travel on the sea ice by breaking up ice bridges or disturbing wildlife.

Third, the rise in global temperatures is expected to influence the movement, biomagnification, and bioaccumulation of contaminants in marine systems, like the HBME (Alava et al. 2017). In some studies, reduced sea ice and resulting shifts in marine wildlife diets were linked with higher contaminant levels in polar bears, seals, and murres. However, these relationships are complex and influenced by a suite of variables. These documented trends in contaminant bioaccumulation vary in magnitude and direction, making blanket predictions near impossible (McKinney et al. 2015).

The three examples above offer a view to the diversity, complexity, and interconnectedness of change in the Arctic marine environment. The impact, scale, and scope of these types of interactions will vary depending on the magnitude of the development, the geography of the affected area, and the engagement and support of local people, and will need to be assessed as projects arise and the northern economy develops. Lastly, beyond the effect of climate change on development, it is now imperative that assessing cumulative effects of development also include an understanding of the greenhouse gas footprint. Certainly, large-scale development can contribute significant amounts of greenhouse gases to the global system, but the cumulative contribution of many small sources (e.g. the massive increase in the number of vessels traversing the Arctic) should not be discounted.

6.1.5 Other sources of effects on the HBME

There is an exploratory interest in oil and gas deposits in the region (Gavrilchuk & Lesage 2014), particularly near Coral Harbour (Figure 6.5) (Kuzyk & Candlish 2019). However, the 2016 federal moratorium on offshore Arctic oil and gas drilling remains in place for the time being and no land-based interests have been pursued beyond exploration. The cumulative effects and risks of even one such development in the HBME could be considerable, but would also be highly dependent on the location, mitigation measures, and local preparedness.

Commercial fisheries, particularly for Arctic char, already exist within the northern HBME, with interest to expand these opportunities to other communities (see sections 3.5 and 5.8 for more detail on commercial harvests; Government of Nunavut 2016, Hurtubise 2016). With commercial fishing comes the need for transport to markets beyond the Canadian North. In many cases, transport would be by boat, although a few communities in the southern part of the HBME are serviced by rail or road. While access to outside markets is essential to the viability of northern fisheries, like the growing shrimp, turbot, and Arctic char industries (see Species of Commercial Interest, Chapter 3), increased shipping poses a threat to local and regional food webs that sustain these fisheries, as discussed above. Of course, ship traffic related to fisheries accounts for only a small portion of Arctic shipping (Arctic Council 2008). Environmental degradation from other types of development, including those discussed above, could also affect current and future fisheries (e.g. oil spills, disruption of anadromous fish migration routes, etc.).

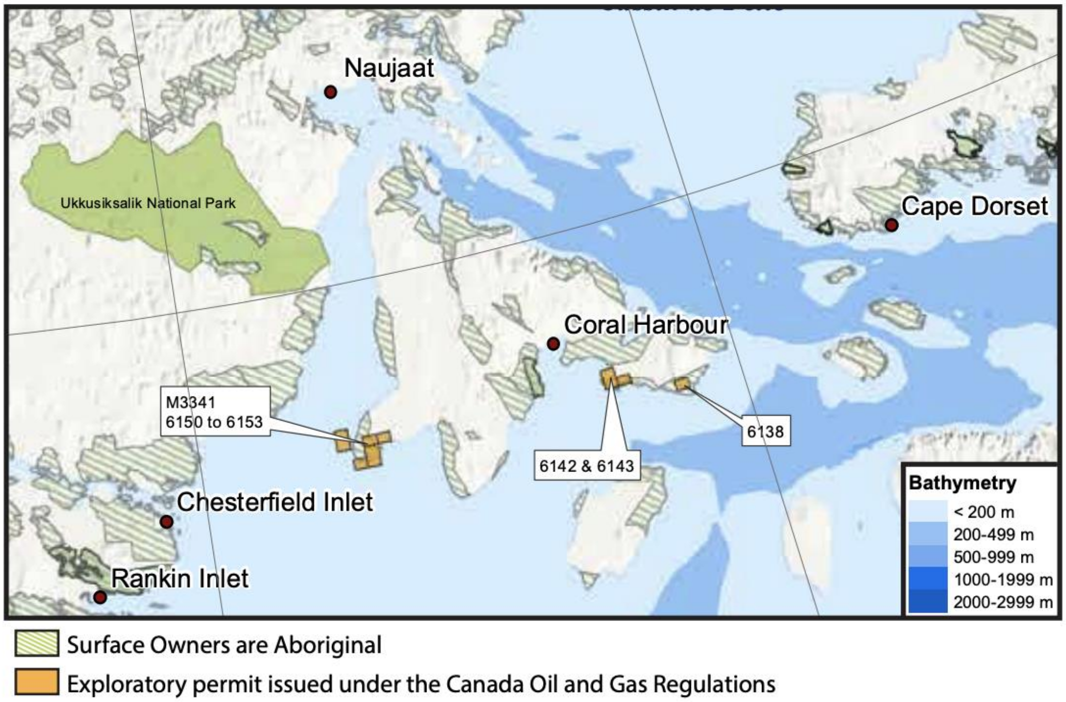


Figure 6.5. Indigenous surface rights and exploratory permits for oil and gas in the northwestern portion of the HBME (Kuzyk and Candlish 2019, p. 365, Adapted from Indigenous and Northern Affairs Canada June 2016)

The commercial whaling and the peak of the commercial fur trade have long passed, but the socio-cultural and economic effects of these practices should be considered in the examination of current and potential cumulative effects throughout the region. The geographic and temporal scoping of cumulative effects is a challenge. What is considered “baseline” will differ based on cultural perspectives, the nature of a proposed development, and motive. However, the effects of these extractive industries of the past are still being felt in communities throughout the Hudson Bay Marine Region today. Thus, the effects of new development occur in the context of these existing effects.

6.2 DEVELOPMENTS IN INDIGENOUS ECONOMIC, CULTURAL AND FOOD SECURITY

In 2017, Mary Simon, the Special Representative to the Minister of Indigenous and Northern Affairs Canada, issued a report entitled *A Shared Arctic Leadership Model* that outlined priorities and goals for collaboration between Inuit and Canada towards achieving goals related to conservation and the social and economic priorities of Arctic leaders and peoples (Simon 2017). Canada’s new Arctic and Northern Policy Framework, released in 2019, takes guidance from this document and develops a shared vision and long-term roadmap for implementation (CIRNAC 2019a). Priorities include nurturing healthy families and communities; creating jobs, fostering innovation and growing Arctic and northern economies; supporting science, knowledge and research that is meaningful for communities and for decision-making; addressing the effects of climate change and supporting healthy ecosystems in the Arctic and North; and advancing reconciliation and improving relationships between Indigenous and non-Indigenous peoples. This framework will guide Canada's investments and activities in the Arctic through 2030.

Additionally, Canada and all four Inuit rights-holding bodies plus Inuit Tapiriit Kanatami (the national Inuit representative body, comprised of the four rights-holding bodies) signed an agreement on Inuit-Crown Partnership in 2017, which sets out a framework for a bilateral partnership on shared priorities (Canada et al. 2017). Since its inception, the Inuit-Crown Partnership Committee (ICPC) has worked on a number of social and health priorities, including the co-development of an Indigenous Early Learning and Child Care Framework, endorsement of the Inuit Tuberculosis Framework and the co-development of the Inuit Nunangat Housing Strategy. Over 2019, the ICPC established its first work plan focused on the environment and climate change, and signed the Pikialasorsuaq Joint Leaders Statement—a commitment between governments of Canada, Denmark and Greenland and Inuit leaders to work in partnership on protecting the ecologically and culturally significant Pikialasorsuaq (North Water Polynya) (Inuit-Crown Partnership Committee 2019).

Regionally, Inuit are also taking actions to further self-determination and the full implementation of existing land claims. In 2019, Makivik Corporation signed a Memorandum of Understanding with Canada regarding Nunavik Inuit self-determination, launching a formal process for Nunavik Inuit to establish a new governance structure based on Inuit laws, values, identity, culture, and language. In 2019, the Government of Canada, Government of Nunavut and Nunavut Tunngavik Incorporated signed an agreement-in-principle on devolution; this will serve as a guide for the negotiation of a final devolution agreement in relation to Nunavut (CIRNAC 2019b). Central to the agreement is transferring and devolving responsibilities and powers for land and resource management to the territory. Additionally, the *Nunavut Fisheries Regulations*, which will provide a management regime for implementing fisheries and resource management principles under the *Fisheries Act,* are currently being negotiated and will bring fisheries management in the Nunavut waters and areas of joint use and occupancy with Nunavik Inuit in line with the *Nunavut Agreement* (DFO 2019).

Similar trends towards increased self-determination, strengthening control over lands and resources, and collaboratively addressing systemic issues to enhance prosperity and address determinants and of health and wellbeing can be seen among the Cree. In 2012, the Cree of Eeyou Istchee and Québec government signed the *Agreement on Governance in the Eeyou Istchee James Bay Territory*, grounded in the 2002 *Agreement Concerning a New Relationship Between le Gouvernement du Québec and the Crees of Québec* (also known as the *Paix des braves*). The purpose of the 2012 agreement was to modernize governance structures created by the JBNQA and create a new public management model in the territory at the municipal and supra-municipal levels. In February 2020, the Crees of Eeyou Istchee signed a new agreement with the Québec government, *La Grande Alliance*, in keeping with the desire to broaden the collaboration supported by the 2002 agreement (Cree Nation Government 2020). The 2020 agreement focuses on balanced economic development and infrastructure development over the next three decades, but also includes the identification of new protected areas conducive to the connectivity of the territory’s wildlife habitats.

Further, of direct relevance to the HBME is a Memorandum of Understanding (MOU) signed between Canada, represented by Parks Canada, and the Crees of Eeyou Istchee in 2019 for the assessment of the feasibility of establishing a National Marine Conservation Area (NMCA) in the Eeyou Marine Region. The feasibility assessment will consider the social, environmental, and economic benefits and impacts of establishing an NMCA in the Eeyou Marine Region, with the expectation that the feasibility assessment would be completed in 2022. This effort and the provisions around protected areas in *La Grande Alliance* advance the realization of the Cree vision for conservation and land use in their traditional homeland of Eeyou Ischtee, as expressed in the Cree Regional Conservation Strategy (Cree Nation Government 2015). Within the strategy, which aims to maintain strong ties to Cree cultural heritage and way of life and sustain biodiversity, full Cree participation in conservation planning and management and the centrality of Cree knowledge, culture and land management systems in conservation are key tenets. Arqvilliit (Ottawa Islands, in northeastern Hudson Bay) Indigenous Protected and Conserved Area establishment project led by the community of Inukjuak and Qikiqtait, a community-driven project led by the Arctic Eider Society for the Belcher Islands Archipelago in southeastern Hudson Bay, are also examples of land conservation projects within the HBME in which Indigenous Knowledge and governance will be prioritized (Government of Canada 2020).

These achievements demonstrate strong trends towards strengthened self-determination for Indigenous peoples around the HBME and build on decades of effort. These efforts and successes in expanding and deepening Indigenous control and decision-making over Indigenous lives and lands are expected to continue.

6.3 DEVELOPMENTS IN CANADIAN OCEAN LAW AND POLICY

In the last five years, there have been a number of changes to Canadian ocean law and policy that, when taken together, significantly strengthen ocean protection. In 2016, Canada launched the national Oceans Protection Plan, which dedicated $1.5 billion to strengthening marine shipping safety, protection, and restoration of marine ecosystems, strengthening the evidence base for ocean management, and strengthening engagement of Indigenous peoples in ocean management and protection. The Oceans Protection Plan accelerated changes in ocean law and regulation in Canada in the last several years which may be of relevance to the HBME now or in the future, and which are summarized by Hewson (2019):

- *Oceans Act* (1996) , amended by Bill C-55 (2019): provides powers for interim Marine Protected Areas (MPA) to be created quickly; introduced the principle of ecological integrity for the first time in Canadian marine law; incorporated the precautionary principle into the *Act*.

- *Fisheries Act* update (2019): provides new power to develop regulations to establish long-term spatial restriction on fishing activities (marine refuges); makes it easier to designate Ecologically Significant Areas; restores protection for fish and fish habitat, including the prohibitions on habitat alteration, damage and destruction and on causing death of fish through means other than fishing; includes duty to maintain fish stocks to or above reference point levels; provides for inclusion of Indigenous knowledge in decision-making; requires consideration of adverse effects on Indigenous rights when making decisions under the Act; allows for creation of Indigenous governing bodies to carry out purposes of the Act; creates a public registry for fish habitat proposals and decisions; provides Ministerial powers to stop fisheries and address urgent situations such as whale entanglement in fishing gear
- *Marine Mammal Regulations* update (2018): define what qualifies as a disturbance of marine mammals; sets approach distances for vessels
- *Canada Petroleum Resources Act* (1985), amended by Bill C-55 (2019): provides powers for government to rescind oil and gas leases within *Oceans Act* MPAs
- *Canada Shipping Act* update (2019): updated marine pollution framework to support faster and more effective response to marine pollution
- *Marine Liability Act* update (2018): updated Ship Source Oil Pollution Fund to remove caps on compensation for responders and victims of ship-source oil spill, funded by a levy on receivers and exporters of oil
- *Wrecked, Abandoned or Hazardous Vessels Act* (2019)*:* ensures that ship owners are liable for wrecks, which can be a pollution source, and requires wreck removal insurance for large vessels
- *Pilotage Act* amendments (2020): updates to standardize ship pilotage regulation and increase oversight and enforcement
- *Navigation Safety Regulations* update (2019)*:* expanded carriage requirements of navigation safety and radiocommunication equipment to a wider category of vessels, allowing better monitoring of compliance with speed restrictions and avoidance zones closed to ship traffic; monitoring of ship traffic and noise; and improve collision avoidance
- *Canadian Environmental Protection Act* update (2019): enhancement of regulatory controls for several contaminants (flame retardants and oil and water repellants)

The *Nunavut Fisheries Regulations*, which will provide a management regime for implementing fisheries and resource management principles under the *Fisheries Act,* are currently being negotiated. These will replace the *Northwest Territories Fisheries Regulations*, which predate the *Nunavut Agreement*, and ensure that the *Nunavut Fisheries Regulations* are in line with the *Nunavut Agreement* as well as the *Nunavik Inuit Land Claims Agreement*. The *Nunavut Fishery Regulations* are being developed in collaboration with Nunavut Tunngavik Incorporated, the Government of Nunavut, and the Nunavut Wildlife Management Board, along with Makivik Corporation representing the interests of Nunavik Inuit in areas of equal use and occupancy (DFO 2019).

Policy changes in relation to Indigenous relations and co-governance have also meant that Canada has moved forward on agreements with Indigenous nations that strengthen Indigenous stewardship and management of ocean areas. While the agreements are not directly relevant to the geography of the HBME, they are relevant in terms of policy approaches and precedent. Hewson (2019) identifies several agreements:

- *Reconciliation Framework Agreement for Bioregional Oceans Management and Protection on the Pacific North Coast*, signed by Canada and 14 First Nations in 2018 to support the development of an MPA network planning process in the Northern Shelf Bioregion
- *Coastal First Nations Fisheries Resources Reconciliation Agreement*, signed by Canada and 7 First Nations in BC in 2019 to increase the role of First Nations in fisheries management decisions within their traditional territories, and improve access to community-based commercial fishing opportunities
- SGaan Kinghlas-Bowie Seamount MPA 2018 agreement between Fisheries and Oceans Canada and the Council of the Haida Nation to close all bottom contact fishing within the MPA, to protect sensitive benthic habitat within the MPA

Further, a number of MPAs and management plans for MPAs have also been created in the last several years. The Anguniaqvia niqiqyuam MPA, established in 2016, is the first MPA to identify a conservation objective based fully on Indigenous traditional and local knowledge. The Tallurutiup Imanga National Marine Conservation Area (NMCA) Impact Benefit Agreement was signed between the Qikiqtani Inuit Association and Canada, which in many ways enacts the vision set out by Mary Simon in her report *A New Shared Arctic Leadership Model* of creating Indigenous Protected Areas in Inuit Nunangat that are “based on the idea of a protected area explicitly designated to accommodate and support and Indigenous vision of a working landscape” (Simon 2017, p. 23). This vision is also being enacted in the Imappivut (“Our Waters”) Marine Plan, which is being developed by the Nunatsiavut Government to implement Chapter 6 of the *Labrador Inuit Land Claims Agreement* and will extend over the full coastal and ocean area of Nunatsiavut.

Lastly, a significant policy change is the decision in 2018 to create a new, stand-alone Arctic Region under Fisheries and Oceans Canada (DFO) and the Canadian Coast Guard that will be inclusive of the four Inuit regions in Canada (DFO 2018). This change is reflective of the government of Canada’s recognition of the importance of the Inuit Nunangat as a unified geographic, social, and policy space.

6.4 DEVELOPMENTS IN SPECIES PROTECTION

The NWMB, EMRWB and NMRWB are instruments of wildlife management as defined by the respective land claims under which these co-management boards were established, as described in section 2.2. Each land claim also specifies principles regarding respecting Indigenous harvesting rights and priorities, providing optimum protection for the renewable resource economy to ensure long-term sustainability of wildlife resources. The co-management boards are responsible for making wildlife management decisions, subject to final approval by the Minister. Based on the timing of signing the NILCA and EMRLCA, implementation of the land claims and their wildlife management regimes is still fairly new. With time and continued land claim implementation, species protection in the HBME through these wildlife management regimes will continue to be strengthened. For example, the Nunavut Marine Council—a mechanism for Nunavut's co-management boards to coordinate activities and share information—was only established in 2012, almost two decades after the *Nunavut Agreement* was signed. While the NILCA provides for the establishment of a Nunavik Marine Region Council, it has not yet been established, although joint meetings of the co-management boards have been proposed to the NILCA Implementation Committee for the second decade of NILCA implementation.

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed most of the marine mammal populations in the HBME as Special Concern (bowhead, narwhal, Atlantic walrus, polar bear and ringed seal) (COSEWIC 2009, 2004, 2017a, 2018), while some, for example the Eastern Hudson Bay (EHB) beluga, have been assessed as endangered (COSEWIC 2004). However, very few of the HBME populations have been listed under the federal Species at Risk Act (SARA) legislation, with the exception of polar bear. Some of the migratory birds that travel through or summer on the offshore islands of the HBME have noted conservation concerns. Red knot *rufa* subspecies and Red-necked Phalarope were assessed and listed as Endangered and Special Concern under SARA, respectively (COSEWIC 2007b and 2014). Thanks to the ban of DDTs and captive breeding programs, peregrine falcon was recently delisted as a species of concern (COSEWIC 2017b).

Given the conservation concerns for EHB beluga there have been varying forms of restrictions on the harvest of this stock of whales since the 1980s. With the establishment of the NMRWB, the Board became the main instrument of wildlife management in the Nunavik Marine Region and therefore assumed responsibilities over beluga management. In 2020, the NMRWB held its second in person public hearing, to consider new management decisions related to EHB beluga. This marked the first opportunity that Nunavik Inuit had to sit face to face with decision makers to present proposals for how beluga should be managed in the region with many calls for an Inuit led approach to management.

In 2019, COSEWIC requested that ringed seals be listed as a species of special concern under Canada's Species at Risk Act (SARA), based in part on the vulnerability of ringed seals to changing sea ice due to climate change and observations from Inuit of changes in species distribution (Brown 2019).

COSEWIC is expected to complete a reassessment of all beluga Designatable Units in 2020 and narwhal and killer whale (Northwest Atlantic/Eastern Arctic populations) in 2021(COSEWIC 2020).

6.5 INFORMATION NEEDED FOR SUSTAINABLE FISHERIES

Much has changed in the development of commercial fisheries in the HBME since they began centuries ago; there are significant efforts currently underway to improve our understanding of sustainable fisheries development that benefits local communities and regions and maintains traditional subsistence food supplies. Nonetheless, information gaps remain.

The *Nunavut Fisheries Strategy* identifies a number of information needs for fisheries development (Government of Nunavut 2016). Priority 1 is Inuit Qaujimajatuqangit, Science and Sustainability, with the goal of developing a coordinated, consultative, prioritized approach to fisheries and aquatic research within and adjacent to Nunavut while embedding Inuit Qaujimajatuqangit into research and management to improve the understanding of Nunavut's resources and how to grow fisheries sustainably. The priority identifies knowledge needs regarding small and large-scale changes that can affect fisheries productivity (e.g. temperature, invasive species, species migration); the need for Nunavut-specific science and local knowledge-based research and monitoring programs regarding key environmental drivers and how harvesting and environmental change may be affecting them; and a whole-ecosystem approach to understanding fisheries in Nunavut. Under Priority 2, Governance and Regulation, the need for regulatory clarity is highlighted. Under Priority 7, Marketing and Market Access, addresses the need for improving understanding of how non-local char demand can be increased and how the inshore fishery can meet the local market demand for char. Some of these research needs are currently being addressed through actions associated with the *Nunavut Fisheries Strategy*; for example, the Qikiqtaaluk Corporation is undertaking a five-year community-based survey of the state of Arctic char using its research vessel.

In 2017, DFO received funds to expand and support regional Indigenous commercial fisheries in Canada's North (National Indigenous Fisheries Institute 2018). This initiative resulted in a final report, *Northern Integrated Commercial Fisheries Initiative: Final Report* (2019), which identifies a number of information needs (National Indigenous Fisheries Institute 2019). The primary information need identified related to improving the understanding of local stock abundance and other information needed for capture fisheries development. Limited baseline knowledge of fish biomass at local and regional scales was identified as a key knowledge gap and business planning need. Some communities also identified the need for understanding the impact of small-scale commercial fisheries development on waterways, and others identified the need to better understand how existing and future developments may impact water levels and quality, and thus fish habitat and health. During consultations, communities identified significant knowledge gaps about local fish stocks and marine mammals and stated that fishery development research and hydrographic charts are needed for freshwater and marine areas. Communities also identified knowledge sharing and translation needs for existing research, where research results on topics of relevance are not sufficiently reaching communities or local decision-makers. Utilization of knowledge derived from scientific methods and Indigenous knowledge was also highlighted as a need.

The report also states that fishery managers and communities in Nunavik that have long been involved in commercial fishing enterprises also identified information needs related to aquaculture development, including information needs regarding viable infrastructure and species. Further, information needs regarding understanding and addressing market realities in business planning and productivity issues, such as costs of getting products to market, were identified. The report also clearly identifies the need to mobilize Indigenous Knowledge regarding fisheries and management, and the need to ensure that Indigenous communities and regions are at the centre of resource management decision-making.

The information needs regarding fish stocks and identified in the *Northern Integrated Commercial Fisheries Initiative Final Report* and the *Nunavut Fisheries Strategy* are echoed in the limited literature on northern commercial fisheries development. For example, Tai et al. (2019) explains that there are very few recent reports or articles on catch statistics in Canada's Arctic; these gaps make it more difficult to project and monitor how climate change and other factors may affect fish and commercial fishing initiatives. From a policy perspective, Bennett et al. (2018) assert that ongoing lack of access to ocean and coastal resources undermines the ability of governments to effectively address topics related to coastal and Indigenous community wellbeing. The authors suggest that developing a better understanding of how changes in access, driven by institutional, social, ecological, and economic changes, affect wellbeing and how these impacts and benefits are distributed requires attention to ensure equitable advancement of integrated coastal and ocean management and integrated fisheries management. The authors outline future research priorities in this area (Table 6.2)

Table 6.2. Future research priorities related to access to marine and coastal resources and areas in Canada, which also applies to the North (after Bennett et al. 2018, p. 7-8)

Themes	Research questions
Access in legal and policy frameworks	• Where and how are decisions related to access made in the current federal legal framework? Who, ultimately, is responsible for making the decisions? • Who is able to participate in current decision-making and policy processes regarding access and benefits? • How does Fisheries and Oceans Canada's (DFO) mandate shape the extent to which coastal community access is considered in policy and practice? How is DFO's authority to manage access defined and implemented on Canada's three coasts? • How and to what extent are current laws and policies related to access being applied? • What Indigenous legal frameworks currently exist to support Indigenous access? How do the access rights of other groups impinge on these traditional frameworks? • What might an alternate governance regime for facilitating an Indigenous rights-based fisheries look like within the Canadian legal context?
Access impacts, benefits and well-being	• To whom and how are benefits from Canadian fisheries and marine resource allocations currently distributed? How and why has this changed over time? How are quotas and licenses allocated between different groups and types of fisheries, and how are these groups benefiting economically?

Themes	Research questions
	• Through what pathways does access to fisheries and other marine resources, and changes to this access, impact the well-being of different groups (e.g., producers, independent fleet, workers, processors, Indigenous peoples, men, women, youth, etc.) in coastal communities? • What have been the economic, social, health, and cultural impacts of different past resource allocation regimes? • How will coastal community access issues change under future socio-economic and environmental scenarios? How might climatic and global environmental change alter access? • How might notions of equity, justice and fairness guide decisions related to resource allocations and access?
Spatial access valuation and issues	• What values are associated with access to areas of the oceans and coast? How do different values and uses conflict? • What social and cultural activities require access to the ocean? Which areas are important for different groups? • How do various uses of the marine environment impact the ability of different groups to access areas of the ocean?
Barriers and supports for access	• What factors influence (support or undermine) the ability of different coastal and Indigenous communities, as well as sub-groups within these communities, to access marine resources, and areas of the ocean or coast? How might these barriers be overcome?
Prioritization and transfer of access	• How, for what activities and for whom, should access be prioritized and who should be involved in processes defining prioritization? What might a doctrine of priority look like? • How is (and in the future, should) access be transferred: inter-generationally, between fisheries sectors (small- scale, Indigenous, industrial), and between industries? • How might decisions about allocations be made to align with principles of historical use and adjacency? • What factors contribute to reconciling society's need to access marine resources with declining ecosystem goods and services (i.e. availability) arising from human impacts due to access?
Implementation of Integrated Coastal and Ocean Management (ICOM)	• How can and should integrated coastal and ocean management (ICOM) and marine spatial planning (MSP) processes take coastal community access to marine space (current and future) into account? • What are the best practices for taking coastal community access to the marine environment into account across the three coasts of Canada? • How might local communities gain better access to marine spatial planning processes, or even drive the process from the bottom-up, to ensure that local visions and needs are considered?
Best practices for maintaining,	• What are priority policies and actions for supporting access and increasing the level of benefit to coastal communities from adjacent

Themes	Research questions
supporting or increasing access and benefits	fisheries and resource harvesting? What supports are needed to enable the next generation to enter fisheries? • What are the potential implications of different fisheries future management scenarios for access and associated social impacts? • What community-oriented access policies have been implemented elsewhere in the world and to what effect? Where have significant reallocations been made? • What actions might be taken to increase local benefit from development activities occurring in adjacent territories?
Decision-making methods and processes	• How can and should different types of knowledge (scientific, local, traditional) be integrated into deliberations related to marine access? • How might decentralized decision-making, collaborative governance arrangements or co-management processes contribute to protecting community access? How might international norms, principles and institutions contribute to these processes? • How can different levels of government and agencies work together to better support the viability of community-based fisheries economies? What factors prevent inter-agency and inter-jurisdictional collaboration and coordination on this issue? • What methods are available to aid decision-making to optimize access for different groups and uses, in particular, under conditions of scarcity and uncertainty and considering trade-offs and cumulative effects?

6.6 INTERNATIONAL PRECEDENTS

While large areas around and within the HBME are subject to comprehensive land claims and thus Indigenous jurisdiction is recognized and affirmed, international precedents related to the enhancement of involvement of Indigenous peoples and knowledge in decision-making related marine and coastal areas is of potential significance to the HBME. Several examples will be discussed.

First, there are a number of international instruments and organizations that are continuing to evolve to enhance participation of Indigenous peoples and knowledge, and/or where work is being done towards more effective implementation of existing instruments and norms for this purpose. For example, Indigenous peoples' and local communities' conserved territories and areas (ICCAs) are natural and/or modified ecosystems containing significant biodiversity values, ecological services and cultural values, voluntarily conserved by Indigenous peoples and local communities through customary laws or other effective means (Kothari et al. 2012). ICCAs have been gaining recognition in international areas in the last ten to fifteen years, including by the International Union for Conservation of Nature (IUCN) and through the Convention on Biological Diversity (CBD), specifically under the Programme of Work on Protected Areas (PoWPA) (Kothari et al. 2012). Contributing to this change is a strengthened recognition of Indigenous rights, and an increasing realization that states need not be the only vehicle for conservation and protection The PoWPA has four major elements, the second of which is Governance, Participation, Equity and Benefit-sharing; within this element, the PoWPA calls for the recognition of ICCAs as one governance type of protected areas. Indigenous Protected Areas are one type of ICCA, which emerged in Australia to support Indigenous groups in establishing and managing protected areas on their own lands, including through the provision of funding (Kothari et al. 2012), and have recently become of increasing interest to Indigenous communities in Canada and elsewhere as a potential mechanism for strengthening Indigenous stewardship over traditional homelands (Okalik Eegeesiak et al. 2017, Simon 2017, Groenewoud 2018). Other instruments of relevance to Indigenous peoples in the HBME and elsewhere include international human rights instruments, bodies and norms, including International Labour Organization (ILO) Convention No. 169, United Nations Declaration of the Rights of Indigenous Peoples (UNDRIP), the United Nations Permanent Forum on Indigenous Issues (UNPFII), Expert Mechanism on the Rights of Indigenous Peoples (EMRIP), and the UN Special Rapporteur on the situation of human rights and fundamental freedoms of Indigenous peoples, among others (Kothari et al. 2012). Under the UN Framework Convention on Climate Change (UNFCCC), the Local Communities and Indigenous Peoples Platform (LCIPP) was established by the *Paris Agreement* in 2015 to strengthen adaptive capacity to respond to impacts of climate change; to exchange experiences, best practices, and lessons learned on mitigation and adaptation; and to engage local communities and Indigenous peoples in the UNFCCC process. Inuit in Canada, through the Inuit Circumpolar Council (ICC), have been participating in developing the LCIPP to help ensure that Inuit concerns and needs are respected and responded to.

Second, a new UN treaty on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ)—developed under the UN Convention on the Law of the Sea—is currently being negotiated. These areas relate to the high seas, located beyond 200 nautical miles off the coasts of states, and the seabed located beyond the limits of States' continental shelves. While outside of immediate traditional marine and coastal territories in the HBME, this treaty may be significant for the HBME and Indigenous peoples around the HBME in several respects. Connectedness of ocean water systems related to marine resources as well as long-range marine transport of contaminants means that activities or protections that occur in marine areas beyond national jurisdiction matter to the HBME and the peoples that depend on it. For example, a number of migratory marine mammals and birds that utilize the HBME and are important country foods travel large distances and cross or use marine areas beyond national jurisdiction, such as the Eastern Canada-West Greenland bowhead and Atlantic walrus. Draft text of the BBNJ treaty recognizes and affirms the inclusion of traditional knowledge of Indigenous peoples and local communities alongside the best available scientific information, including in the identification of areas requiring protection, as part of consultation for assessment of proposals, and in impact assessment. Draft BBNJ text also provides for the establishment of a scientific and technical body composed of experts to provide advice to the Conference of Parties, and directs that experts should have multidisciplinary expertise, including expertise in relevant traditional knowledge of Indigenous peoples and local communities. While still to be finalized, this draft text provides for potential inclusion of Indigenous knowledge experts via the scientific and technical body, and for inclusion of Indigenous knowledge in decision-making, to strengthen protections in marine areas that affect areas of Indigenous jurisdiction and use but where currently Indigenous peoples do not have direct control or authority (personal comm., Camille Fréchette, Feb. 11, 2020). In these ways, the BBNJ has the potential to expand Indigenous stewardship over marine areas where, as non-state actors, Indigenous interests, rights, and knowledge have been generally underrepresented in decision-making.

Third, the *International Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean* (CAO) was signed by Canada in 2018. As part of this agreement, a commitment was made that fishing will be guided by research and monitoring programs that includes knowledge gained through scientific methods and Indigenous knowledge. A Provisional Scientific Coordinating Group (PSCG) has been established to identify mechanisms to incorporate Indigenous knowledge, and Canada has proposed that a single committee that brings both scientific knowledge and Indigenous knowledge together to inform decision-making would be most appropriate. Canada, though Fisheries and Oceans Canada, has sought inclusion of Inuit representation in its delegation to the a PSCG meeting in 2020, where terms of reference for inclusion of Indigenous knowledge are being decided (personal comm., Camille Fréchette, Feb. 11, 2020). While the final mechanisms for inclusion of Indigenous knowledge in research and monitoring for this agreement are still to be confirmed, a single committee, as is being considered, would likely strengthen inclusion of Indigenous knowledge in management decision-making. Thus, structures being developed under this agreement for Indigenous knowledge inclusion may set a valuable precedent that can be applied to other international or national forums related to fisheries or wildlife management.

6.7 REFERENCES

Alava JJ, Cheung WWL, Ross PS, Sumaila UR (2017) Climate change–contaminant interactions in marine food webs: Toward a conceptual framework. Global Change Biology 23:3984–4001.

AMAP (2011) How Does Climate Change Influence Arctic Mercury? In: AMAP Assessment 2011: Mercury in the Arctic, 1st ed. Arctic Monitoring and Assessment Programme (AMAP), Oslo, p 67–83

Andrews JS, Babb D, Barber DG (2017) Climate change and sea ice: marine shipping access in Hudson Bay and Hudson Strait (1980 – 2014). Elem Sci Anth 5:15.

Arctic Council (2008) Arctic Council: Arctic marine shipping assessment 2009 Report.

Aulanier F, Simard Y, Roy N, Gervaise C, Bandet M (2017) Effects of shipping on marine acoustic habitats in Canadian Arctic estimated via probabilistic modeling and mapping. Marine Pollution Bulletin 125:115–131.

Bennett NJ, Kaplan-Hallam M, Augustine G, Ban N, Belhabib D, Brueckner-Irwin I, Charles A, Couture J, Eger S, Fanning L, Foley P, Goodfellow AM, Greba L, Gregr E, Hall D, Harper S, Maloney B, McIsaac J, Ou W, Pinkerton E, Porter D, Sparrow R, Stephenson R, Stocks A, Sumaila UR, Sutcliffe T, Bailey M (2018) Coastal and Indigenous community access to marine resources and the ocean: A policy imperative for Canada. Marine Policy 87:186–193.

Bodaly RA, Johnston TA (1992) The mercury problem in hydro-electric reservoirs with predictions of mercury burdens in fish in the proposed Grande Baleine complex, Quebec, 1st ed. Karamessines C, Bisaillon P, Campbell S, Kramer V, McCutcheon S, Wollock J (eds) Montreal: North Wind Information Services, Montreal.

Brown B (2019) Label ringed seals a species of concern, wildlife advisers tell feds. CBC News.

Canada, ITK, IRC, NTI, NG, Makivik Corporation, NTI (2017) Inuit Nunangat Declaration on Inuit-Crown Partnership. Iqaluit, NU.

Chan FT, Stanislawczyk K, Sneekes AC, Dvoretsky A, Gollasch S, Minchin D, David M, Jelmert A, Albretsen J, Bailey SA (2019) Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. Global Change Biology 25:25–38.

CIRNAC (2019a) Canada’s Arctic and Northern Policy Framework. https://www.rcaanc-cirnac.gc.ca/eng/1562782976772/1562783551358

CIRNAC (2019b) Nunavut devolution. https://www.rcaanc-cirnac.gc.ca/eng/1352471770723/1537900871295

COSEWIC (2020) COSEWIC status report in preparation with anticipated assessment dates. http://www.cosewic.ca/index.php/en-ca/reports/status-reports-preparation

Cree Nation Government (2015) Cree Regional Conservation Strategy.

Cree Nation Government (2020) The Québec Government and the Cree Nation sign a Grand Alliance. https://www.cngov.ca/the-quebec-government-and-the-cree-nation-sign-a-grand-alliance/

Dawson J, Carter N, van Luijk N, Parker C, Weber M, Cook A, Grey K, Provencher J, Luijuk N van., Parker C, Weber M, Cook A, Grey K, Provencher J, van Luijk N, Parker C, Weber M, Cook A, Grey K, Provencher J (2020) Infusing Inuit and local knowledge into the Low Impact Shipping Corridors: An adaptation to increased shipping activity and climate change in Arctic Canada. Environmental Science and Policy 105:19–36.

DFO (2018) Fisheries and Oceans Canada, the Canadian Coast Guard and Inuit Tapiriit Kanatami announce new Arctic Region. https://www.canada.ca/en/fisheries-oceans/news/2018/10/fisheries-and-oceans-canada-the-canadian-coast-guard-and-inuit-tapiriit-kanatami-announce-new-arctic-region.html

DFO (2019) Nunavut Fishery Regulations. https://www.dfo-mpo.gc.ca/acts-lois/rules-reglements/rule-reglement35-eng.htm

Gavrilchuk K, Lesage V (2014) Large-scale marine development projects (mineral, oil and gas, infrastructure) proposed for Canada's North. Mont-Joli, Québec.

Goldsmit J, Howland KL, Archambault P (2014) Establishing a baseline for early detection of non-indigenous species in ports of the Canadian Arctic. Aquatic Invasions 9:327–342.

Government of Nunavut (2016) Nunavut Fisheries Strategy 2016-2020. Iqaluit, Nunavut.

Groenewoud T (2018) Informing Indigenous Marine Protection in Gitga'at Territory. Simon Fraser University

Hewson S (2019) Ocean law developments in Canada 2015-2019. Vancouver, BC.

Hornig JF (1999) Social and environmental impacts of the James Bay hydroelectric project, 1st ed. Hornig JF (ed) McGill-Queen's University Press, Montreal, Kingston.

Hovelsrud GK, McKenna M, Huntington HP (2008) Marine mammal harvests and other interactions with humans. Ecological Applications 18:135–147.

Hsu-Kim H, Eckley CS, Achá D, Feng X, Gilmour CC, Jonsson S, Mitchell CPJ (2018) Challenges and opportunities for managing aquatic mercury pollution in altered landscapes. Ambio 47, 141–169

Hurtubise J (2016) Evolution of subsistence and commercial Inuit fisheries in the Territory of Nunavut, Canada. Marine Affairs Program Technical Report 14. Halifax.

Indigenous and Northern Affairs Canada (June 2016) Oil and Gas Rights Digital Files. https://www.aadnc-aandc.gc.ca/eng/1100100036298/1100100036301

Inuit-Crown Partnership Committee (2019) Inuit-Crown Partnership Committee releases national Inuit housing strategy and continues progress on shared priorities.

Koke PE (2008) The Impact Of Mining Development On Subsistence Practices Of Indigenous Peoples: Lessons Learned From Northern Quebec And Alaska. The University of Northern British Columbia

Kothari A, Corrigan C, Jonas H, Neumann A, Shrumm H (eds) (2012) Recognising and supporting territories and areas conserved by indigenous peoples and local communities: global overview and national case studies. Secretariat of the Convention on Biological Diversity, Montreal.

Kuzyk ZZ, Candlish L (eds) (2019) From Science to Policy in the Greater Hudson Bay Marine Region: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. Quebec City.

Liu X he, Ma L, Wang J yue, Wang Y, Wang L na (2017) Navigable windows of the Northwest Passage. Polar Science 13:91–99.

MacDonald M, Arraqutainaq L, Novalinga Z, McDonald M, Arragutainaq L, Novalinga Z (1997) Voices from the Bay: Traditional Ecological Knowledge of Inuit and Cree in the Hudson Bay Bioregion, 1st ed. MacDonald M, Arraqutainaq L, Novalinga Z (eds) Canadian Arctic Resources Committee, Environmental Committee of Municipality of Sanikiluaq, Ottawa, Ontario.

McDonald MA, Arragutainaq L, Novalinga ZZ, Canadian Arctic Resources Committee (1997) Voices from the Bay: Traditional ecological knowledge of Inuit and Cree in the Hudson Bay bioregion. Canadian Arctic Resources Committee, Environmental Committee of Municipality of Sanikiluaq, Ottawa, ON.

McKinney MA, Pedro S, Dietz R, Sonne C, Fisk AT, Roy D, Jenssen BM, Letcher RJ (2015) A review of ecological impacts of global climate change on persistent organic pollutant and mercury pathways and exposures in arctic marine ecosystems. Current Zoology 61:617–628.

Miller WA, Ruiz GM (2014) Arctic shipping and marine invaders. Nature Climate Change 4:413–416.

National Indigenous Fisheries Institute (2018) Northern Integrated Commercial Fisheries Initiative: Discussion Paper

National Indigenous Fisheries Institute (2019) Northern Integrated Commercial Fisheries Initiative: Final Report.

Niezen R (1993) Power and dignity: The social consequences of hydro-electric development for the James Bay Cree. Canadian Review of Sociology and Anthropology 30:510–529.

Okalik Eegeesiak, Aariak E, Kleist K V. (2017) People of the ice bridge: The future of the Pikialasorsuaq. Report of the Pikialasorsuaq Commission. Ottawa.

Rodon T (2017) Development in Nunavik: How Regional and Local Initiatives Redefine Sustainable Development in Nunavik. The American Review of Canadian Studies 47:176-188

Rodon T, Lévesque F (2015) Understanding the Social and Economic Impacts of Mining Development in Inuit Communities: Experiences with Past and Present Mines in Inuit Nunangat. The Northern Review 41:13–39.

Rosenberg DM, Berkes F, Bodaly RA, Hecky RE, Kelly CA, Rudd JWM (1997) Large-scale impacts of hydroelectric development. Environmental Reviews 5:27–54.

Roy D, Messier D (1989) A review of the effects of water transfers in the La Grande Hydroelectric Complex (Québec, Canada). River Research and Applications 4:299–316.

Simon M (2017) A New Shared Arctic Leadership Model.

Stewart DB, Howland KL (2009) An Ecological and Oceanographical Assessment of the Alternate

Ballast Water Exchange Zone in the Hudson Strait Region. Winnipeg

Tai TC, Steiner NS, Hoover C, Cheung WWL, Sumaila R, Sumaila UR (2019) Evaluating present and future potential of arctic fisheries in Canada. Marine Policy 108:11.

Whiteman G (2004) The Impact of Economic Development in James Bay, Canada: The Cree Tallymen Speak Out. Organization & Environment 17:425–448.

7 APPENDIX

Table 7.1. Keywords used in systematic searches

Topics	Keywords (geography AND subject matter)	
	Geography	Subject matter
Geographical boundaries		
Ecological boundaries	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" OR (Nunavik AND marine) OR (Nunavut AND marine)	Ecozone OR "ecological boundaries" OR ecological boundary OR "ecological region"
Marine habitat: Structure and function		
Bathymetry	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	Oceanography OR bathymetry
Marine and freshwater stratification	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	Freshwater OR (stratification AND marine) OR salinity
Foxe Basin inflow and Hudson Strait outflow	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	Flow OR inflow OR outflow OR current OR tide OR tidal
Marine food web	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	(marine AND food web) OR (marine AND biota) OR (marine AND feeding ecology) OR (marine AND trophic level)
Ice dynamics	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	"ice dynamics" OR "sea ice"
Ice flaw leads and polynyas	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	"Flaw lead" OR polynya OR "ice edge"
Ice-algae and the ice-edge food web	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	(Ice AND algae) OR (ice AND biota)
Ecological hot spots/significant areas	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	"Ecologically significant areas" OR "biologically significant areas" OR "ecological hotspots"
Primary productivity	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	"primary productivity"
Benthos	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	"Benthic species" OR benthos
Keystone species	"Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay"	"Keystone species"
Thelon River	"Thelon River" (Alternate: "Thelon River" AND "Hudson Bay")	(Estuary OR coast OR mouth) AND habitat
Nelson River	"Nelson River (Alternate: "Nelson River" AND "Hudson Bay")	(Estuary OR coast OR mouth) AND habitat
Albany River	"Albany River" (Alternate: "Albany River" AND "James Bay")	(Estuary OR coast OR mouth) AND habitat
Moose River	("Moose River" AND Ontario) OR ("Moose River" AND James Bay)	(Estuary OR coast OR mouth) AND habitat
Rivière Nottaway	"Nottaway River" OR "Rivière Nottaway" (Alternate: "Nottaway River" AND "James Bay")	(Estuary OR coast OR mouth) AND habitat
Rivière La Grande	"Grand River" OR "Rivière La Grande" (Alternate: "Grand River" AND Quebec OR "Grand River" AND Hudson Bay)	(Estuary OR coast OR mouth) AND habitat

Topics	Keywords (geography AND subject matter)	
	Geography	Subject matter
Inputs/impacts of smaller rivers	"Hudson Bay" OR "Foxe Basin" OR Hudson Strait OR James Bay	"River input" OR "riverine input" OR (freshwater AND river AND input)
Estuarine food webs	"Hudson Bay" OR "Foxe Basin" OR Hudson Strait OR James Bay	("Coastal zone" OR coast OR coastal OR estuary) AND ("food web" OR "feeding ecology" OR biota)
Implications of climate forcing		
Ice loss	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	Ice AND ("climate change" OR "climate forcing" OR "climate impacts" OR "climate warming")
Primary productivity	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	"Primary productivity" AND ("climate change" OR "climate forcing" OR "climate impacts" OR "climate warming")
River inputs	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	"River input" OR "freshwater input" AND ("climate change" OR "climate forcing" OR "climate impacts" OR "climate warming")
Food webs	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	("Food web" OR "trophic levels") AND ("climate change" OR "climate forcing" OR "climate impacts" OR "climate warming")
Storminess	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	(Storminess OR "extreme weather" OR storms) AND ("climate change" OR "climate forcing" OR "climate impacts" OR "climate warming")
Acidity	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	(Acidity OR pH) AND ("climate change" OR "climate forcing" OR "climate impacts" OR "climate warming")
Climate change uncertainties	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	(Uncertainty OR model) AND ("climate change" OR "climate forcing" OR "climate impacts" OR "climate warming")
Effects on subsistence harvesting and ecosystem services	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	(Harvesting OR "traditional food" OR "country food" OR "ecosystem services" OR subsistence) AND ("climate change" OR "climate forcing" OR "climate impacts" OR "climate warming")
Effects on commercial harvests (existing or projected)	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	("commercial fishing" OR commercial AND harvest) AND ("climate change" OR "climate forcing" OR "climate impacts" OR "climate warming")
Uncertainty, predictive trends and discussion		
Cumulative impacts (e.g. hydroelectric developments)	*Primary:* "Hudson Bay" OR "Foxe Basin" OR "Hudson Strait" OR "James Bay" *Secondary:* (Nunavik AND marine) OR (Nunavut AND marine)	(mine AND impacts) OR ("cumulative impacts") OR ("commercial fishing" AND impacts) OR (industrial AND impacts) OR (shipping AND impacts) OR (hydroelectric AND impacts)

Table 7.2. List of 23 rivers used in analysis by Déry et al. (2011)

Number	River
1	Churchill
2	Hayes
3	Nelson
4	Seal
5	Chesterfield Inlet
6	Thlewiaza
7	Albany
8	Attawapiskat
9	Ekwan
10	Moose
11	Severn
12	Winisk
13	Boutin
14	Broadback
15	Eastmain
16	Grande rivière de la Baleine
17	Harricana
18	La Grande Rivière
19	Nastapoca
20	Nottaway
21	Petite rivière de la Baleine
22	Pontax
23	Rupert