# State of Canada's Arctic Seas

Andrea Niemi, Steve Ferguson, Kevin Hedges, Humfrey Melling,
Christine Michel, Burton Ayles, Kumiko Azetsu-Scott, Pierre Coupel,
David Deslauriers, Emmanuel Devred, Thomas Doniol-Valcroze,
Karen Dunmall, Jane Eert, Peter Galbraith, Maxime Geoffroy,
Grant Gilchrist, Holly Hennin, Kimberly Howland, Manasie Kendall,
Doreen Kohlbach, Ellen Lea, Lisa Loseto, Andrew Majewski,
Marianne Marcoux, Cory Matthews, Darcy McNicholl, Arnaud Mosnier,
C.J. Mundy, Wesley Ogloff, William Perrie, Clark Richards,
Evan Richardson, James Reist, Virginie Roy, Chantelle Sawatzky,
Kevin Scharffenberg, Ross Tallman, Jean-Éric Tremblay, Teresa Tufts,
Cortney Watt, William Williams, Elizabeth Worden, David Yurkowski,
Sarah Zimmerman

Fisheries and Oceans Canada
Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6

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## Canadian Technical Report of Fisheries and Aquatic Sciences 3344

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# State of Canada’s Arctic Seas

by

A. Niemi[1], S. Ferguson[1], K. Hedges[1], H. Melling[2], C. Michel[1], B. Ayles[3], K. Azetsu-Scott[4], P. Coupel[4], D. Deslauriers[1], E. Devred[4], T. Doniol-Valcroze[5], K. Dunmall[1], J. Eert[2], P. Galbraith[6], M. Geoffroy[7], G. Gilchrist[8], H. Hennin[8], K. Howland[1], M. Kendall[9], D. Kohlbach[1], E. Lea[10], L. Loseto[1], A. Majewski[1], M. Marcoux[1], C. Matthews[1], D. McNicholl[1], A. Mosnier[6], C.J. Mundy[11], W. Ogloff[1], W. Perrie[4], C. Richards[4], E. Richardson[12], J. Reist[1], V. Roy[6], C. Sawatzky[1], K. Scharffenberg[1], R. Tallman[1], J-É. Tremblay[13], T. Tufts[9], C. Watt[1], B. Williams[2], E. Worden[1], D. Yurkowski[1], S. Zimmerman[2]

1 Fisheries and Ocean Canada, Winnipeg, MB, R3T 2N6
2 Fisheries and Ocean Canada, Sidney, BC V8L 5T5
3 Fisheries Joint Management Committee, Inuvik, NT, X0E 0T0
4 Fisheries and Oceans Canada, Dartmouth, NS B2Y 4A2
5 Fisheries and Ocean Canada, Nanaimo, BC, V9T 6N7
6 Fisheries and Ocean Canada, Mont-Joli, PQ, G5H 3Z4
7 Memorial University, St. John's, NL, A1C 5R3
8 Environment and Climate Change Canada, Ottawa, ON, K1A 0H3
9 Fisheries and Sealing, Government of Nunavut, Iqaluit, NU, X0A 0H0
10 Fisheries and Ocean Canada, Inuvik, NT, X0E 0T0
11 University of Manitoba, Winnipeg, MB R3T 2M6
12 Environment and Climate Change Canada, Winnipeg, MB, R3C 4W2
13 Université Laval, Québec, PQ, G1V 0A6

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Fisheries and Oceans Canada (DFO) committed to informing Canadians on the state of Canada's three oceans as part of an Ecosystem Reporting initiative established in 2016. This report presents a synthesis of current knowledge, focusing primarily on information from the past five years, for the Canadian Arctic region. Information from scientific research programs and Inuit knowledge assessments is included. Structuring elements of the Arctic Ocean are discussed to provide the context for how ecosystems are currently functioning and/or changing. Ecosystem variability and neighbourhood connectivity are key themes presented in the report and specific sections focus on co-management and coastal ecosystems. Case studies provide theme-based examples of current ecosystem status. Key messages identify new baseline understanding of the Canadian Arctic region and current ecosystem responses to changes in sea-ice conditions.

# RÉSUMÉ

Niemi, A., Ferguson, S., Hedges, K., Melling, H., Michel, C., Ayles, B., Azetsu-Scott, K., Coupel, P., Deslauriers, D., Devred, E., Doniol-Valcroze, T., Dunmall, K., Eert, J., Galbraith, P., Geoffroy, M., Gilchrist, G., Hennin, H., Howland, K., Kendall, M., Kohlbach, D., Lea, E., Loseto, L., Majewski, A., Marcoux, M., Matthews, C., McNicholl, D., Mosnier, A., Mundy, C.J., Ogloff, W., Perrie, W., Richards, C., Richardson, E., Reist, R., Roy, V., Sawatzky, C., Scharffenberg, K., Tallman, R., Tremblay, J-É., Tufts, T., Watt, C., Williams, W., Worden, E., Yurkowski, D., Zimmerman, S. 2019. State of Canada's Arctic Seas. Can. Tech. Rep. Fish. Aquat. Sci. 3344: xv + 189 p.

Dans le cadre d'une initiative de rapports sur les écosystèmes lancée en 2016, Pêches et Océans Canada s'est engagé à informer les Canadiens sur l'état des trois océans du Canada. Le présent rapport fait une synthèse des connaissances actuelles sur la région du Canada arctique, en particulier celles des cinq dernières années. Il comprend des informations issues de programmes de recherche scientifique et d'évaluations fondées sur les connaissances inuites. Les éléments structurants de l'océan Arctique sont discutés afin d'établir le contexte dans lequel les écosystèmes fonctionnent ou évoluent à l'heure actuelle. La variabilité des écosystèmes et la connectivité des quartiers comptent parmi les principaux thèmes du rapport, dont certaines sections portent sur la cogestion et les écosystèmes côtiers. Des exemples de l'état actuel de l'écosystème sont offerts sous forme d'études de cas axées sur des thèmes. Les points saillants du rapport offrent un nouvel éclairage permettant de mieux comprendre la région de l'Arctique canadien et les réponses actuelles de l'écosystème aux conditions changeantes des glaces de mer.

# ACKNOWLEDGEMENTS

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The knowledge shared in this report reflects a massive effort of researchers, technicians, ship crews, co-management boards and community members – to name a few. We acknowledge the commitment of all those who invest themselves in understanding Arctic ecosystems.

Thank You
Nakurmiik
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Quyanainni
Merci

## 1.0 Ocean Reporting

As part of Fisheries and Oceans Canada's (DFO) commitment to inform Canadians about the current state of Canada's Oceans, the Department is regularly preparing ecosystem-based reports for the Pacific, Atlantic and Arctic oceans. The State of the Ocean ecosystem reporting initiative, for all three Oceans, began in 2016 with an emphasis on preparing publicly accessible information based on expert knowledge. In this Technical Report we present both scientific and Inuit knowledge to describe our current (primarily within the last five years), collective understanding of the state of the expansive Canadian Arctic region.

An integrated ecosystem approach was used to structure this report. Trophic levels and species are not described sequentially; rather we aimed for a thematic approach. Status is discussed within topics that represent key aspects of ecosystem connectivity and function.

## 1.1 What We Need to Describe the State of the Canadian Arctic Ocean

This report describes the State of the Arctic Ocean, specifically the Canadian Arctic region. But what do we mean by State and how have we assessed it? In an ecological context, state can be defined as the set of abiotic and biotic conditions observed for a focal ecosystem or component thereof. Inherently connected to a description of condition is the assessment of variability. Are abiotic and biotic conditions stable or changing (i.e., trends) relative to a point in time or an assessed average condition? To scientifically identify the change of an ecosystem state, statistical analyses supported by adequate and appropriate data are needed. In the Arctic, the "burden of proof" for ecosystem change is a challenge given the paucity of adequate data across multiple spatial and temporal scales.

**State:** the characteristics used to describe the status of an ecosystem at a particular domain in space and time. For deterministic systems, the state is the values of variables used to describe the system, and for stochastic systems it could refer to either the probability distribution of these state variables or realized values of the state variables. In practice, definitions of system state include both the mean and variability of systems (Ratajczak et al. 2018).

The measurement of mean conditions from which to assess change is complicated by the variation of environmental conditions over time (Section 5). The most obvious manifestations of variability are the dramatic seasonal differences between winter and summer conditions in Arctic waters, but large changes are also seen from year to year and between clusters of years, a phenomenon known as interannual and inter-decadal variation, respectively. An average condition is comparatively easy to determine if observations are continuous in time. However, many annually repeated ocean-observing campaigns are seasonally biased and short-lived, spanning perhaps a few weeks in summer. Nonetheless, if observations have been repeated at the same time in the annual cycle we can use them to describe a state, at that particular time of year. Observations that have not been repeated annually, whose seasonal timing has varied appreciably (in summer, by a month or more), or whose geographic domain has shifted from year to year, limit our capability to provide a reliable description of mean conditions and ultimately ecosystem state.

Reliably distinguishing progressive change from the influences of cyclic variability is a daunting challenge in data-sparse regions like the Canadian Arctic. There are 4 million $km^2$ of ocean in Canada's Arctic, an area equal to 41% of Canada's land area. Because ocean conditions vary greatly over this area (Case Study 1), the domain over which any particular set of observations is representative or relevant is an important concern of this report. The domain size varies with the variables of interest, its depth and the geographic feature (shelf, slope, basin, strait, etc.) with which it is associated.

With full acknowledgement of data and knowledge deficiencies, environmental variability, and challenges of scope, we report on the status of the Arctic Ocean by presenting, 1) statistically significant means and trends for ecosystem components for which adequate data exist, and 2) current knowledge of the structure and function of the Arctic Ocean based on recent scientific studies and collections of Inuit knowledge. We report on current knowledge relevant to the past five years. Current conditions are described within key themes including, habitat linkages, seasonality, biodiversity, ecosystem variability, connectivity and coastal ecosystem processes.

## 1.2 Boundaries of the Arctic Ocean Report

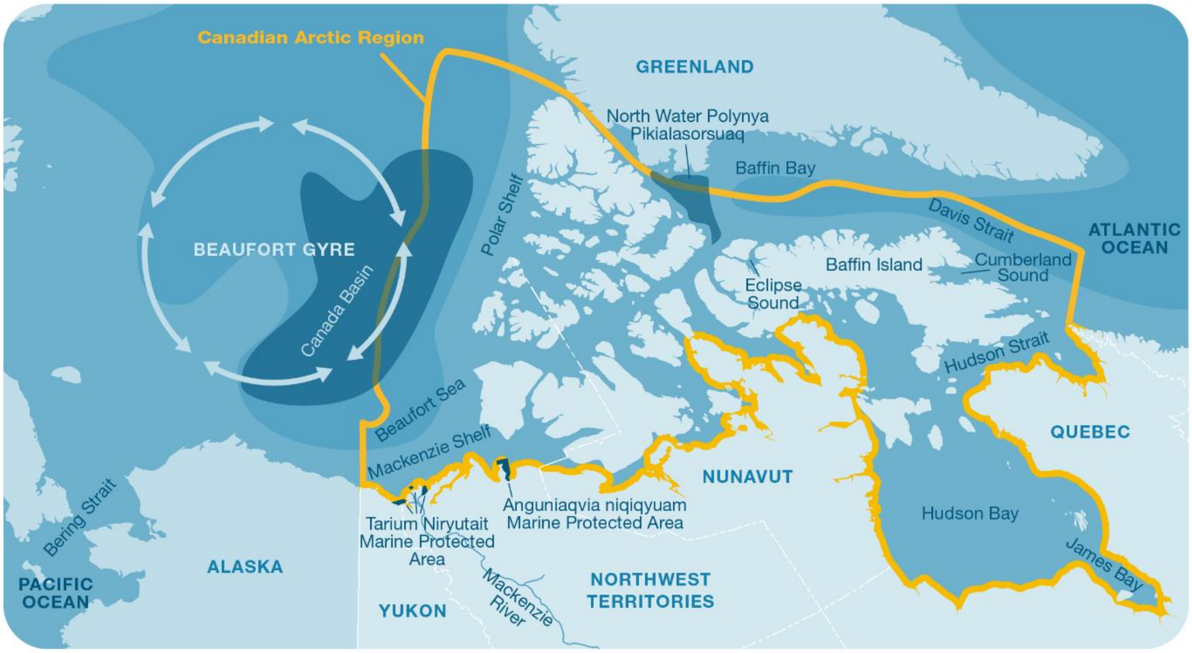


**Figure 1**. Boundary of the Canadian Arctic Ocean region and areas referenced within the State of the Arctic Ocean report.

This report focuses on an immense area (51-86° N, Figure 1) that includes the five Arctic marine bioregions (DFO 2009) classified by DFO for use in conservation planning. Case Study 1 describes unique features and challenges of this expansive geographical area. In this report, marine habitats and species are the primary focus although relevant knowledge associated with anadromous species is also included (e.g., chars). We present current knowledge from each of the five bioregions and information is unavoidably weighted towards more accessible regions and focal areas within them. Locations referred to in the Key Messages are identified in Figure 1. Ecosystem status for coastal regions and the location of Canada's Arctic communities are included in Section 7. The coastal data are generally collected within 5 km of shore, inshore of the 20 m isobath. The data and knowledge from Arctic coastal areas are often generated through community-based monitoring and this is the area most informed by Inuit knowledge.

This report highlights that the Canadian Arctic region is connected to the Pacific and Atlantic Oceans and functions within a larger Arctic system (Figure 2). However, trends and conditions within the Canadian Arctic region are not necessarily the same as other Arctic regions.

The 'Canadian Arctic region' described herein does not delineate boundaries for the new DFO Arctic Region. The term 'Canadian Arctic region' reflects the study area for this report, which includes a portion of the Artic Ocean as well as the Canadian Polar Shelf, Baffin Bay and the Hudson Bay complex.

**Figure 2**. Connectivity of the Canadian Arctic region to neighbouring Arctic and sub-Arctic regions.

## CASE STUDY 1: What's So Special about the Canadian Arctic Region?

**Figure 3**. Global perspective of the Canadian Arctic region (source: MODIS).

The Arctic Ocean is the smallest ocean, with less than 1% of the total volume of the World's oceans. Unlike other Oceans, the Arctic Ocean is a semi-enclosed ocean surrounded by land masses, with only a few connections to the northern Pacific and Atlantic Oceans. The Arctic Ocean is disproportionally affected by river runoff compared to other oceans, as it receives ca. 10% of global river runoff on its wide continental shelves. As a result, there are strong shelf-basin gradients in term of biogeochemical properties, impacting the distribution and abundance of marine resources, all evidenced in the Canadian Arctic region (Monier et al. 2014; Coupel et al. 2015; Ardyna et al. 2017). The Arctic Ocean also differs from other oceans in terms of extreme seasonality, alternating from several months of 24-h darkness in winter to 24-h daylight in summer and from extreme cold temperatures in winter to above zero in summer, influenced by latitudinal gradients.

The Canadian Arctic is a physically diverse and vast region (Table 1). The region spans more than 30 degrees of latitude, from southern James Bay (51°N) to Canada's Exclusive Economic Zone (EZZ) off Alert, Nunavut (86°N). The Canadian Arctic region encompasses a wide range of ecosystems, including a wide productive shelf subject to large river inputs (i.e., Mackenzie shelf), the oligotrophic Arctic Basin, a series of passages around islands, with narrow straits, sills and shallow waters (i.e., Canadian Archipelago), a relatively small deep Basin (Baffin Bay), and a semi-enclosed sea (Hudson Bay). The residence time of surface waters (top few hundred meters) in the Canadian Arctic region is rather short (Rudels 1986) from the entrance of Pacific waters into the Beaufort Sea to their exit through Baffin Bay and south to the Labrador Sea. During this transition time, nutrients available in the water sustain the entire marine ecosystem, from small algae up to the highest trophic levels. One of the key features of the Arctic Ocean, sea ice, is ubiquitous within the Canadian Arctic region, despite the region's wide latitudinal spread. Importantly, sea ice plays a key role in the biodiversity, ecology, and biochemical cycles of the Canadian Arctic region, and is fundamental to Indigenous culture.

Species that inhabit the Canadian Arctic region have adapted to and benefitted from the presence of sea ice. Some species are also specially adapted to the extreme seasonality of the region. For example, an increase in photoprotective pigments is a key physiological adaption for phytoplankton exposed to continuous summer daylight (Neukermans et al. 2016). Even during the dark period, life thrives (Berge et al. 2009; Darnis et al. 2017). During summer, many species of birds and marine mammals migrate to the Canadian Arctic to feed on abundant marine resources and to breed (Hauser et al. 2017a).

**Table 1.** Physical features of the Canadian Arctic region.

| | |
|---|---|
| Ocean Area of the Canadian Arctic region | Almost 4 million $km^2$, equivalent to 41% of Canada's land mass |
| Canadian Ocean area overlying continental shelf | 3.2 million $km^2$, excluding islands |
| Coastline (mainland) | >176 000 km (Yukon to Labrador), representing >70% of all Canadian coasts |
| Communities | 58 communities, >70 000 people, the majority of whom are Inuit. |
| Islands | 94 major islands (>130 $km^2$) and ca. 36 470 minor islands together representing a total area of 1.4 million $km^2$. Baffin Island is 18X larger than Vancouver Island. |
| Land-fast ice | Canadian Archipelago hosts the broadest expanse of land-fast ice found in the Arctic. |
| Multi-year ice (MYI) | In summer 1.12 million $km^2$ (value from 2015 excluding the northern boundary of the Canadian Archipelago,) of MYI resides in the Canadian Arctic region, representing ca 30% of the total MYI area in the entire Arctic Ocean. |

The Arctic is undergoing dramatic and fundamental changes associated with the warming climate and increased economic development. Arguably one of the most dramatic changes in many Arctic regions is the rapid decline in sea ice, both in terms of sea-ice extent and type, and sea-ice cover duration, triggering cascading impacts throughout the food webs. Declines have differed regionally across the Canadian Arctic region (e.g., Howell et al. 2008), statistically significant declining trends in the annual minimum of sea-ice extent, which occurs in September, have been observed in all regions over the 1968 to 2015 period, ranging from a 3% decrease per decade in the Kane Basin (north of Baffin Bay) to a 17% decrease per decade in the Northern Labrador Sea (Environment and Climate Change Canada 2016). Current regional sea-ice trends are described in Section 5.2.

In the Canadian Arctic region there are now longer periods of open water. Longer open-water seasons shift the balance of primary producers towards pelagic production in open waters (Ardyna et al. 2014). Changes in light transmission through thinner ice cover can also augment the potential for productive under-ice phytoplankton blooms (Arrigo et al. 2012; Assmy et al. 2017; Johnsen et al. 2018), modifying the location, timing, and predictability of primary resources for grazers and fisheries resources. Changes in the distribution and abundance of key species, range extensions, and cascading effects on species interactions have occurred at different locations across the Canadian Arctic region. These changes modify the architecture of Arctic marine ecosystems, and therefore require distributed ocean observatories and comprehensive monitoring to inform adaptive resource management and conservation actions.

## 2.0 Key Messages

Arctic surface air temperature since the mid-1960s has risen at double the global mean rate in response to anthropogenic production of carbon dioxide and other greenhouse gasses. The Arctic's ice-adapted marine ecosystem is responding to numerous environmental changes, in particular decreases in the extent and thickness of sea ice, and changes in seasonal duration. Climate variability and change have already affected Arctic ecosystems to a significant extent, both directly and indirectly, and will continue to do so for the foreseeable future.

Functioning as part of the Arctic Ocean system, the Canadian Arctic region experiences the same drivers and stressors as the broader Arctic, but the responses to these factors vary geographically (between the central Arctic Ocean and the Barents Sea for example). Therefore, trends and generalizations from other Arctic Ocean regions do not necessarily describe the state of the Canadian Arctic region.

Our knowledge of ecological changes within the Canadian Arctic region over the last decade is built upon Indigenous and scientific sources. All reveal wide variations in conditions from year-to-year, decade-to-decade, and among areas within the Canadian Arctic region. The wide range of natural variability in Arctic marine environments restricts our ability to identify change in physical, chemical or biological components of the ecosystem. Natural variability also complicates our understanding of the mechanisms of change. Whereas ocean monitoring has been a solid element of ocean management in Canada's Atlantic and Pacific sectors for many decades, this has not been so in the Canadian Arctic region, and thus a comprehensive assessment of ecosystem status and trends is challenging.

Our Key Messages for the status of the Canadian Arctic region fall into two categories: 1) knowledge of baselines for biodiversity, habitat use, ecological hot spots, and ecosystem connectivities; 2) observed changes in Arctic ecosystems that are cascading effects of changes in sea ice. The first category reflects the reality that a comprehensive baseline of ecosystem structure, food web linkages, ecosystem processes, and system variabilities is lacking in most of the Canadian Arctic region. The second category reflects how the majority of documented ecosystem changes are linked to changes in sea ice.

### Key Messages for advancements in baseline understanding

- The ongoing collective efforts of scientists and Indigenous peoples have yet to produce holistic knowledge adequate for management of ecosystem-level changes in the Canadian Arctic region. Baseline knowledge is patchy across the Canadian Arctic and intermittent over time. Inuit knowledge which, provides the longest perspective over time, is generally constrained to coastal areas.

### Biodiversity

- Knowledge of the biodiversity of key ecosystem components, i.e., ice-associated algae, benthic invertebrates, and marine fishes, has expanded in recent years but it is not yet spatially, and even less temporally (intra and interannually), comprehensive. Local assessments have facilitated the identification of unique benthic habitats and regions (e.g., Churchill estuary) vulnerable to new species' introductions via ships or other factors. Information is also accumulating on the capacity of Arctic species to adapt to change, allowing the resilience of Canadian Arctic marine ecosystems to be assessed.

**Coastal Ecosystems**

- New information is emerging from community-based monitoring on nearshore movements and distributions of anadromous and coastal fishes in the Beaufort Sea, Kitikmeot area of the central Nunavut, and in Baffin Bay and adjacent fiords. The occurrence and abundance of Pacific salmon (*Oncorhynchus* spp.) are also being tracked at their northern distributional extremes in the western Canadian Arctic.

- Community-based monitoring is expanding the window of seasonal observations for coastal ecosystems. Attention was focused on species Arctic Char (*Salvelinus alpinus*) and beluga (*Delphinapterus leucas*), important to communities, and has recently expanded to include environmental observations. Inuit knowledge also informs the selection of measurements (e.g., indicators of beluga health and condition in the western Canadian Arctic) to be used in monitoring programs.

**Habitat**

- Strong associations of marine (offshore) fishes with water depth have been identified in the Beaufort Sea and Baffin Bay, with some species (e.g., Arctic Cod (*Boreogadus saida*))) preferring transition zones between water masses, indicating that changes in water column structure represent changes in habitat availability for multiple species.

**Connectivity**

- Sustained observations now show that the Pacific inflow to the Arctic via the Bering Strait has become more acidic, highlighting the connectivity of stressors between oceans.

- Telemetry studies of numerous mobile marine predators have revealed the dynamics of energy flow within the Canadian Arctic, including distinct ecosystem hot spots in summer-autumn versus winter-spring. Such data reveal the dynamics of energy flow and the space-time connectivities of habitats that should guide conservation efforts.

- Tracking of migratory and highly mobile species (e.g., beluga, Greenland Halibut (*Reinhardtius hippoglossoides*), herring gulls (*Larus argentatus*)) identifies where and when energy moves into and out of the Canadian Arctic region. Migratory strategies and routes differ among individuals and species. Knowledge of these differences in connectivity contributes to assessing the effects of environmental change and human activities in both Arctic breeding/feeding and remote wintering grounds.

- Knowledge of marine fish movements and genetic separation is informing management strategies for harvested species (e.g., Greenland Halibut, redfishes (*Sebastes* spp.)) and conservation strategies for rare species and at-risk populations (e.g., wolffishes (*Anarhichas* spp.)). In contrast to other taxa, the movement patterns of most marine fishes in the Canadian Arctic are not directly affected by sea ice, they respond to water temperature and the distributions of other species.

## Variability

- Detecting change in the environment and ecosystems of the Canadian Arctic region is hampered by large variations from year-to-year and decade-to-decade as well as by spatial variabilities. Data streams of at least 20-year duration are typically required to discriminate variability from change at a useful level of confidence. Such lengthy databases are generally not available, thus appropriate long-term monitoring programs are required.

- The submerged layer of Pacific-derived water, centered at about 150-m depth in the Canadian Arctic region is the primary source of nutrients supporting marine productivity. Primary productivity is facilitated where this layer rises closer to the sunlit zone. During the last 15 years, this layer has been pushed deeper in the central Beaufort Sea, whereas over the shallow Beaufort shelf and slope it has been forced upward. The response of primary producers to changes in nutrient supply is both local and regional, with possible increases in primary production on the continental shelf of the Beaufort Sea.

## Key messages for ecosystem response to the changing cryosphere:

### How is the ice system changing?

- Viewing the Arctic as a whole, the area of sea ice at summer's end has decreased by about 40% in the last 20 years, affecting both the Arctic's marginal seas and its central basins. The mean thickness of the mix of multi-year and seasonal ice that comprises the polar pack has decreased because much of the thicker mutli-year ice has been replaced by seasonal ice.

- The area of ice at winter's end has decreased by about 10%, chiefly affecting the sub-Arctic seas (Okhotsk, Bering, Labrador, Greenland, Barents) and bays (Hudson, Baffin, St Lawrence).

- In the Canadian Arctic, ice thicknesses on the northern portion of the polar shelf appear little changed from the 1970s. Although much thick old sea ice has disappeared from the central Arctic Ocean, prevailing wind continues to pack the remainder into Canadian waters of the eastern Canada Basin and the northern polar shelf. Its persistence is enabling the survival of a unique ice-associated ecosystem in Canadian Arctic.

- Changes in the seasonal sea-ice zone have varied across the Canadian Arctic region. Generally, ice clears earlier (i.e., ice melt and break up) in summer and returns later in the fall. The general outcome is the lengthening of the open-water period.

- There are very few data on seasonal ice thickness, but half-century records of coastal fast ice and the only long record of seasonal pack ice (28 years in the southern Beaufort Sea) suggest it may have decreased, but less than 10 cm per decade compared to a 40 cm per decade loss in the Canada Basin over 11 years (2006-2017). This suggests that ice on the continental shelves is responding differently to climate change than is old ice over the deep Arctic Ocean basin.

- Nunavut Inuit knowledge documents changes in the locations of floe edges in the Baffin region during the last 10 years. However, because the character and stability of fast ice is strongly affected by the varying effects of storms, tidal currents, oceanic heat, and snow accumulation, it is difficult to establish at this time that observed changes constitute a regime change.

- Melting of ice-rich coastal terrain, primarily in the western Canadian Arctic, is accelerating the collapse of shorelines and accelerating coastal erosion, thereby changing coastal habitats and turbidity, and making terrestrial carbon accessible to marine food webs.

**Changes in sea ice affect the timing of events, which can have consequences throughout food webs.**

- Observed changes in the ice season are shifting the timing of peak primary production (i.e., blooms) and altering nutrient dynamics, thereby affecting the foundation of the oceanic food web. Changes in nutrients and blooms, and follow-on implications for zooplankton grazers and larval fishes, dependent on coordinated feeding with the blooms, have not been monitored over time.

- Over the last 25 years, a shrinking ice season in Hudson Strait has allowed beluga to migrate into Hudson Bay earlier and leave later, thereby spending more time in their summering grounds.

- The migration of Arctic Char to marine waters in the western Canadian Arctic is occurring earlier in the year due to earlier ice break-up along the coast. This allows the fish to feed longer in the marine system with positive consequences for life history and population dynamics.

- A key ecosystem change associated with sea-ice variability is the increased use of different forage fish species, e.g., Capelin (*Mallotus villosus*) and Sand lance (*Ammodytes* spp.), by predatory fishes and marine mammals.

- As a result of an increasing open-water period, the Cumberland Sound ecosystem has undergone a distinct transition in pathways of energy flow and trophic roles for marine predators. These food-web changes include a greater use of phytoplankton rather than ice-algae based energy sources.

- Changes and variability in sea ice have led to a decrease in prey quality and availability for some species, reducing their body condition. One example is terrestrial foraging of polar bears (*Ursus maritimus*) on marine bird eggs rather than ice obligate seal species.

- Biotracer studies reveal the use of multiple food webs in the diets of key species. Ice algae is an important diet subsidy for species from multiple trophic levels and the use of terrestrial carbon by marine species is documented in the western Arctic.

**Changes in sea ice influence habitat directly (i.e., as a platform) and indirectly by affecting the structure and stability of the water column.**

- With extremely early ice breakup, ringed seals (*Pusa hispida*) are not able to complete their moult (loss and re-growth of body hair) predisposing the seals to disease. Also, high ocean temperatures may cause hyperthermia in seals resulting in unusual behaviour that results in a higher risk of polar bear predation. For example, an anomalously warm year in 2010 resulted in poor ringed seal body condition in Hudson Bay with reduced ovulation, pup survival, abundance and greater stress in the following years.

- Satellite data indicate that, from an annual perspective, greater surface area of open water across the Canadian Arctic region is leading to increased rates of primary productivity. However, decreasing trends in primary production have been observed in some regions (e.g. North Water) due to different factors affecting nutrient availability in surface waters.

- Seasonal movements by Greenland Halibut have been observed in Cumberland Sound and Scott Inlet, with individuals moving into shallower water (i.e., moving from habitats at depths of 800-1400 m to 400-600 m habitats) each fall when landfast ice extends over the shallower habitats. The fish are not directly interacting with the sea ice but are responding to changes within the water column or the distributions of other species.

- Thinner sea ice and an increase in melt pond coverage are creating surface water habitat suitable (i.e., sufficient light available) for an increase in under-ice phytoplankton blooms. This shift in the timing/location of blooms has implications for nutrient availability for summer primary production and will alter how energy is transferred through marine food webs.

**Changes in sea ice affect access for biota and humans to ice-covered areas and affect access, at a larger scale, to ice-free areas.**

- Polar bear population declines in Hudson Bay are driven by reductions in sea-ice extent that reduce the availability of seals, resulting in a decline in bear body condition. More time on shore also has a negative effect on nesting behaviour of common eiders (*Somateria mollissima*) due to egg predation by bears. However, this negative effect on eiders is expected to be offset by better feeding conditions created by less sea ice.

- Sea-ice reductions in the eastern Canadian Arctic have resulted in greater regional and temporal access for killer whales (*Orcinus orca*) to Canadian Arctic marine mammal prey (e.g., bowhead (*Balaena mysticetus*), narwhal (*Monodon monoceros*), beluga, seals). Sea-ice declines in the Arctic region are also allowing species such as harp seals (*Pagophilus groenlandicus*) to move northward, to feed in areas that were previously unavailable due to sea ice. These, and other ice-related changes in geographical distributions, are altering competition and, predation, and causing shifts in migrations and distributions of endemic Arctic species, primarily in the eastern Canadian Arctic.

- For all coastal Arctic communities, human access to sea ice is critical for hunting and other land use activities, including subsistence and commercial fishing. Changing sea ice has become a serious issue affecting safety, travel, food security, and costs for Indigenous peoples.

- The extended ice-free season is enabling an increase in marine traffic within the Canadian Arctic region, especially by cruise ships and pleasure craft. The increased frequency and longer season of shipping is projected to produce noisier marine environments in some locations, increase the risk of invasive species and potentially lead to increased environmental harm. Commercial offshore fisheries may benefit from longer open-water seasons, increasing fishing seasons in currently fished areas and creating new opportunities in areas that were not historically open long enough to be of interest.

## 3.0 Stressors of Arctic Ocean ecosystems

In the Arctic several factors can change the state (i.e., mean condition and/or amount of variability) of marine ecosystems. These factors may be described as **drivers** (naturally sourced) or **stressors** (anthropogenic-based) on the system. Many would argue that the greatest anthropogenic stressor affecting the Canadian Arctic is climate change. Climate change brings about effects that extend outside the realm of natural variability with respect to both temporal (e.g., seasonal, annual, decadal) and spatial (e.g., local, regional, pan-Arctic) scales. The power and challenge of climate change is that it encompasses multiple variables in different domains (e.g., atmospheric, physical, chemical, habitat, etc.) and it is directly or indirectly linked to all other anthropogenic stressors of the marine environment. This interconnectedness represents a serious challenge for ocean and resource management as Arctic scientific and Inuit knowledge combined continues to be insufficient to 1) distinguish natural variability from climate-driven changes, and 2) adequately address the nature (e.g., additive, synergistic) and outcomes of individual and cumulative effects of climate change and other stressors.

Climate change effects in the Canadian Arctic are ultimately linked to rapidly increasing global air temperature, with the oceans absorbing ca. 93% of the energy imbalance created by the anthropogenic release of greenhouse gasses (Cheng et al. 2019). Therefore the World's oceans are warming, especially surface layer waters, affecting ocean oxygen concentrations, the severity of storms, sea level, and the hydrological cycle. Warming is amplified in the Arctic as air temperatures are increasing at double the global rates. From 2014 to present, mean annual Arctic air temperatures (measurements from land stations north of 60°N) have exceeded mean temperatures recorded in the Arctic since 1900. Satellite derived sea surface temperatures indicate that the temperature of the sea surface in ice-free areas of the Arctic, in the month of August, has risen in some areas as rapidly as 1°C per decade since 1981 due to a combination of factors including declining sea-ice extent, increased solar absorption and increased horizontal transport of ocean heat (Osborne et al. 2018).

The 40-year satellite record of sea-ice extent for the Arctic as a whole provides a baseline (1978-2010) from which a rapid decline in summer (September monthly average) Arctic sea ice has been detected (12.8% per decade, Figure 4a). Extreme losses of Arctic summer sea-ice extent occurred in 2007 and 2012 but consistent, below average conditions have continued in recent years (Figure 4a). Losses and variability of summer sea ice are primarily accounted for by the East Siberian, Chukchi, Beaufort, Laptev and Kara seas (Stroeve and Notz 2018). Sea ice is becoming younger and, on average, thinner across the Arctic, and the Canadian High Arctic harbours a substantial fraction of remaining thick multi-year ice. The overall loss of old, thick ice is striking. In April 2018, only 2% of winter sea ice, excluding that over the Canadian Polar Shelf, was estimated to be older than 5 years, compared to ca. 30% in 1984 (Figure 4b). The loss of thick ice is compensated by an increase in first-year sea ice representing a more fragile and mobile ice cover for the Arctic. Sea-ice loss is now evident in all seasons and the open-water season continues to lengthen (Figure 4c). In 2016/2017 freeze-up was 17 days later than average, at a pan-Arctic scale. Pan-Arctic sea-ice loss, in all seasons, is significantly correlated with total anthropogenic $CO_2$ emissions (Stroeve and Notz 2018). The anthropogenically-driven (**stressor**) loss of sea ice is also amplified by climate variability (**driver**). Together they modify atmospheric and ocean forcings on sea ice thereby indirectly causing reductions in sea-ice extent, concentration and thickness.

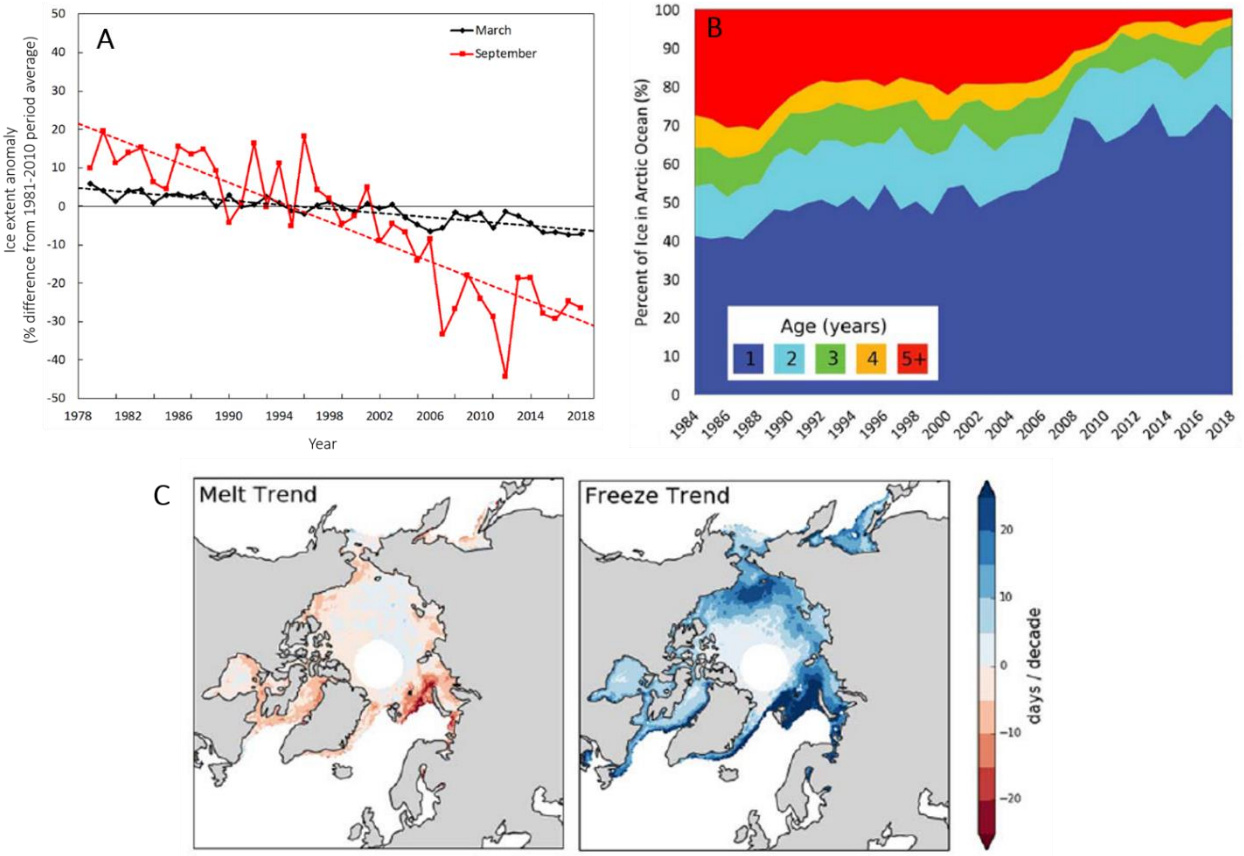


**Figure 4.** Pan-Arctic sea-ice trends showing a) sea-ice extent anomalies in March and September relative to averages conditions in the period 1981 to 2010, b) the decline in thick, multi-year sea ice (excluding the Canadian Polar Shelf) leading to a thinner, younger Arctic sea-ice cover, and c) earlier melt-onset and later freeze-up trends (1929-2017) (sources: Perovich et al. 2018; Stroeve and Notz 2018).

The large-scale drivers and stressors of the Arctic system interact with additional stressors within the Canadian Arctic region (e.g., Table 2). These stressors vary among areas and differ in their manageability. Some stressors may be reasonably addressed with proper management and/or stewardship (e.g., sustainable fisheries, invasive species, Section 3.1) whereas others (e.g., microplastics) are pervasive and possibly adverse. Case studies 2, 3, and 4 provide stressors-related information pertaining to ocean acidification, climate warming and environmental noise in the Canadian Arctic. Table 2 provides details on some other local (e.g., commercial fisheries) and transboundary (e.g., contaminants, microplastics, and shipping) stressors potentially affecting Arctic ecosystems.

**Table 2.** The status of some direct anthropogenic stressors relevant to marine ecosystems in the Canadian Arctic.

| Stressor | Current status | Recent references |
|---|---|---|
| Shipping | -Distance traveled by vessels tripled from 1990 to 2015 with pleasure/tourist vessels representing the fastest growing vessel type.<br>-Pond Inlet, Baker Lake, Cambridge Bay, and Chesterfield Inlet have experienced the largest increases in shipping while Churchill and Resolute had decreased vessel activity.<br>-In some regions, increased shipping is significantly correlated with reductions in sea-ice concentrations.<br>-Management efforts (e.g., shipping corridors) ongoing. | Pizzolato et al. 2016; Dawson et al. 2018; Halliday et al. 2018; Hauser et al. 2018; PAME 2019 |
| Microplastics | -Present in Canadian Arctic waters at low concentrations relative to other Arctic regions (i.e., 0-5 g $km^{-2}$).<br>-Plastic particles are concentrated in Arctic sea ice.<br>-Multiple research programs are currently focused on Arctic microplastic presence and food-web effects. | Obbard et al. 2014; Cozar et al. 2017; Peeken et al. 2018; Barrows et al. 2018; Osborne et al. 2018 |
| Contaminants | -Despite international regulations, legacy persistent organic pollutants continue to be found in the Arctic in apex predators (e.g., polar bears, belugas).<br>-Climate change influences contaminant concentrations in high trophic level species by affecting fate and transport pathways (i.e., oceanographic currents) and by altering food webs (i.e., food web length, guild) thus affecting bioaccumulation and biomagnification processes of contaminants such as mercury and persistent organic pollutants. Results vary regionally and between/within species.<br>-Chemicals of emerging concern are found in Arctic waters and biota, many of which are not included in a regulatory system and require ongoing monitoring. | Loseto et al. 2015; AMAP 2017; AMAP 2018a; Brown TM et al. 2018; Daugaard-Petersen et al. 2018; Letcher et al. 2018; Noël et al. 2018; Smythe et al. 2018 |
| Hydrocarbon development | -In 2016 a joint Canada-US statement issued a moratorium (drilling ban) for the Arctic offshore, to be tested every five years through a science based review. Existing rights were not affected by the moratorium. Alaskan waters were subsequently re-opened in 2017 for development.<br>-Indigenous and Northern Affairs Canada and Natural Resources Canada began a consultation process in 2017 regarding longer-term oil and gas interests in Canada's Arctic waters.<br>-There is currently ca. 27 000 $km^2$ and 2 250 $km^2$ of exploration and significant discovery licences, respectively, in the Canadian Arctic, the majority residing in the Inuvialuit Settlement Region. | |
| Fishing | -The largest ground fish fishery in Canada is located in the Arctic (Davis Strait and Baffin Bay).<br>-Between 2006 and 2014 Nunavut commercial fisheries increased in total value from 38 to 86 million CAD. In 2017 the commercial fishery value was estimated at \$174M (\$102M for the Greenland Halibut fishery and \$72M for the northern shrimp fishery). | Integrated Fisheries Management Plan (IFMP), unpublished data |
| Subsistence harvesting | -Subsistence harvesting has been an element of Arctic marine ecosystems for millennia and is not thought to be more stressing today than it has been in earlier times. | |

## 3.1 Modelling and Risk Assessment for Species Introductions in the Arctic

Non-native species introductions are an emerging threat for the Arctic and the Arctic Council has recommended strategies for limiting risks (CAFF and PAME 2017). Shipping is the primary vector responsible for the majority of marine introductions through movement of large communities of organisms in ballast water or biofouling on the outer surfaces of vessels (Ruiz and Carlton 2003) and is of particular concern in a warming and increasingly accessible Arctic (Dawson et al. 2018; Goldsmit et al. 2018). In vast and often remote areas such as the Arctic where there are limited resources and information, modelling and risk assessment approaches are a valuable means of identifying potential risks and prioritizing introduction pathways, species, and geographic areas for management and/or monitoring. In the Canadian Arctic, where there are limited known introductions of marine invasive species (Goldsmit et al. 2019a), these methods have been used to assess shipping pathways and associated invasive species of concern for the region (Chan et al. 2012; Goldsmit et al. 2018, 2019a, 2019b).

Relative risks of different shipping pathways (e.g., international versus within Canada only) for introducing non-native species to Arctic ports for ballast- or hull fouling-mediated invasions have been compared using vessel arrival/ballast discharge data (Figure 5), environmental compatibility between source and Arctic ports and numbers of high impact non-indigenous species known from ecoregions of connected ports (Chan et al. 2012). This assessment enabled identification of higher risk ports which have subsequently been targeted for follow-up baseline surveys and implementation of community-based monitoring (Goldsmit et al. 2014; Lacoursière-Roussel et al. 2018) (Case Study 18).

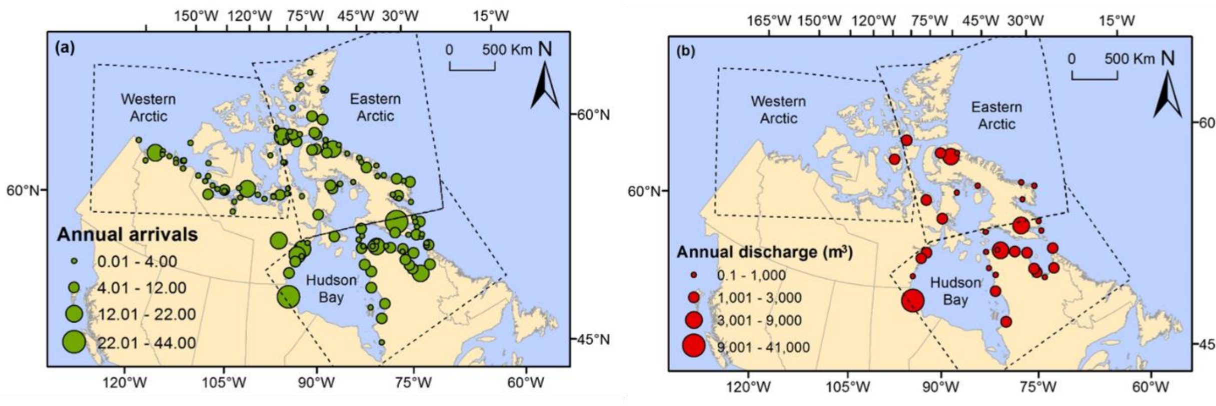


**Figure 5.** Total annual vessel arrivals (a) and ballast discharge (b), corrected for mid-ocean exchange between 2005 and 2008 for the Canadian Arctic (source: Chan et al. 2012).

Species distribution modelling has predicted the extent of suitable habitat in the Canadian Arctic under current and future climatic conditions for potential ship-mediated benthic invertebrate invaders known to be present in connected ports (Goldsmit et al. 2018, 2019b). These methods have shown the Beaufort Sea and Hudson Bay regions to be particularly vulnerable, with suitable habitat predicted for three of eight species evaluated under current conditions, (Goldsmit et al. 2018, 2019b) (Figure 6). Species identified as high risk have been presented in educational workshops and included in watch lists as part of outreach materials that are now being circulated to Indigenous communities (Case Study 18).

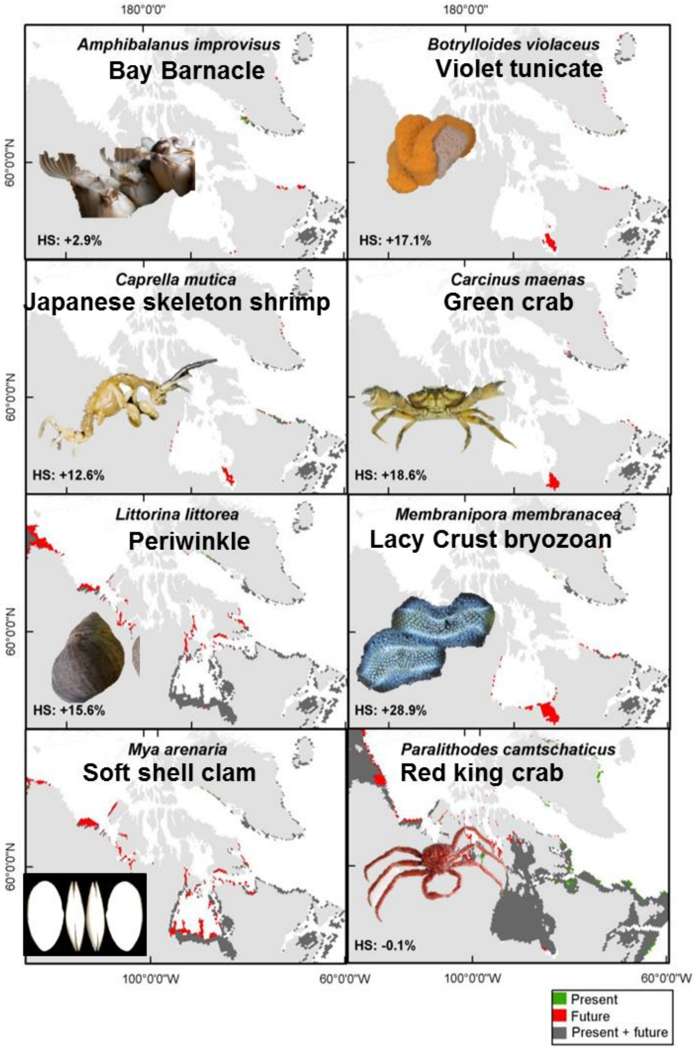


**Figure 6.** Predicted suitable habitat under present and future environmental conditions for eight potential IAS in the Canadian Arctic. The percentage change in suitable habitat (HS) between present and future (2050) is indicated in the lower left corner of each panel (source: modified from Goldsmit et al. 2018).

## CASE STUDY 2: Ocean Acidification in the Canadian Arctic

The concentration of carbon dioxide ($CO_2$) in the atmosphere is increasing. Consequently the planet is warming and the chemical composition of the ocean is changing. $CO_2$ dissolves in the surface ocean and forms carbonic acid, which in turn decreases ocean pH (measure of acidity, lower pH being more acidic) and also the carbonate ion ($CO_3^{2-}$) concentration, a building block of shells and skeletons of marine organisms made of calcium carbonate ($CaCO_3$, these organisms are called “calcifying organisms”). Ocean acidification refers to the decrease in pH and carbonate ion concentrations due to the increase in dissolved $CO_2$ released by human activities (anthropogenic $CO_2$) in the ocean. Global oceans have absorbed about a quarter of anthropogenic $CO_2$ since the start of the Industrial Revolution and consequently the surface acidity has increased by about 30%. $CaCO_3$ shells and skeletons are more soluble at lower temperatures and the solubility of gases, including $CO_2$, is higher in cold water than in warm water. Thus, although ocean acidification is a global threat, the polar oceans are particularly vulnerable. Additionally, large amounts of fresh water from rivers, seasonal ice melt and glacial meltwater in the Arctic Ocean has little buffering capacity and naturally reduces the pH and carbonate ion concentration of Arctic waters. Decreasing ice cover enhances the uptake of atmospheric $CO_2$, further accelerating Arctic acidification.

The first observations of surface ocean waters being corrosive to calcifying organisms, indicated by the saturation state of $CaCO_3$ ($\Omega$), were reported in 2008 for the Canada Basin (Yamamoto-Kawai et al. 2009) and in 2005 for the Canadian Polar Shelf (Chierici and Fransson 2009). Since that time there is growing evidence of increasing acidification in Canadian Arctic waters. Studies have found that corrosive conditions can occur in regions of glacier and freshwater influence, e.g., fjords (Cumberland Sound, Turk et al. 2016) and in Hudson Bay (Azetsu-Scott et al. 2014, Burt et al. 2016). In the Beaufort Sea the Mackenzie River contributes significantly to surface freshening. However, corrosive waters on the Mackenzie shelf occur in lower water layers of Pacific-origin (Cross et al. 2018; Mol et al. 2018). The acidification of Pacific halocline waters is a relatively recent phenomenon appearing over a period of 10 years (1975 to 1985) and is suggested to persist at the shelfbreak for an estimated 80% of the year (Cross et al. 2018). Acidified conditions in deeper waters adjacent to the Mackenzie shelf appeared between 1990 and 2010 (Miller et al. 2014; AMAP 2018b), although it is not known if these conditions persist. Canada Basin surface waters have become more acidic since 2003 (Figure 52) whereas in Davis Strait (Figure 64) corrosive waters occur in the Arctic outflow, with no evident trend.

The volume of corrosive water in the Arctic is increasing with time (Miller et al. 2014; Qi et al. 2017), reducing the suitable habitat for calcifying organisms (Steiner et al. 2015). The negative effects of ocean acidification on non-calcifying organisms, including physiological, reproductive and immune systems, and behavioural changes, have been reported in other oceans. Our knowledge of biological responses to ocean acidification in polar oceans is limited at present. A recent study found that small pelagic sea snails (pteropods, *Limacina helicina*) collected in 2014 and 2017 from Cape Bathurst and embayments in the Amundsen Gulf had high levels of shell dissolution due to acidified waters (A. Niemi, unpublished data) (Figure 7). To our knowledge this is the first direct evidence of ocean acidification impacts in Canadian Arctic waters. However, many other studies and assessments of biological effects are underway (AMAP 2018b).

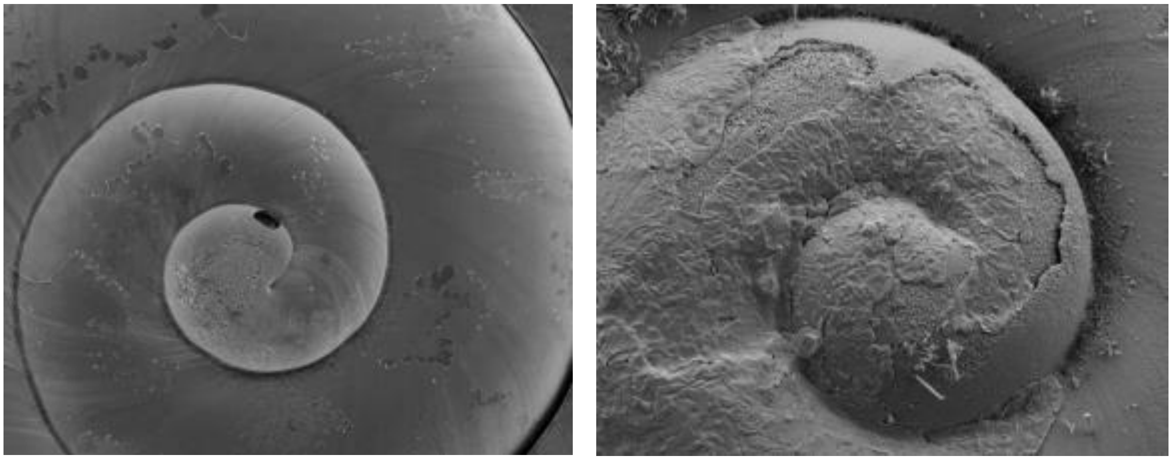


**Figure 7.** Scanning electron microscope images of Beaufort Sea sea snail shells showing evidence of damage due to Ocean Acidification (photo credit: Nina Bednaršek).

Ocean acidification in the Canadian Arctic evolves along its flow pathways. The Pacific Water that flows into the Arctic through Bering Strait inherently contains high $CO_2$ from organic carbon decomposition carried by the global circulation. This water is further acidified by Mackenzie River runoff, decomposition of terrestrial organic matter, sea-ice meltwater, primary productivity on the shelves, $CO_2$ uptake by surface waters, and upwelling of deep (Atlantic) corrosive waters on the Beaufort Shelf and in the Canada Basin. This corrosive water travels through the Canadian Arctic Archipelago, flows out to Baffin Bay and can be traced downstream to the Labrador Shelf (Azetsu-Scott et al. 2010; Yamamoto-Kawai et al. 2013). Since regional variability is large and temporal changes are fast in the Arctic (e.g., Tynan et al. 2016), coordinated efforts to study ocean acidification are required, including a large area survey and long-term monitoring in critical regions, to protect, mitigate and adapt to the future effects of acidification.

## CASE STUDY 3: The Changing Soundscape of the Arctic

The soundscape is the combination of sounds that can be perceived by an animal in an environment. Is the soundscape of the Canadian Arctic getting noisier? To answer this question we need to consider two sources: natural or ambient noise and man-made noise. In the Arctic Ocean ambient noise is made by physical (i.e., wind, precipitation, sea ice) and biological (e.g., marine mammals and fishes) sources.

Marine animals produce under water sound for several reasons including communication and navigation. Some fish species produce courtship and spawning sounds during the mating season. The baleen bowhead (*Balaena mysticetus*) whale makes long complex songs from late April to November concentrated between 30 Hz to 5 kHz (Delarue et al. 2009) as well as a more simple call at <500 Hz (e.g., Blackwell et al. 2013). Bowhead sounds measured near Alaska could be detected up to 40 km away depending on the noise conditions (Abadi et al. 2014; Bonnel et al. 2014) and an incredible 130 km away in Greenland (Tervo et al. 2012). Sounds from Arctic toothed whales, narwhal (*Monodon monoceros*) and beluga (*Delphinapterus leucas*), do not travel nearly as far (e.g., <5 km) and these whales produce echolocation clicks, whistle and pulse sounds for communication. There are also several seal species in the Arctic which produce underwater sounds associated with reproduction and territoriality. Their sounds are mostly heard during mating seasons. Walrus produce clicks, rasps, a bell-like tone and grunts. Vocalizations recorded as part of ambient sound monitoring near Sachs Harbour (Northwest Territories) in 2015 and 2016 (Halliday et al. 2018) (Figure 8) and near Hall Beach (Nunavut) in 2012-2013 (Marcoux et al. 2017) documented a strong connection between the vocalizations of multiple species and sea ice, reflecting migration and habitat use phenologies.

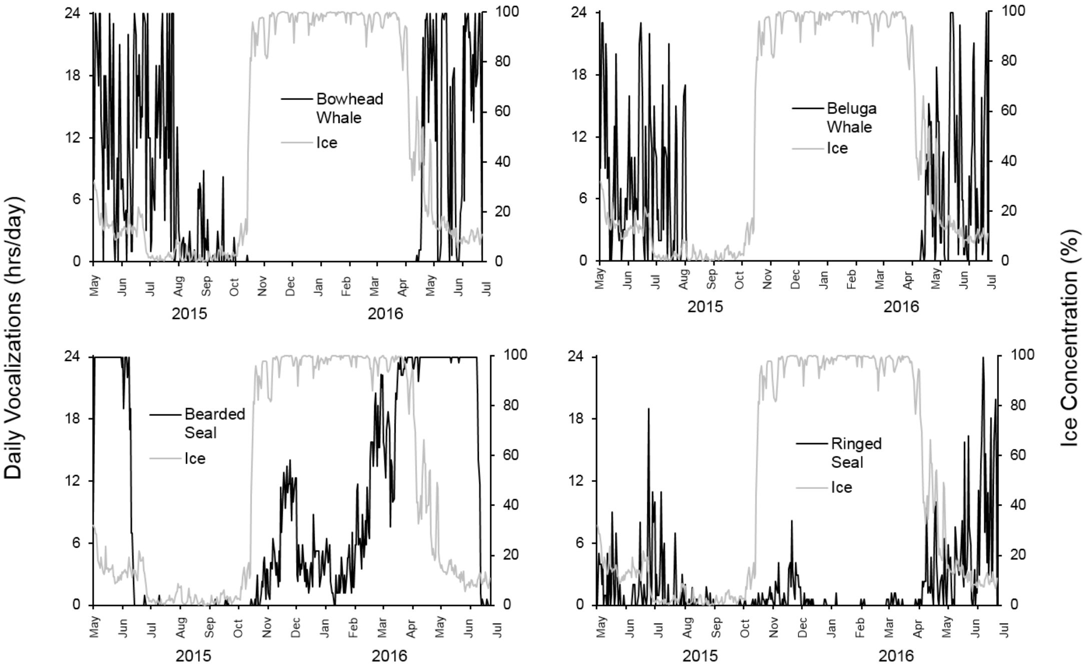


**Figure 8.** Seasonal pattern of marine mammal vocalizations near Sachs Harbour, NT relative to sea-ice concentrations (source: Halliday et al. 2018).

Sea ice generates different frequencies of ambient noise as it moves, cracks, and pushes together into ridges (Kinda et al. 2015). During the open-water period, ambient noise is generally positively related to the sea state. In the Arctic, stronger winds increase noise although it is strongly modulated by ice conditions (Insley et al. 2017). The ambient noise of wind can mask (interfere with or block the signal) the vocalizations of marine mammals (e.g., beluga and bowhead whales), however, increased ice concentrations may decrease this masking effect (Halliday et al. 2018). The level of ambient noise and interactions with vocalizations may be affected by climate-driven changes in sea ice and wind.

Human activities such as shipping, seismic exploration, extraction, construction and demolition, military operations (sonar) and ice-breaking also produce underwater sounds. Very loud sounds such as seismic and air guns could have serious effects during migration, potentially leading to entrapment and may inhibit the calls of bowheads (Blackwell et al. 2013; Heide-Jørgensen et al. 2013a). In a noise modelling exercise, it was determined that marine mammals in the Western Canadian Arctic could be affected by the noise of a tanker at about 50 km away. Ice-breaking is also a noisy type of shipping and is about 10 dB louder during backing and ramming ice-breaking than during open-water transit (Roth et al. 2013; PAME 2019). With a decrease in sea ice and a lengthening of the shipping season, shipping traffic is increasing in the Arctic Ocean (Dawson et al. 2018). A lengthening shipping season and increased vessel traffic may result in a noisier soundscape for marine mammals during different life events including migrations. Aulanier et al. (2017) calculated changes in ambient noise related with a ten-fold increase in shipping traffic in four different Arctic regions (Amundsen Gulf, Foxe Basin, Hudson Strait and Lancaster Sound). They concluded that under a ten-fold scenario, shipping noise will become the dominant contributor of ambient noise in these regions. This contribution would be a significant change since under the current shipping intensity, shipping noise only contributes to ambient noise intermittently. However, a significant increase in the amount of ship-based export from active mines in the Canadian Arctic has been proposed (Baffinland 2018).

Man-made noise can be problematic because the sound frequencies overlap with biological vocalizations, thereby potentially affecting marine mammal behaviour and communication (PAME 2019). Man-made noise can mask animal calls as well as reduce their communication space (Pine et al. 2018). For example, it was calculated that the noise emitted by an ice-breaker would mask beluga communication within 14-71 km of the ship (Erbe and Farmer 2000). The impact of underwater noise on marine mammals and fishes in the Canadian Arctic has been recently summarized in the Underwater Noise in the Arctic: A State of Knowledge Report produced by PAME (PAME 2019). Impacts vary among species and depend on the activities of the individuals at the time of the disturbance (e.g., foraging or migrating). Recent telemetry research from Resolute Bay, Nunavut, found that both Arctic Cod (*Boreogadus saida*) and Shorthorn Sculpin (*Myoxocephalus scorpius*) altered their home range and movement in the presence of vessels, even when the vessels were stationary (Ivanova 2016; Ivanova et al. 2018). As vessel traffic increases in the Canadian Arctic region, work is ongoing to understand the effects on the soundscape (Aulanier et al. 2017) as well as how to best mitigate shipping effects by considerations of ship speed (Pine et al. 2018) and the positioning of Arctic shipping routes (Halliday et al. 2017).

## CASE STUDY 4: An Extreme Warm Event in Hudson Bay and Ringed Seal Response

One of the main story lines of climate change is the loss of sea ice in Polar Regions, particularly as it relates to critical habitat loss for mammals. Over the last 2-3 decades, marine mammals studied in the Beaufort Sea have responded differently to changes in the extent and persistence of sea ice. The condition of young bowhead whales (*Balaena mysticetus*) improved over time, whereas ringed seals (*Pusa hispida*) and beluga (*Delphinapterus leucas*) experienced declines in condition (Harwood et al. 2015a). Questions remain, however, with respect to the actual causes of these divergent responses and what such responses mean for a given species or marine ecosystem. A recent study in the Canadian Arctic focused on demographic changes (e.g., disruption to reproduction, low pup survival, high mortality) of ringed seal (Figure 9) populations related to environmental stressors.

**Figure 9.** Ringed Seal on sea ice (source: NOAA Seal Survey, public domain, via Wikimedia Commons).

Seasonality of sea ice is critical for ringed seals (Section 4.5). They require sea ice in the spring when they molt, an extended time period during which they shed their fur and skin and grow a new coat, and reproduce. In the ice-free summer season, ringed seals forage in open water and build up their fat stores. During winter, they give birth and nurse but are restricted to smaller ranges. While they are well-adapted to the seasonality of sea ice, sea ice is declining in response to warming. Ferguson et al. (2017) examined ringed seals in Hudson Bay, one of the southernmost reaches of their distribution, as well as the extent of sea ice. The area goes through a complete cycle of ice loss and re-formation (Figure 10).

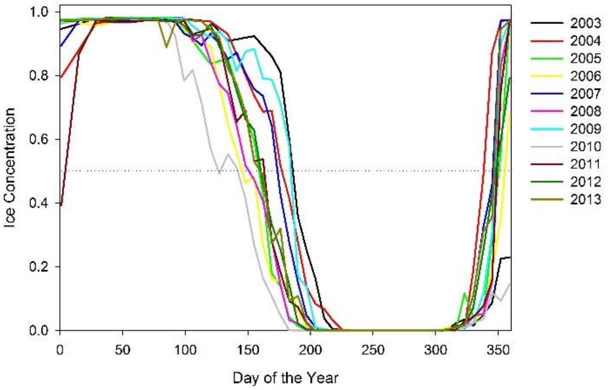


**Figure 10.** Sea-ice concentration each day of the year from 2003-2013 in Hudson Bay. The various colours represent different years. 50% concentration is shown by the dotted horizontal line and is considered the breakpoint for sea-ice break-up (<50%) and freeze-up (>50%). Note grey (2010 lowest concentration to left) and purple (2011 lowest concentration to right) years (source: Ferguson et al. 2017).

By analyzing sea ice and climate data it was evident that sea ice is gradually breaking up earlier and freezing up later in Hudson Bay, indicating that the ice season is getting shorter. Between 1979 and 2014, there was no relationship between any of the climate indices and the dates of break-up or freeze-up. What this means is that the shortening of the sea-ice season is not related to natural climate patterns, but instead likely a direct result of human-induced climate change. The longest ice-free season occurred in 2010 with ice break-up arriving in May and not freezing again until January of 2011 (Figure 10).

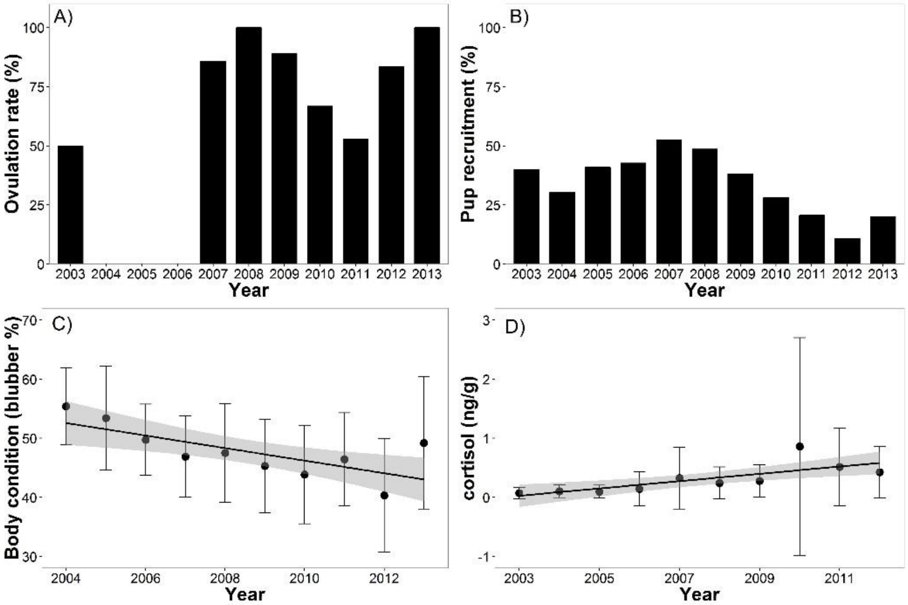


**Figure 11**. a) Annual ovulation rate each year (note 2011 low), b) Annual percentage of pups in the harvest (a representation of pup recruitment; note recent declining trend), c) relationship between seal body condition and year (note decline), d) relationship between cortisol (stress) level and year (note increase over time) (source: Ferguson et al. 2017).

By examining body condition, reproductive condition, pup recruitment, and stress level from 1425 seals harvested as part of Inuit subsistence hunting in Hudson Bay between 2003 and 2013, it was found that ringed seal body condition declined from 55% blubber mass in 2004 to only 40% in 2012, with the caveat that it did increase again to 48% in 2013. The decline in body condition was related to the increased period of open water (shorter sea-ice season). Cortisol concentration (a measure of stress) increased over time in ringed seals. In 2010, cortisol levels were high and showed high variability. Ovulation rates were low the following year (2011), likely attributable to the high stress ringed seals experienced in 2010 (Figure 11).

**Figure 12.** Ringed seal pup (source: Shawn Dahle, NOAA, Polar Ecosystems Program research cruise, public domain, via Wikimedia Commons).

What might this mean and the bigger picture? This study showed declining ringed seal body condition is concurrent with sea-ice decline, one of the many consequences of climate change. In addition, the study documents a relationship between the 2010 climatic event and ringed seal demographic changes, as body conditions were reduced, seals were stressed, and ovulation in seals decreased, leading to fewer pups (Figure 12) in the following years. This climatic event is linked to large-scale climatic patterns indicating that climate-controlled cycles will continue to impact body condition and seal demographics. In Hudson Bay, seal condition showed some recovery in the years following 2010. However, the 2010 cohort will be few in number due to the extreme conditions of 2010.

What is the mechanism by which ringed seal body condition was reduced and stress increased by sea-ice loss (or other factors)? The longer open-water period of 2010 may have affected the ringed seals' access to prey items as well as the abundance and distribution of the prey. Higher sea temperatures late into the fall may have resulted in hyperthermia in fat seals and seals hauling out on shorelines. The seals also showed evidence of anomalous lethargic behaviour which may indicate disease/illness, possibly a consequence of disrupted molting. Illness may have in turn increased their risk of predation by polar bears (*Ursus maritimus*) (Figure 13). The mechanism behind declining seal body condition with longer open-water periods is not yet well understood.

According to long-term atmospheric patterns, episodic events such as the one in 2010 are expected to occur every 10-15 years but be unpredictable. It is the combination of climate-change-driven gradual sea-ice loss and these unpredictable episodic events that is most likely to have major implications for ringed seal body condition and over the long-term their abundance and distribution.

This research provides more information on what may be expected in the future, but reliable prediction of the future is still elusive. Further research will be required to determine the mechanism behind body condition declines with sea-ice loss, how seal populations will adapt to climate change, and how the larger ecosystems will also be affected.

**Figure 13.** Polar bear eating a seal caught on land north of Churchill in October 2010 during the unusual year when ringed seals crawled out of the water in the vicinity of polar bears awaiting the return of sea ice (photo credit: Daryl Hedman).

## 4.0 Structure of the Arctic Ocean ecosystem

The following sections provide the ecosystem context for understanding how the Canadian Arctic Ocean works. Such context is needed to both detect and explain observed changes. The physical (Section 4.1) and chemical (Section 4.2) components of the marine ecosystem create dynamic habitats for all biota. There is no single food web for Canadian Arctic Ocean ecosystems and recent research has shown that some food webs are being modified as species respond to changing habitats and prey (Section 4.3, Case Studies 6 and 7). The structure and function of Canadian Arctic Ocean ecosystems vary across spatial scales and here we describe known linkages between habitat types and marine life (Section 4.4, Case Studies 8 and 9). Additionally, the Arctic functions differently over time, on multiple temporal scales (i.e., days to decades). Here we only discuss the seasonal scale (Section 4.5), illustrating that an annual Arctic cycle is better understood from an events-perspective rather than a calendar.

## 4.1 Where Life Lives: The Ocean Environment of the Arctic

### 4.1.1 Oceanographic Boundaries of the Arctic

The edge of sea ice at its maximum extent in late March provides the simplest delineation of the marine Arctic. This boundary also approximates the maximum extent of cold, low salinity Arctic Surface Water at this season. It encompasses the deep central basins of the Arctic Ocean, the shallow continental shelves that surround it and lobes that extend southward into the Pacific and Atlantic Oceans. The lobe in Canada's domain pushes as far south as Newfoundland.

### 4.1.2 The Submarine Landscape

Ocean waters are stacked in layers with those of lowest density at the surface and those of highest at the seabed. Because energy is required to lift denser water back towards the surface, ridges on the seabed tend to block seawater flow and valleys tend to channel it. The submarine landscape thereby constrains how seawater can move, making knowledge of that landscape critical to understanding the ocean environment. Such topographic constraints on ocean currents influence the properties of seawater and planktonic life found in particular areas of the Arctic. Those properties of particular relevance to the ocean's ecology are seawater temperature, salinity, dissolved oxygen, dissolved nutrients and acidity. Specific associations of these attributes define water masses in the Arctic.

Oceanographers commonly use contour lines that connect points of constant depth to map the landscape of the seabed. Contours crowd together where the seabed slopes steeply, at the edge of the continental shelf for example; they encircle isolated areas of deep water known as basins and isolated areas of shallow water known as banks; they form a distinctive pattern at sills, the marine equivalent of mountain passes, which separate shallower areas when viewed along one heading and deeper areas when viewed along one at right angles to it. It is easiest for deep ocean waters to cross between basins at sills.

The Canadian Arctic region encompasses two deep basins – Canada Basin and Baffin Bay – separated by a broad, shallow continental shelf – the Canadian Polar Shelf – which acts as a sill between the Pacific and Arctic. A broad and relatively deep sill in the southeast separates Baffin Bay from a third basin, the Labrador Basin. Hudson Bay and James Bay occupy an appreciable fraction of the Canadian Polar Shelf.

The glacial history of the Canadian Polar Shelf has left it littered with islands comprising the Canadian Arctic Archipelago, with channels and sills. The most obvious sills line along the northwestern rim of the Canadian Polar Shelf and cluster near its centre; the intervening basins are as deep as 800 m. The sills rise to within 300-400 m of the sea surface in the north-west and much higher near the centre, within 15-220 m of the surface. Even preliminary seabed surveys are lacking over wide areas of the Canadian Arctic region, particularly in remote icebound northern areas and in the near-shore estuaries, bays, and fjords important to people whose livelihood comes from the sea. The lack of good seabed maps restricts scientists' capability to understand Canadian Arctic marine ecosystems and their vulnerability.

### 4.1.3 Seawater Sources

There are three main contributors of water to the Canadian Arctic region, the North Pacific and the North Atlantic that contribute seawater and the atmosphere that contributes fresh water as snowfall, rainfall and inflow from rivers. These waters are distinguishable in three characteristics – salinity, temperature and dissolved nutrients - which in addition to dissolved oxygen and acidity are key elements of marine habitat and key factors in determining what organisms thrive where.

Water from the Atlantic has high salinity (34.5-34.95) and relatively high temperature (0-3˚C) year-round (Figure 14). There are three variants of Atlantic Water in the Canada Basin: a warm layer entering via Fram Strait and a colder layer entering via the Barents Sea, refreshed every few decades, and a dense layer at the bottom of the basin that has been trapped for several centuries. A fourth variant enters the Canadian Arctic region waters via Baffin Bay but does not reach the Canada Basin. Water from the Pacific has moderate salinity (31-33), lower in summer than in winter, is warm (near 3˚C) in summer and cold (near -1.5˚C) in winter and has high concentrations of dissolved nutrients (nitrate, phosphate, silicate). Fresh water has a salinity of zero, a temperature that varies with source and season from 0-10˚C and is relatively low in dissolved nutrients. Arctic Water is a mixture of Pacific, Atlantic and fresh waters, modified in the Arctic by physical, chemical and biological processes. Arctic sea ice is a frozen version of Arctic Water.

At the low temperatures of the Arctic, salinity is the main factor controlling water density. Fresh water of lowest salinity floats on the top, Atlantic Water of highest salinity sinks down deep and Pacific Water slips in between. It is the shallow cap of ice, Arctic water and Pacific water that make the Arctic so different from the Atlantic.

The thickness of each layer depends on how much of each type is present and on ocean circulation. Fresh water is scarce overall but concentrated in the uppermost 50-150 m. Pacific water is more abundant and dominant between 50 and 250 m in the Canadian Arctic region. Atlantic water is by far the dominant water mass, filling the basins from about 300-m depth to the seabed. Mixing creates depth zones with properties transitional between water types.

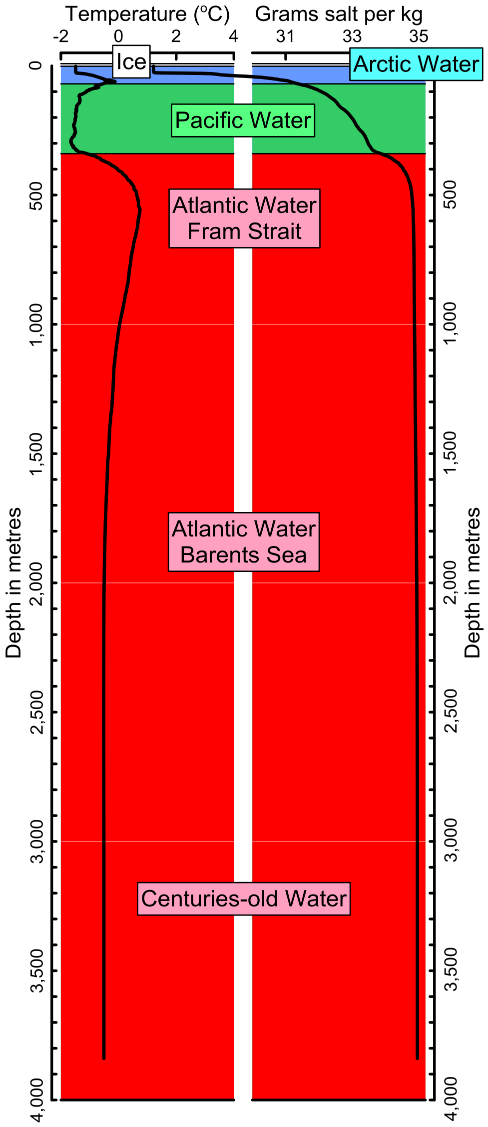


**Figure 14**. Depth variation in the temperature and salinity of seawater in the Canada Basin of the Arctic. Domains of the principal water masses are shown.

Phytoplankton at the base of the food web need dissolved nutrients and light in the same place to thrive. The Sun's return initiates planktonic growth in spring, but continual replenishment of nutrients is necessary to sustain primary production. Nutrients are plentiful in the Arctic's sub-surface Pacific layer but must be mixed into the photic zone where photosynthesis occurs. This uplift is driven by the kinetic energy of storms and tides, but only in certain places under special conditions.

Where elevated terrain rises above the layer of nutrient-rich Pacific water, it can restrict the nutrient supply to basins beyond it. It is likely that this mechanism operates in Coronation Gulf, Dease Strait and Queen Maud Gulf, for example, where bounding sills rise to 15-30 m depth and only nutrient-poor surface water can enter from outside under normal conditions.

From a broader perspective, the depths of sills that can block possible paths of flow control the presence of each seawater type at locations across the Canadian Polar Shelf. Figure 15 displays the areas of the Canadian Arctic region that are accessible to each seawater type, combining knowledge of the depth of occurrence of each type with knowledge of the seabed's landscape. Pacific or Atlantic water can only be present at a location of interest if there is a path to the Arctic from that ocean that is everywhere at least as deep as the shallowest depth of occurrence of that type. The areas isolated from nutrient-rich Pacific Water are of particular interest.

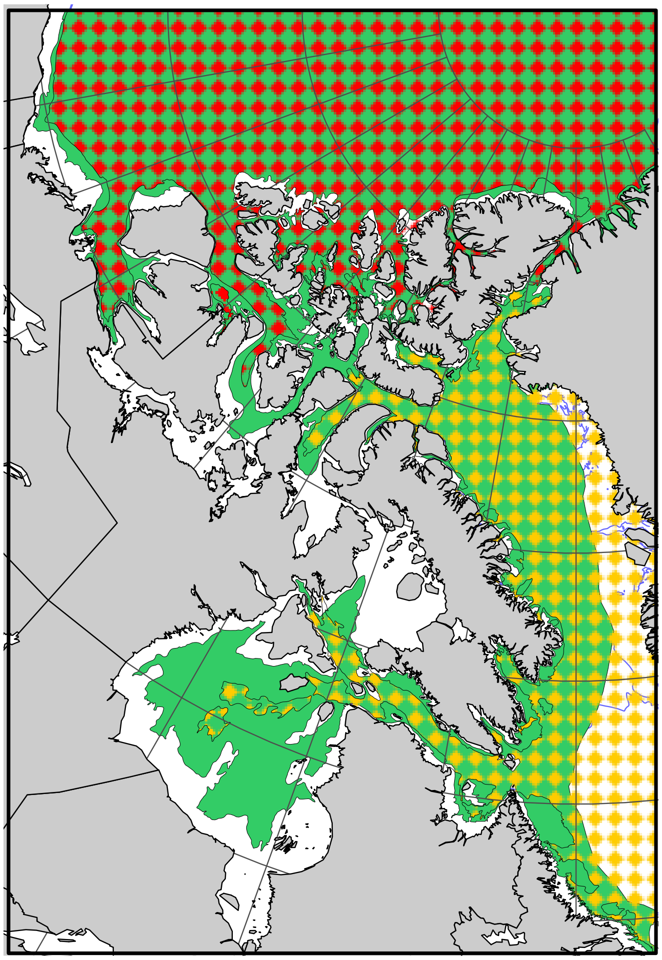


**Figure 15**. Presence of seawater types in the Canadian Arctic region: Pacific water in green, Atlantic water via Fram Strait and the Barents Sea in red, and via Baffin Bay in yellow. Arctic water covers the entire area except for eastern Baffin Bay (no green underlay). Pacific nutrients are not readily available in the white areas on southern parts of the Canadian polar shelf.

### 4.1.4 Seawater Movement

The implications of water-mass distribution are more easily seen in combination with knowledge of how water actually moves. A discussion is complicated by the variation of current speed and direction with depth, ice cover, tide, storm, season, year and decade. Information is sparse. A schematic of the average circulation of surface waters of the Canadian Arctic region is shown in Figure 16.

In general, prevailing winds in the Baffin Basin maintain a counter-clockwise gyre that brings Atlantic water up the Greenland side and takes it southeast along the eastern side of the Canadian Polar Shelf. Those in the Canada Basin maintain a clockwise gyre that moves surface water slowly south-west along the Arctic side of the Canadian Polar Shelf and more rapidly westward across the southern Beaufort. Some of the flow on the Arctic side, responding to a drop in sea level of about 15 cm towards Baffin Bay, leaves the gyre to cross the Canadian Polar Shelf and join the Baffin Current that takes it to the Atlantic. This picture is complicated by the numerous islands on the polar shelf, which in combination with Earth's rotation allow surface water also to move towards the Arctic if it hugs land on its right side. Atlantic water from Baffin Bay also floods the basins on the eastern side of the Canadian polar shelf.

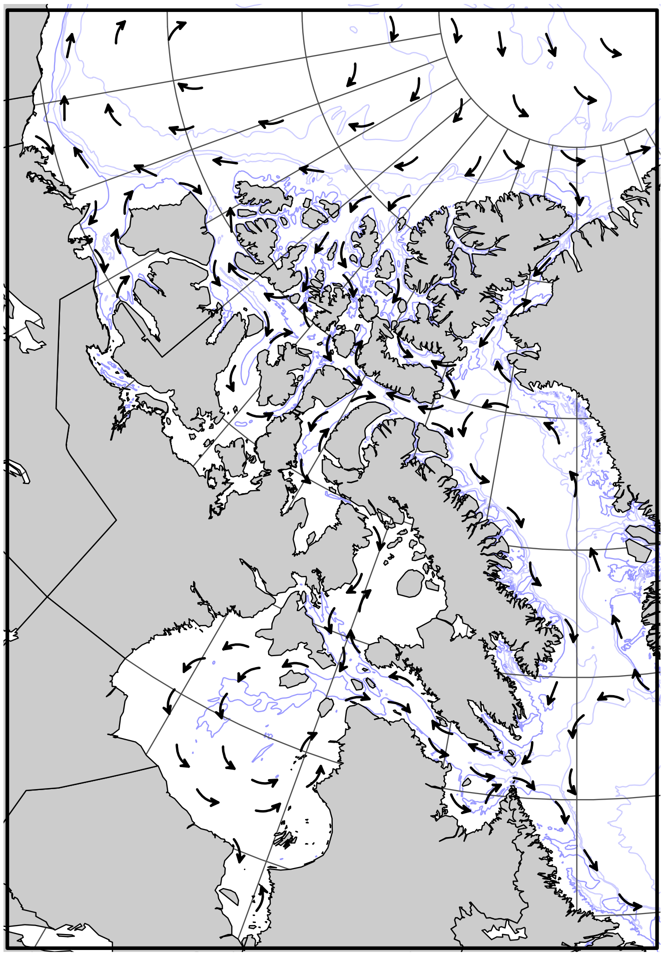


**Figure 16.** Schematic view of surface water movement within the Canadian Arctic region. Arrows represent the average direction of currents without regard to the speed of flow.

The submerged pathways followed by Pacific and Atlantic water within the Arctic Ocean are not well known. However, observations have revealed a current flowing beneath the surface counter-clockwise along the Beaufort continental slope and into the deep basins of the western Canadian Polar Shelf simply by following their steeply sloping sides. The Atlantic component is too dense to move eastward and may remain in the deep western basins for decades. Because of sills, the Canadian Arctic through-flow is comprised only of Arctic Surface and Pacific Waters. The latter bring nutrients to feed marine ecosystems of the Baffin coast, Hudson Bay and the Maritimes region of Canada. Part of the southbound Baffin Current enters Hudson Bay along the northern side of Hudson Strait and joins the counter-clockwise circulation of local river inflow around the bay to exit along the southern side of Hudson Strait.

### 4.1.5 Sea Ice

Extensive ice cover during at least part of the year is a defining characteristic of the Canadian Arctic region. The ice forms by freezing seawater during cold winter weather. In Canada's far north, sea ice grows to more than two meters in thickness by early June. Near the southern limit in James Bay winter's growth is about 1 meter.

Freezing seawater is only the beginning of sea ice. The forces of wind and tide move the ice against shorelines causing it to fracture and stack into thick sinuous piles (ridges). These can attain 10-m thicknesses even very early in winter and 30 m or more by winter's end. The stacking of ice briefly creates space for ice-free leads elsewhere. Drifting sea ice (or **pack ice**) becomes a chaotic landscape of ridges and floes of widely varying thickness as winter continues.

Pack ice gets stronger as it gets thicker with time during winter. Where coastlines or islands provide shelter, it may become strong enough to resist the forces of wind and current, so that it stops fracturing and drifting and is held fast, forming **fast ice.** The channels among islands on the Canadian Polar Shelf are unique in harbouring vast expanses of fast ice every winter.

Air temperature rises with strengthening sunshine as the polar night fades, causing ice growth to slow. With temperature near 0˚C, the Sun's radiation is able to melt accumulated snow, forming ponds that trap the Sun's heat and promote decay of the sea ice beneath. By early August, much of the level (thinner) **seasonal ice** in the southern part of the Canadian Arctic has melted. Further north where the ice is thicker, summer is too short for all the ice to melt. When open areas start freezing here in late August, new ice also starts freezing onto the bottom of last winter's floes that still remain. On October 1 these rejuvenating floes enter the second-year ice category. If they survive a second summer, they become **old** or **multi-year ice**. Most of the Arctic's multi-year ice resides in the Canadian Arctic region. The combined areas of first, second and multi-year ice define the minimum extent of ice cover at summer's end.

Ice is the surface of the sea where it is present and moves generally as described for surface currents, except where the ice is fast. As do currents, the drift of ice varies greatly over time (hours, days, seasons, years). Indeed sea ice greatly enhances our knowledge of surface currents because its movements can be readily tracked from space. Ice both enters and leaves the Canadian Polar shelf on all sides as winds change. In the west however, ice is more likely to move from the Canada Basin onto the shelf north of Parry Channel and is more likely to move off shelf into the Canada Basin to its south. On the eastern side, ice generally moves off the shelf into Baffin Bay via Smith and Jones Sounds, whereas it commonly drifts some distance into Lancaster Sound and Hudson Strait before crossing the channel and coming back out along the other side. Ice circulates counter clockwise around Hudson Bay; that ice which does not melt within the bay exits via Hudson Strait.

Sea ice exerts a strong influence on all aspects of Arctic marine ecosystems. It is itself a habitat (substrate) for life – bacteria, phytoplankton, zooplankton, fish, seals, walrus (*Odobenus rosmarus*), birds, whales, foxes, polar bears and Inuit. Its presence reduces the penetration of sunlight into ocean water. Its roughness helps mix dissolved nutrients upward into the photic zone when moving, but it creates a layer of brackish surface water that impedes that mixing when thawing. Its solidity provides support for bears, foxes and birds but at the same time impedes easy access to marine food sources. Its presence protects marine mammals from marine predators but may also isolate these same creatures from needed air. The edge of fast ice in winter and spring (the floe edge) allows, with favourable wind, the formation of polynyas (areas of thin ice or open water) which foster blooms of plankton early in spring and provide sanctuary for creatures needing both ocean and atmosphere to survive.

The scope of ecosystem-relevant sea-ice metrics embraces far more attributes than the much discussed yearly minimum ice extent. However the seasonal variation of ice extent within the Canadian Arctic region (Figures 17 and 18) does provide a useful overview. The extent of ice in late winter coincides with the domain of Arctic Surface Water depicted in Figure 15, and therefore with the Canadian Arctic region as we have defined it.

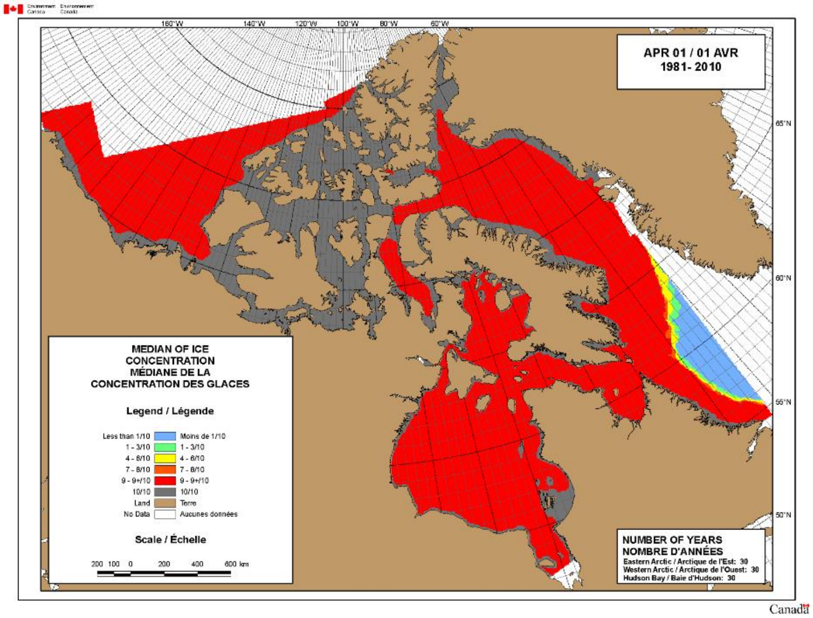


**Figure 17.** Sea-ice coverage of the Canadian Arctic region near the time of maximum extent. Red denotes an almost complete cover of pack ice and grey a complete cover of fast ice. The information depicted is the median value over the climatological period 1981-2010. Illustration courtesy of the Canadian Ice Service. https://iceweb1.cis.ec.gc.ca/30Atlas/page1.xhtml

Figures 17 and 18 provide no information on the thickness of sea ice, which varies greatly across the region and among seasons. However it is useful to identify the geographic regions most likely to harbor thin ice and very thick ice. In winter thin ice is most common near the ice edge bounding temperate seas and in polynyas. Polynyas exist despite cold atmospheric conditions because ice is physically moved from the freezing area by wind and because the rate of freezing itself can be reduced by upwelling of warmer ocean water. Ice that is very thick on average is most likely to be multi-year ice, which can be detected fairly reliably by satellite radar during the cold months.

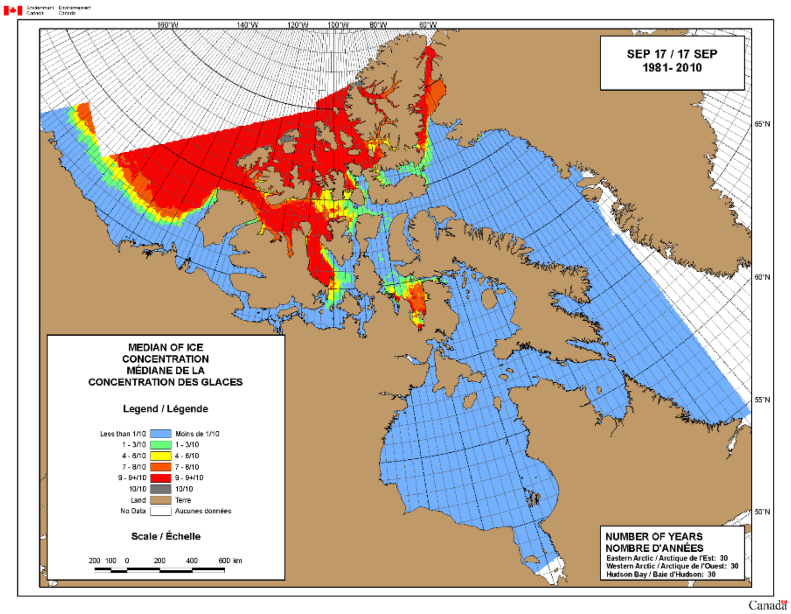


**Figure 18.** Sea-ice coverage of the Canadian Arctic region near the time of minimum extent. The information depicted is the median value over the climatological period 1981-2010. Illustration courtesy of the Canadian Ice Service, https://iceweb1.cis.ec.gc.ca/30Atlas/page1.xhtml

The median concentration of ice within the Canadian Arctic region in early summer (Figure 19) is a good surrogate for

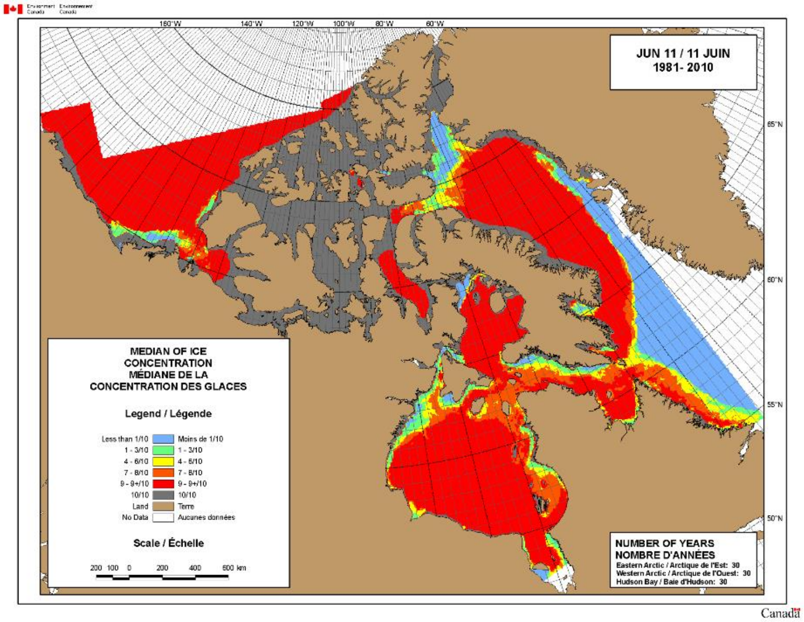


**Figure 19.** Locations of polynyas (blue-green areas bounded by red) in the Canadian Arctic region, evident as areas of light sea ice in early summer. Large polynyas exist in the Beaufort Sea (Bathurst Polynya), northern Baffin Bay (North Water), north-western Foxe Basin and Hudson Bay and Hudson Strait. Smaller polynyas occur in Penny Strait, Cardigan Strait and Cumberland Sound. Illustration courtesy of the Canadian Ice Service, https://iceweb1.cis.ec.gc.ca/30Atlas/page1.xhtml

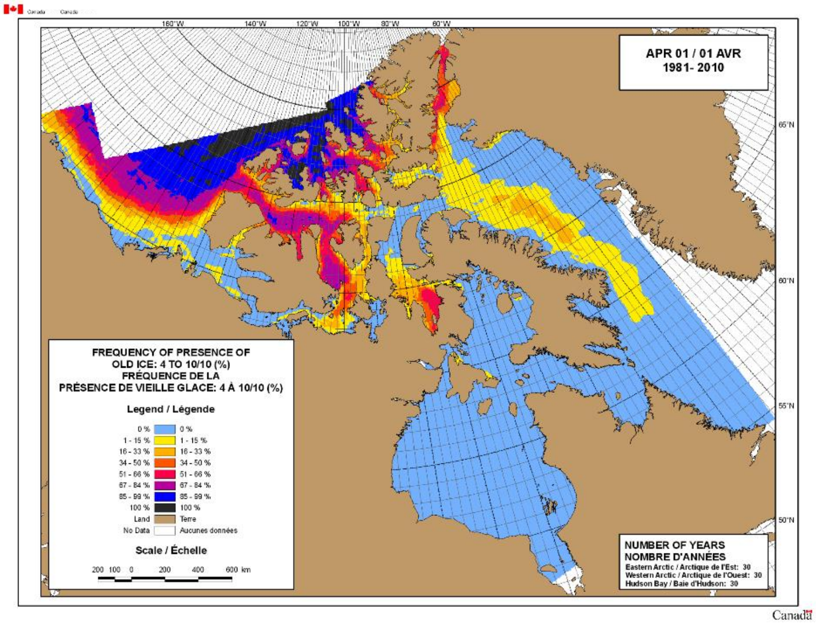


**Figure 20.** Regions of heavy ice in the Canadian Arctic region. The map displays the frequency of occurrence of old ice at 4-10 tenths coverage on this date in terms of the fraction of years in the 30-year climate interval. Illustration courtesy of the Canadian Ice Service, https://iceweb1.cis.ec.gc.ca/30Atlas/page1.xhtml

mapping the larger Arctic polynyas. Thin ice that may have completely covered polynyas six weeks earlier has melted by this time, and waters exposed by later movements of the ice will not have refrozen. There are also myriad smaller polynyas, generally in channels with strong tidal currents that cannot be mapped on this scale.

Figure 20 displays the occurrence frequency of multi-year ice at a concentration of 4 tenths or more, based on data from the most recent 30-year climate interval, 1981-2010. The areas coloured purple, blue and black have been dominated by old ice for at least 20 of the 30 years analyzed. These include the Beaufort Sea south to 73°N and most of the western Canadian polar shelf. Old ice has been less common in the southern and eastern parts of the Canadian polar shelf, and has had negligible presence in Hudson Bay and Foxe Basin.

Because sea ice influences marine life and human activity in so many ways, the scope of ecosystem-relevant sea-ice characteristics embraces far more attributes than those presented here. Some others are: the distribution of ice presence by thickness; the presence, size and fractional area covered by ice ridges above and below the sea surface; the presence, thickness and drifting of snow; the date of freeze-up; the dates of breakup for fast ice and of ice clearance for pack ice, etc. Moreover, the percentiles and extreme values of these attributes may be as relevant as, or more so, than the averages.

### 4.1.6 Tides

Tides are the regular variations of sea level controlled by the positions of the Sun and the Moon, their gravitational pulls and the rotation of the Earth. Solar and lunar gravity create seawater bulges that move around the Earth as it rotates beneath them. There are many tidal components whose periods are clustered in bands. The half-daily and daily bands contain the largest tides.

Irregularities in the depth and shape of the ocean basins modify the bulges, so that the differences between high and low tides – tidal ranges – are larger in some areas than in others. In the Arctic, seasonal changes in the ice cover also change the range and arrival time of the tide.

The rapid movement of the tidal bulges of seawater around the Earth creates tidal currents. These flow back and forth over the same intervals as the sea-level changes that drive them. Half-daily tides alternately expose and flood the inter-tidal habitat at the coast by changing sea level four times each day. The width of the inter-tidal zone depends upon the tidal range and the slope of the shoreline – narrow on steep shores. Tides in winter raise and lower sea ice near shorelines, maintaining cracks between ground ice (nearshore) and floating ice (deeper water) that provide breathing opportunities for seals and hunting opportunities for polar bears.

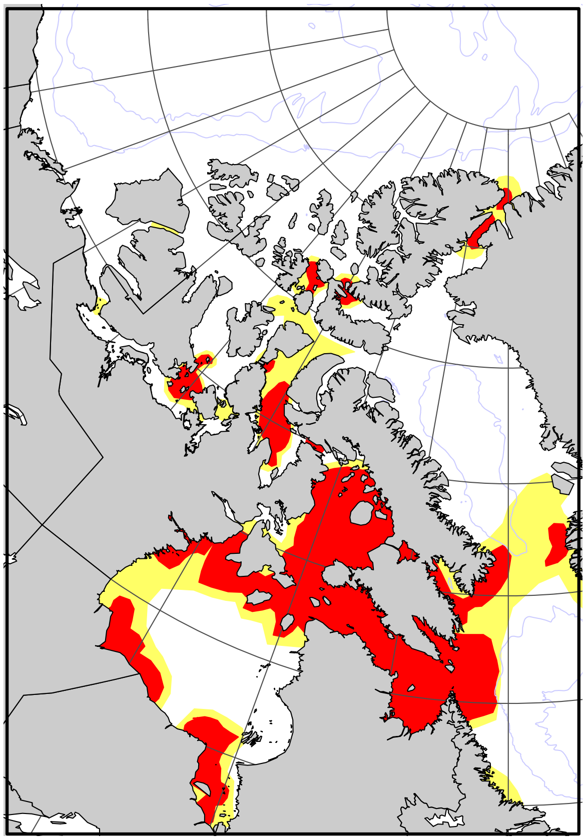


**Figure 21.** Areas with strong tidal currents within the Canadian Arctic region. Flows are most energetic in areas coloured red, less so in those coloured yellow. Data computed by the WebTide Tidal Prediction Model V0.7.1 (Dunphy et al. 2005, http://www.bio.gc.ca/science/research-recherche/ocean/webtide/index-en.php).

The flow of tidal currents over the seabed and under the ice generates swirls and eddies in the water that can mix possibly warmer and more nutrient-rich water upward to the surface. The effect increases dramatically as tidal current strengthens. Upward mixing of nutrients can restore the productive capacity of the photic zone in summer and sustain biological hotspots. An upward mixing of heat can reduce the thickness of winter ice (create small polynyas), providing better wintertime habitat for walrus and seals and facilitating earlier breakup in spring. However, both of these ecological benefits are dependent upon the occurrence of both strong tidal action and of warm water and nutrients at depth. Currents are strongest in narrow, shallow channels where the tidal range and/or timing of high and low tides differs markedly from end to end. Figure 21 depicts areas of the Canadian Arctic region where tidal currents are strong.

## CASE STUDY 5: Nunavut Community Observations of Coastal Sea-ice Change

Coastal communities in Nunavut frequently utilize and rely upon the sea ice that occupies their coasts for the better part of the year. Data on the location, quality, and use of the sea ice in these communities is recorded by the Nunavut Coastal Resource Inventory (NCRI), a project run by the Department of Environment, Government of Nunavut. The project involves interviewing elders and active hunters and fishers who have intimate knowledge about the Arctic Ocean from having spent the majority of their lives relying upon it for survival. In the NCRI interviews, information about the sea ice is gathered through participatory mapping of the floe edge, travel routes, hunting locations, and seasonal campsites. Participants indicate whether observations are present (within the last 10 years) or from the past (more than 10 years ago) and note whether things have generally stayed the same or if they've witnessed significant change over time. Collective observations from across Nunavut indicate that the location, timing, and quality of sea ice has changed significantly in recent years, which has impacted the way coastal communities interact with it.

Within the last few decades, some coastal communities have lost access to traditional hunting grounds and travel routes due to changes in the location (Figure 22) and quality of sea ice. In Resolute Bay, hunting grounds on Somerset Island have been inaccessible within the past few years because the sea ice no longer reaches the island. Additionally, elders remember travelling to Baffin Island over the sea ice a decade ago but can no longer do so due to reductions in sea-ice extent. In Coral Harbour, the floe edge has been closer to shore than before, making it impossible in recent years to travel via sea ice to mainland Nunavut where the community used to hunt caribou (*Rangifer tarandus*). The communities of Arviat, Whale Cove, and Hall Beach have also experienced reductions in sea-ice extent with the floe edge being closer to the coast in the past decade than during the pre-settlement era.

The timing of sea-ice formation and break-up has been noticeably altered, with the majority of coastal communities in Nunavut having observed the sea ice forming later and/or melting earlier than it used to a decade ago. In Cape Dorset, the ice used to be frozen and safe to travel on in November but in recent years it does not become safe to use until December. In Cambridge Bay, ice formation has been delayed by up to two months. In the spring, the ice starts to thaw much earlier than in the past and breaks up much more quickly because the ice is thinner than it was a decade ago. In Hall Beach, the sea ice forms up to one month later than it did in the past decade. In Pond Inlet, the ice takes up to three months longer to form properly and is thinner at its maximum compared to in the past. To the east of the community, at Button Point, the ice does not form until February which is much later than normal, causing disruptions in the traditional seal harvest in that area. In addition, elders from Pond Inlet recount stories of travel from mainland Nunavut by dog team over the sea ice in July which is no longer possible because the sea ice breaks up approximately one month earlier than it did before.

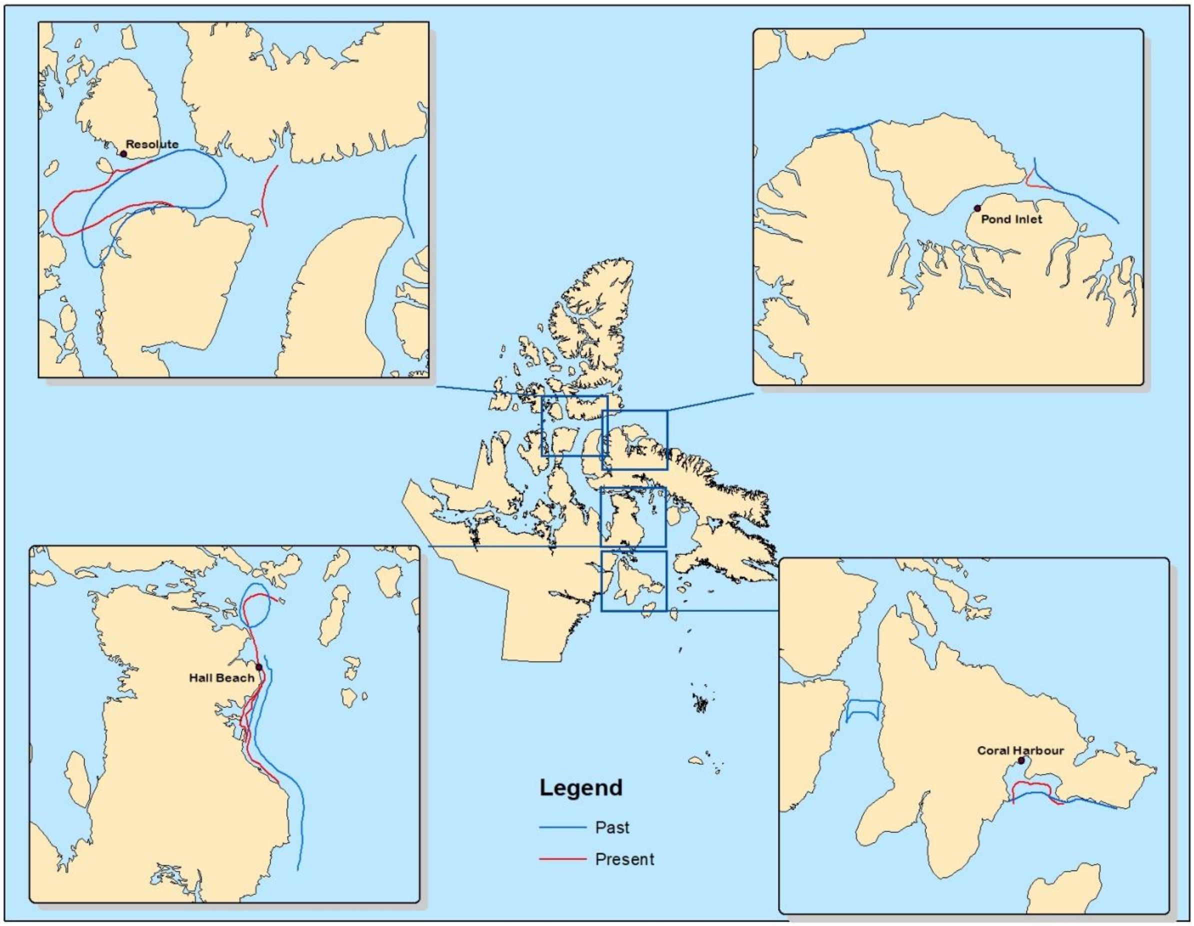


**Figure 22.** Community descriptions of floe edge locations during late winter/early spring in Nunavut. Blue lines represent past (>10 years ago) locations of the floe edge. Blue polygons represent locations of solid, traversable sea ice in the past. Red lines represent present (within the last 10 years) locations of the floe edge.

The quality of sea ice has also changed within the past few decades. In Cape Dorset, the ice near the floe edge (Figure 22) where hunters frequent during the winter months is much thinner than it used to be, with many spots within the sea ice that do not freeze over at all anymore. These changes in the quality of the sea ice pose a severe hazard to community members, demonstrated by the fact that several snowmobiles have broken through the ice in recent years. In Pond Inlet, Kimmirut and Cape Dorset, the ice has been described as ‘softer’, ‘powdery’ and ‘less flexible’ in recent years. The majority of communities in Nunavut have expressed that the sea ice is more hazardous compared to in the past, being thinner, less sturdy and increasingly dangerous.

The information collated here is from the Nunavut Coastal Resource Inventory: www.gov.nu.ca/environment/information/nunavut-coastal-resource-inventory

## 4.2 Overview of Nutrients, the Building Blocks for Ecosystem Productivity

Nutrients such as nitrogen and phosphorous are the fundamental building blocks of life. Their availability determines the overall biological productivity of seasonally ice-free areas in the Canadian Arctic (Tremblay and Gagnon 2009). While nitrogen and phosphorous are required by all algae, a specific group of algae typically associated with productive food webs, the diatoms, also require silicon to build their outer shell. Using light as an energy source, microscopic algae in the water column and sea ice assimilate nutrients and carbon to grow and produce the organic matter that sustains the food web.

Surface waters of the Canadian Arctic are affected by a chronic and severe deficiency in nitrogen with respect to other nutrients (Tremblay et al. 2015). The underlying causes of this imbalance in the nutrient mix are remote and thus treated in Section 6. Another major factor explaining the relatively low availability of nitrogen and to a lesser extent other nutrients in surface waters is the strong vertical stratification driven by the presence of low salinity water on top of relatively salty deep waters (Section 4.1.3). This layering stabilizes the water column and opposes the mixing needed to bring nutrient-rich waters from the subsurface into the sunlit layer (Figure 23).

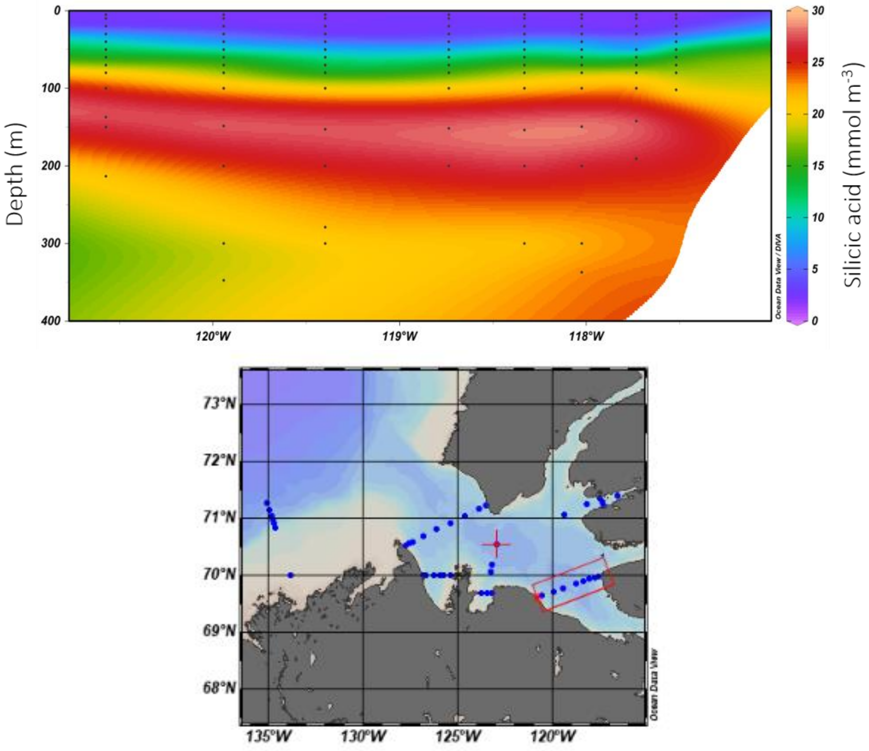


**Figure 23**. Distribution of silicic acid, an essential nutrient for diatom growth, along a cross-shelf transect in Dolphin and Union Strait (red box in insert), in the Beaufort Sea at the end the summer 2017. The high concentrations of silicic acid at mid-depth indicate the presence of Pacific Waters and the low concentrations at surface indicate depletion from phytoplankton uptake. Transect location is the red box in inset (source: C. Michel, unpublished data).

Because primary producers require light to produce organic matter, they are constrained to the euphotic zone (approximately top 100 m) where the penetration of sunlight is sufficient to support net growth. This constraint partly isolates the algae from the deep nutrient reservoir and generally maintains low levels of productivity across the Canadian Arctic (Tremblay et al. 2012). Time-series of observations in the coastal Beaufort Sea and in northern Baffin Bay revealed that net primary production is affected by changes in stratification and that the response can be positive or negative depending on regional settings (Bergeron and Tremblay 2014; Blais et al. 2017) (Section 5.0, Case Study 8).

The disconnect between light and nutrients also favors the establishment of subsurface layers of maximum phytoplankton biomass that contribute substantially to annual primary production (Martin et al. 2010, 2012, 2013). Incidentally, these structures pose a particular challenge when attempting to estimate productivity and its temporal change from space, since satellites do not "see" the subsurface maximum of algal biomass. The productivity of these layers is also susceptible to the depth at which the stratification (or the halocline) begins. Where the halocline is relatively deep, light penetration may be insufficient to support significant algal growth (McLaughlin and Carmack 2010). Conversely, the halocline and the nutrients it contains upwell at the edge of shallow continental shelves, supporting high productivity in the euphotic zone (Tremblay et al. 2014). The halocline is particularly rich in nutrients and especially silicate (Figure 23), to the extent that concentrations in the 75–200 m depth range are much higher than those observed below in the underlying Atlantic layer or anywhere in the water column in the Atlantic sector of the Arctic. This unique feature is tied to the strong connection between the Canadian Arctic and the Pacific Ocean, which is explored in more detail in Section 6. Changes in the remote processes that fuel this subsurface nutrient maximum as well as in the local or regional forcings affecting the position of its upper edge could potentially have strong repercussions on biological productivity.

Warming and recent increases in the freshwater content of surface waters in Hudson Bay (J. Ehn, unpublished data) and in the the Beaufort Gyre of the Canada Basin (Wang et al. 2018) presumably have a negative impact on vertical nutrient supply by strengthening the stability of the upper water column, whereas upwelling, storm-driven mixing events and shelfbreaks, may increase nutrient availability at specific places and times in the Canadian Arctic region (e.g., Mundy et al. 2009; Tremblay et al. 2011, 2014, 2015). The physical impact of ice loss on upward nutrient supply, is also subject to uncertainties, since it may enhance or mitigate upwelling and mixing depending on conditions. Models addressing nutrient supply in the Arctic Ocean struggle to capture the interplay between freshwater loading, horizontal nutrient supply and the impact of changing ice and atmospheric conditions on the average and episodic components of vertical nutrient supply.

On the Canadian Beaufort Shelf, episodic increases in upward nutrient supply and biological production have been caused by the positive impact of easterly winds on upwelling (Mundy et al. 2009; Tremblay et al. 2011; Kirillov et al. 2016) and on reductions in regional ice cover. By contrast, a decline in the nutrient concentration of surface waters offshore in the central Beaufort Sea has been observed (Li et al. 2009) and is predicted by some numerical models (Vancoppenolle et al. 2013), leading to a shift away from diatoms and toward smaller-sized phytoplankton (Li et al. 2009) that is consistent with greater stratification (Peralta-Ferriz and Woodgate 2015). In this setting, previously overlooked nitrogen inputs such as bacterial nitrogen fixation (Blais et al. 2012; Sipler et al. 2017) and atmospheric deposition may play an increasingly important role in supporting very modest primary production in surface waters.

## 4.3 Overview of Arctic Food Webs

Food webs illustrate the flow of energy and matter within a system. They are often compartmentalized by trophic levels, identifying pathways by which matter and energy are used, modified and recycled (Figure 24). As in any food web, the highest biomass of organisms in Arctic marine food webs is represented by small, often unobserved, single-celled species. For example, on the Mackenzie shelf the biomass of phytoplankton >5 µm in size is estimated to be 2.5 g m$^2$, whereas beluga biomass is 0.03 g m$^2$ (C. Hoover, unpublished data). The smallest organisms function within the microbial food web (Figure 25), carrying out essential transformations of carbon and other nutrients. Phytoplankton is a key pathway out of the microbial loop (Figure 25) and is essential for sustaining Arctic food webs. Because they have short generation times (i.e., reproduce or replicate within days), organisms within the microbial food web respond rapidly to the environment and are consequently an early indicator of change that may carry through multiple trophic levels.

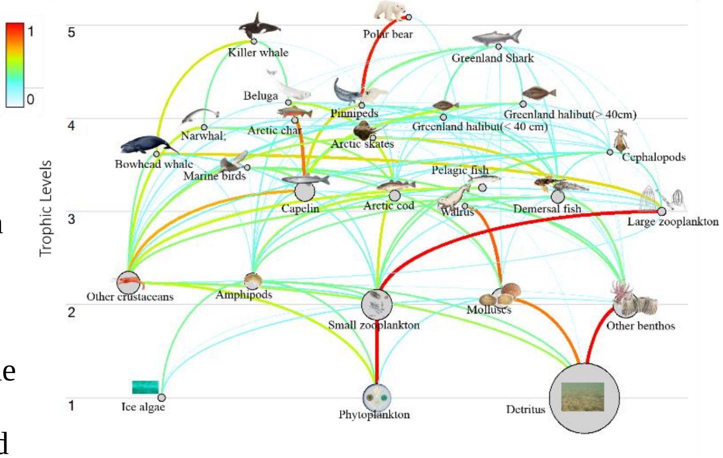


**Figure 24**. Ecopath flow diagram of Cumberland sound ecosystem model. The size of nodes (circles) show the relative biomass and size and color of connecting lines shows the strength of trophic flows between functional groups (Image provided by Y. Janjua).

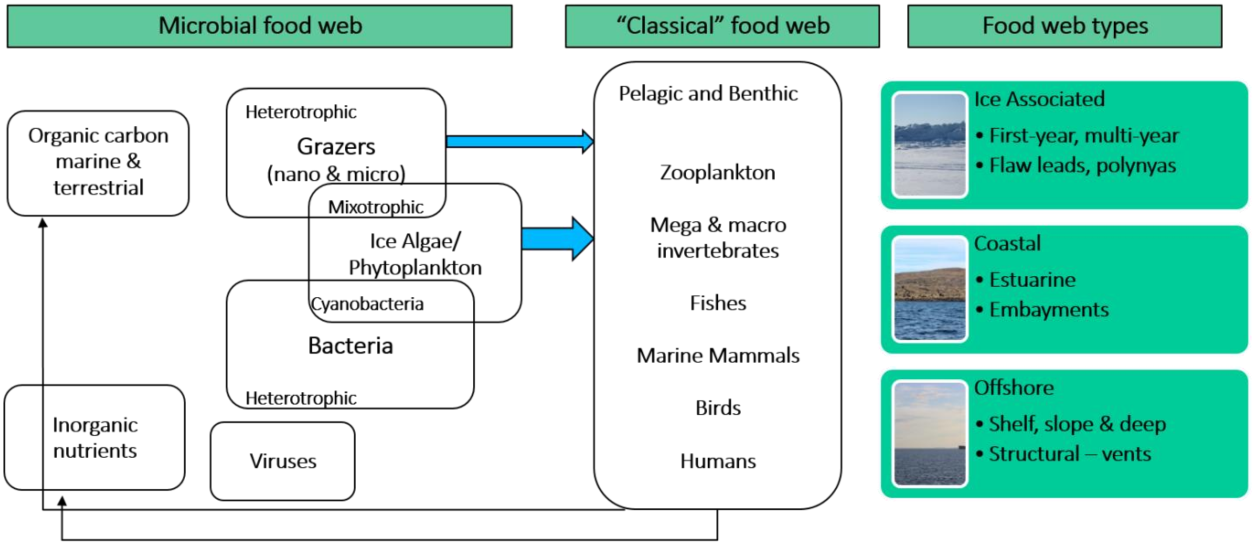


**Figure 25**. Overview of the microbial and classical food webs that function in different types of Arctic food webs. Connections between the microbial and classical food web are shown.

Inuit knowledge provides information on classical food webs as they encompass economic, subsistence and culturally relevant species (Watt et al. 2016; Loseto et al. 2018a; Stasko et al. 2018; Yurkowski et al. 2018). Key species for the transfer of energy to Arctic fishes and marine mammals include *Calanus* copepods and Arctic Cod (Majewski et al. 2015; Smoot and Hopcroft 2017). Despite commonality of key species, food webs are not uniform across the Canadian Arctic region as species composition and linkages can vary based on area (i.e., western or eastern Arctic), habitat type (next section), depth (e.g., shelf or offshore basin), and physical processes (e.g., polynyas, Case Study 8). There have already been trophic shifts in food webs (Case Studies 6 and 7) related to dynamic environmental changes and research continues to better understand how the presence of new species or expanding ranges (Case Study 14) will affect food webs in the Canadian Arctic region. Recent studies have also documented that key species can rely on more than one food web (e.g., Greenland Halibut, Giraldo et al. 2018; polar bears, Brown et al. TA 2018). Therefore, understanding key linkages within and among food webs is critical for managing the Canadian Arctic region at a species and ecosystem level. It should also be noted that in many regions of the Canadian Arctic, food web structure and function remains largely unknown.

## CASE STUDY 6: Changing Food Webs in Cumberland Sound

Opportunistic predators, such as beluga whales (*Delphinapterus leucas*), ringed seals (*Pusa hispida*), Greenland Halibut (*Reinhardtius hippoglossoides*), and Arctic Char (*Salvelinus alpinus*) consume a wide variety of fish and invertebrate species. Therefore, their diets can reflect changing species assemblages lower in the food web (Lowry et al. 1980; Bowering and Lilly 1982; Dempson et al. 2002; Loseto et al. 2009; Giraldo et al. 2018). In Cumberland Sound, Nunavut, recent increases in the availability of Capelin (*Mallotus villosus*) is changing the selection of prey by important marine predators.

Stable isotopes ($\delta^{13}$C and $\delta\,^{15}$N), chemical tracers that provide time-integrated information on habitat use and diet, have revealed diet changes for a marine predator assemblage consisting of beluga whales, ringed seals, Greenland Halibut and Arctic Char over a 22-year period (1990 to 2012). Specifically, a decreasing temporal trend in both $\delta^{13}$C and $\delta\,^{15}$N of beluga whales has occurred, indicating a shift to consuming more pelagic/phytoplanktonic-associated and lower trophic level prey (Marcoux et al. 2012). Bayesian mixing model analysis revealed an increase in the consumption of forage fish by beluga whales with a concomitant decline in consumption of Greenland Halibut (Yurkowski et al. 2017, 2018) (Figure 26). In turn, the proportion of Greenland Halibut in beluga whale diet has decreased, which in theory, could correspond to decreased stability in the Cumberland Sound food web (Yurkowski et al. 2017). Moreover, consumption of forage fish also increased over

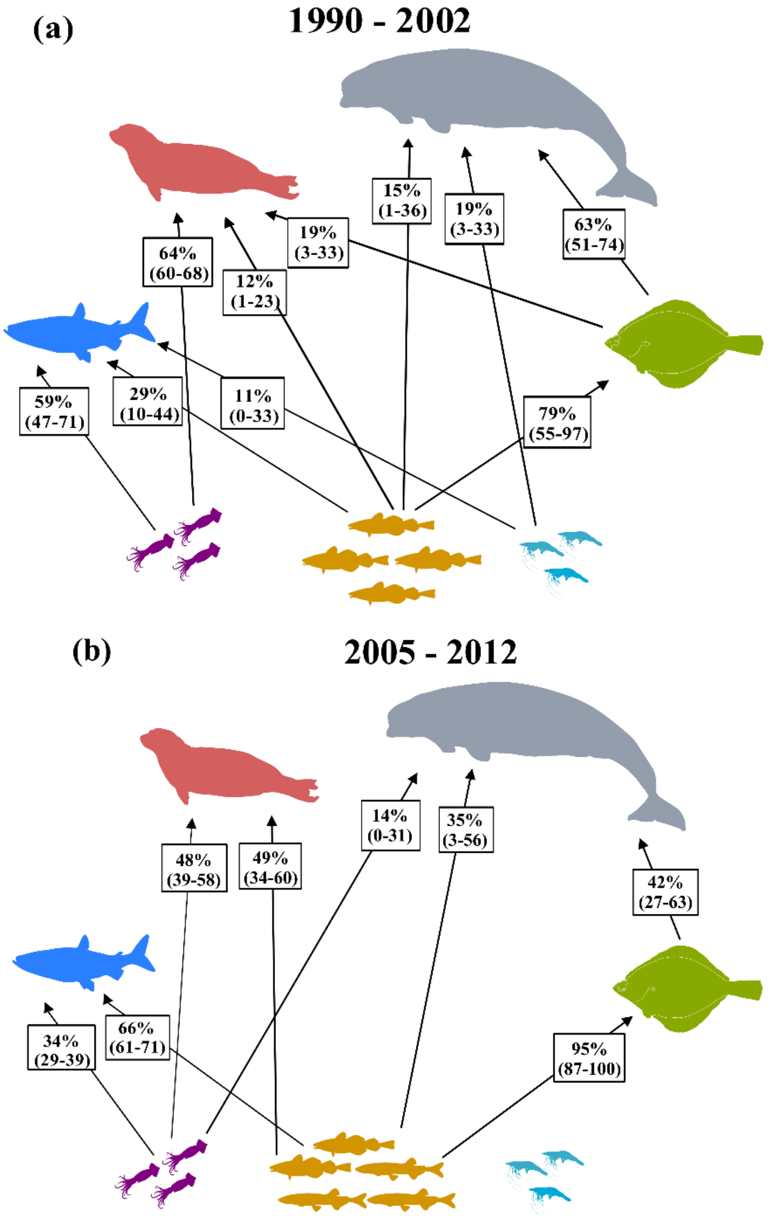


**Figure 26**. Feeding relationships of beluga whales (grey), ringed seals (pink), Greenland Halibut (green) and Arctic Char (blue) in Cumberland Sound, determined by stable isotope mixing models. Prey species are squid (purple), shrimp (blue) and forage fish (yellow, Arctic Cod during 1990-2002 and Arctic Cod/Capelin during 2005-2012) (source: Yurkowski et al. 2018).

time for ringed seals, Greenland Halibut and Arctic Char, suggesting diet flexibility among these predators and climate-driven food web changes associated with the increasing availability of Capelin (Yurkowski et al. 2018, Figure 27). With the observed changes in diets, the predator assemblage in Cumberland Sound now plays a similar food-web role, consuming only pelagic-based resources, rather than a mixture of benthic and pelagic prey (Yurkowski et al. 2018). Furthermore, the summertime Cumberland Sound food web is quickly transitioning from a sympagic (ice-associated) carbon-associated system to a more phytoplankton carbon-associated system (Brown TA et al. 2014a, 2017a). This transitioning along with its associated food web re-structuring will persist and probably intensify in the future as sea-ice coverage continues to decline, leading to continued change in the structure, function and resilience of the Cumberland Sound ecosystem.

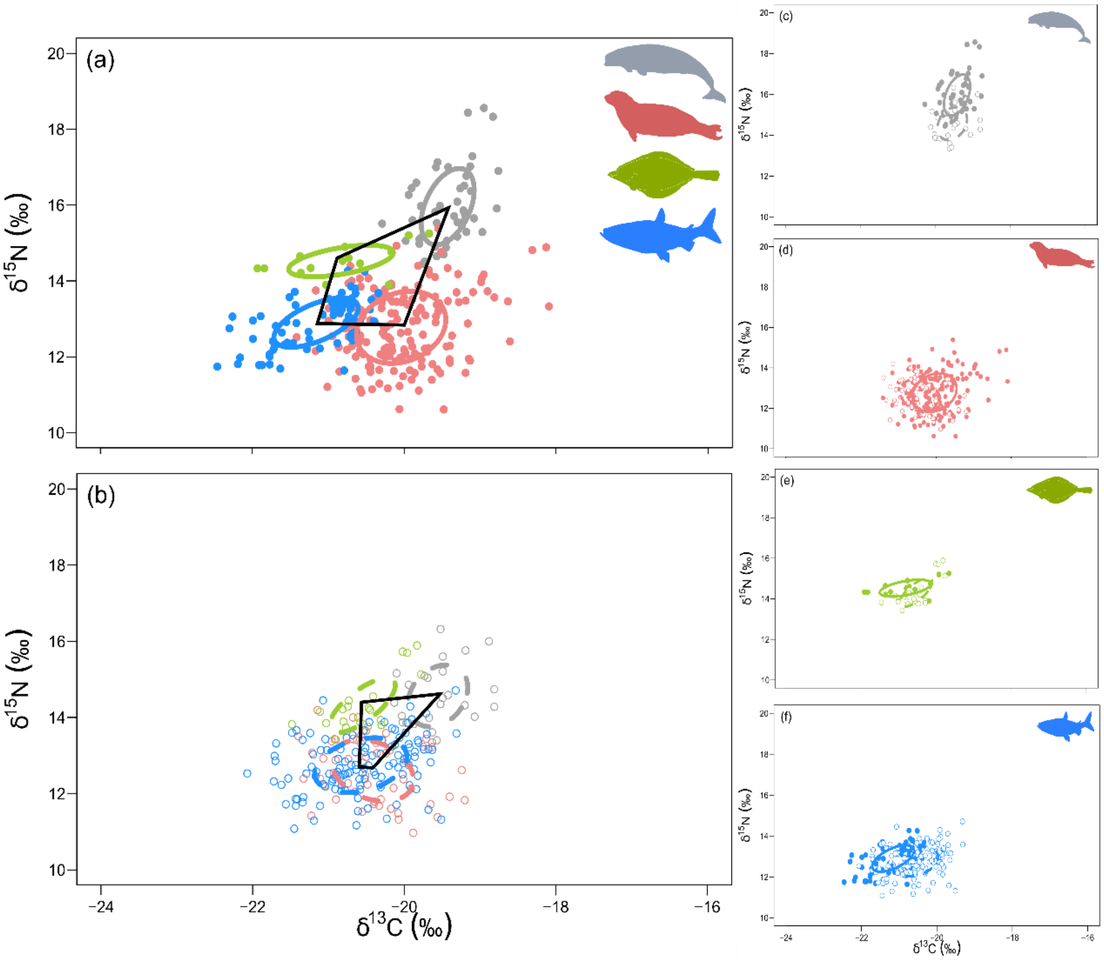


**Figure 27**. Isotopic niche sizes of beluga, ringed seals, Greenland Halibut and Arctic Char during 1990-2002 (solid lines; (a)) and 2005-2012 (dashed lines; (b)). Solid black line represents the community metric of total area. Panels (c), (d), (e) and (f) represent isotopic niche shifts for each predator between both time periods. Symbols and ellipses are colour-coded by species similar to Figure 26 (source: Yurkowski et al. 2018).

## CASE STUDY 7: The Changing Sea Ice Ecosystem

There are two main types of sea ice in the Arctic Ocean. First-year ice, defined as sea ice that goes through a complete annual cycle of growth and melt, is the dominant ice type on Canadian Arctic shelves. Multiyear ice that undergoes repeated cycles of growth and melt, surviving at least two summer melt periods, is typically found over the central Arctic basins and on the northern and western parts of the Canadian Polar Shelf. This is changing. The accelerated loss of sea ice, both in terms of sea-ice extent and duration, and the rapid decline of multiyear ice are dramatically reshaping the Arctic Ocean and its food webs. Loss of the perennial ice cover is shifting Arctic sea-ice conditions towards a seasonal ice cover. This is consequential for ice-associated marine mammals such as seals and polar bears (*Ursus maritimus*) that use the stable and reliable multiyear ice platform for resting, feeding and birthing. Multiyear ice also provides a more stable environment than first-year ice for the growth of ice algae, with potential consequences for the biodiversity and the vulnerability of ice algal production to on-going climate change (Lange et al. 2019). Our current knowledge of biological processes associated with Arctic multiyear ice is limited, both temporally and spatially, and is largely biased towards accessible ice types. This leads to potential underestimations of the overall productivity of the multiyear-ice ecosystem, as suggested by the recent evidence that, thick hummocks may be more productive than generally assumed (Lange et al. 2017). Major knowledge gaps still remain regarding the role of sea ice, in particular that of multiyear ice, on the diversity, productivity and food web transfers in the marine Arctic. There is a pressing need for repeated observational measurements of physical, biochemical and ecological processes associated with the sea-ice ecosystem, throughout the annual cycle.

The northern part of the Canadian Polar Shelf, north of Ellesmere Island, and adjacent waters of the Arctic Ocean between northern Greenland and M’Clure Strait, is the only region expected to retain old multiyear ice in the Arctic Ocean. In an otherwise ice-free Arctic Ocean in summer, this region will constitute a refuge for ice-associated species and for unique biodiversity, requiring a better understanding of the structure and function of its ecosystem and the monitoring of on-going changes. DFO’s Multidisciplinary Arctic Program (MAP) – Last Ice explores the productivity and biodiversity of the multiyear ice habitat and its connectivity to the marine food web, as well as, to upstream (Beaufort) and downstream (Baffin Bay) ecosystems. Early and unexpected findings from MAP – Last Ice include an abundance of benthos, indicating significant productivity export to the ocean floor, and the presence of walruses near the northernmost tip of Ellesmere Island, documenting an extension of their known distribution range in western Baffin Bay (Yurkowski et al. 2019a).

Concomitant with the replacement of multiyear by first-year ice, the Arctic is also experiencing a shift towards longer open-water seasons and open areas in regions that were previously ice covered. Seasonal sea ice is extending from the continental shelves towards the central basins. These new dynamics cause dramatic alterations in the structure and functioning of the marine ecosystem, which is transitioning from ice-associated to open-water marine food webs. In the changing Arctic cryosphere, increased melt pond cover also modifies light transmission through the sea-ice, allowing more light to reach the water column and favouring the development of under ice blooms (Horvat et al. 2017). Changes in primary producer communities have wide-ranging implications, many yet to be understood, for the productivity and food web transfers that support Arctic marine resources.

There is now clear evidence demonstrating the fundamental role of ice-associated production (ice algae) in Arctic pelagic and benthic food webs, including in the Canadian Arctic region (Brown TA et al. 2014a, 2014b, 2017a, 2017b; Roy et al. 2015a). Biomarker studies using fatty acids and ice-specific highly-branched isoprenoids, following from the precursor work of Belt et al. (2007) and Søreide et al. (2010), demonstrate the importance of spring sea-ice production for benthic species in Eclipse Sound (D. Kohlbach, unpublished data), and for ringed seals (*Pusa hispida*) and beluga whales (*Delphinapterus leucas*) in Cumberland Sound (Brown TA et al. 2014b, 2017a). The dependence of important traditional harvest species on sea-ice algal production in the Arctic Ocean (Kohlbach et al. 2016) (Figure 28) and in the Canadian Arctic region raises important questions with regards to the sustainability of marine food webs under reduced ice cover.

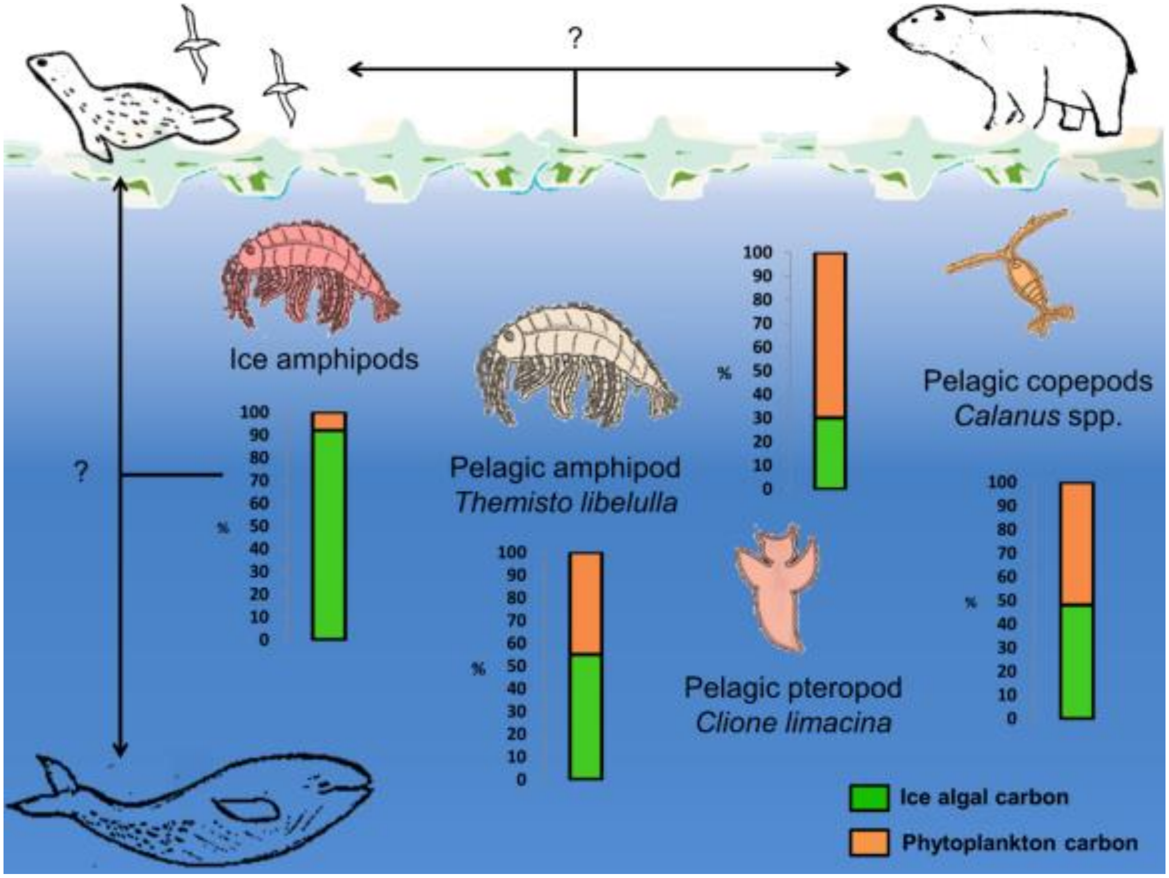


**Figure 28.** Proportional contribution of ice alga- and phytoplankton-produced carbon to the carbon budget of under-ice fauna species in the central Arctic Ocean during late summer. Relative proportions are derived from bulk- and compound-specific stable isotope analysis of fatty acid markers (source: Kohlbach et al. 2016).

## 4.4 Habitat Linkages

This section provides current knowledge and trends for how Arctic marine life is associated with different habitats. Key marine habitats include the benthos (ocean floor), sea ice of different kinds, and the highly dynamic water column itself. These habitats can vary between coastal, shelf, and deeper slope/basin areas. The following sections and Case Studies identify species responses to changing habitats and explain how one habitat can affect the structure and functioning of another habitat.

### 4.4.1. Sea Ice

Sea ice is both a structuring element and a unique habitat, central to the diversity and productivity of Arctic marine ecosystems (Michel 2013; Bluhm et al. 2017). The unique and wide ranging physicochemical conditions in sea ice create a variety of habitats for over 2000 species of small plants and animals associated with the sea ice. As a platform, it is essential habitat for large organisms, including polar bears and seals (Case Studies 4 and 9, Appendix A). Sea ice is also a critical travel link and harvesting platform and, as such, is integral to the lives and livelihoods of Inuit living in the Canadian Arctic (i.e., Inuit Nunangat) (Archer et al. 2017; Ford et al. 2017; Fawcett et al. 2018) (Case Study 5).

The different sea-ice habitats vary in space and time. Small species inhabit the brine channel network within the sea-ice melt ponds that form at the ice surface, and the undersurface of the ice at the ice-water interface. Spatial scales range from the sub-micrometer scale relevant to brine channels to meters and kilometers for snow drift patterns and leads. Temporal scales range from minutes to hours relevant to mixing, day to seasons for solar conditions, and years to decades for climatic and basin-wide oceanographic forcings. The productive microbial communities found in the sea ice are critical to Arctic marine food webs and higher trophic levels.

Sea-ice primary production comprises a strong element of seasonality as photosynthetic activity depends on the return of sunlight during the Arctic spring after the dark winter period (Section 4.5). In the Canadian Arctic, the ecology and production dynamics in sea ice have been primarily studied in landfast sea ice (e.g., Galindo et al. 2015, 2017; Campbell et al. 2016, 2017) and, to a lesser extent, in pack ice (e.g., Piwosz et al. 2013; Poulin et al. 2014; Niemi and Michel 2015; Aslam et al. 2016).

Ice algal species are adapted to the light and nutrient conditions of the sea-ice environment. Pennate diatoms largely dominate landfast sea-ice communities in the Canadian Arctic during spring although other groups may dominate under particular conditions (e.g., Campbell et al. 2016). The widespread chain-forming diatom *Nitzschia frigida*, typically the dominant species during the productive spring ice-algal bloom, is considered a sentinel species for seasonal Arctic sea ice (Różańska et al. 2009). Large accumulations of the diatom species *Melosira arctica* are also observed throughout the Arctic (Figure 29). This species forms meter long strands that attach to the undersurface of the ice. The contribution of *M. arctica* colonies to Arctic production is not well understood due, in part, to its high patchiness. Recent studies show that this ice-algal species can be highly productive and that fresh aggregates can sink to depth in the central Arctic basins, providing a food source for benthic organisms (Boetius et al. 2013). *M. arctica* colonies have been observed in the Canadian Archipelago, however, the factors determining its occurrence and abundance have not yet been elucidated (Poulin et al. 2014).

Differences in species composition exist between the various sea-ice habitats (Deming 2007; Bowman et al. 2012). Important differences between first-year and multiyear ice are linked to selective pressure during repeated melt-refreeze cycles. The habitability of brine channel space, which depends on sea-ice temperature and salinity, is also considered a key factor for differences between old multiyear ice layers and first-year ice. Multiyear sea ice is considered a repository for biodiversity, supported by evidence of diverse microbial communities in different ice layers and with respect to microbial diversity not observed in first-year ice (Bowman et al. 2012; Hatam et al. 2014). By providing a relatively stable habitat over multiple years, multiyear ice can sustain biodiversity through years of succession, whereas the diversity associated with first-year ice depends on the species present in the water at the time of ice formation (Niemi et al. 2011). In addition, the high spatial heterogeneity in multiyear ice environments, from thick hummocks to refrozen leads, provides a diversity of habitats for under-ice fauna. There is recent evidence of a reduction of ice-associated amphipod species due to the dramatic change from multiyear to first-year ice near the North Pole (Melnikov et al. 2017).

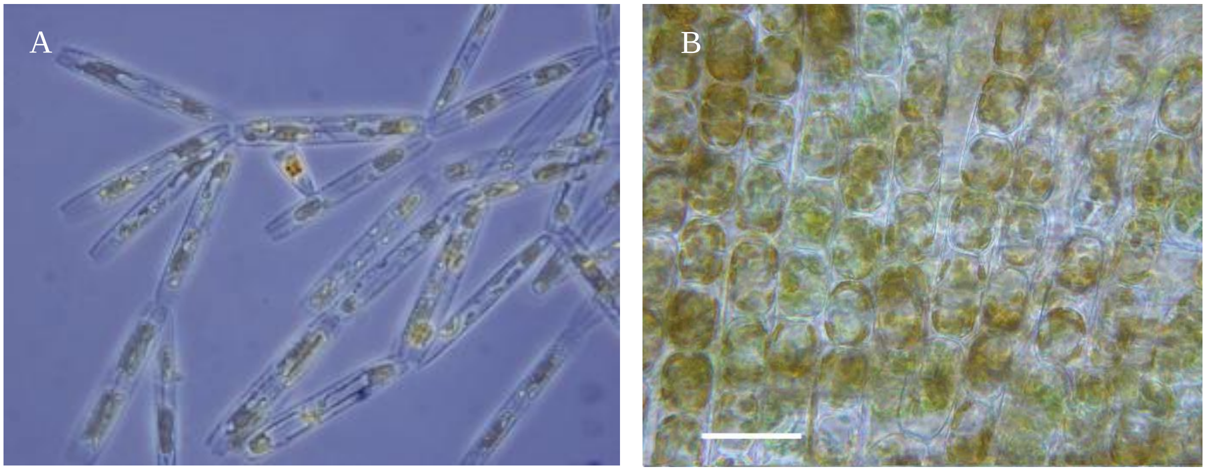


**Figure 29**. Microscopic images of arborescent colonies of the pennate diatom *Nitzschia frigida* (a) and the centric diatom *Melosira arctica* (b) (photo credit: Michel Poulin). Samples collected during DFO sea-ice program BIOTA (Biological Impacts of Trends in the Arctic) and Canadian Arctic Archipelago studies (C. Michel, Program Lead).

Overall, the contribution of ice algae to total primary production (ice + water column) is not necessarily proportional to their importance for pelagic and benthic food webs, especially on continental shelves where phytoplankton production can account for the bulk of primary production. This is because, 1) ice algae provide a seasonally early, abundant, and localized food source utilized by pelagic grazers, 2) ice algae provide essential fatty acids for the reproductive success of pivotal zooplankton species, and 3) ice algae are large cells, also forming aggregates, favouring rapid sinking to the seafloor where they provide a fresh food source for benthic species, as observed on the Canadian Beaufort shelf and in the eastern Archipelago (Renaud et al. 2007; D. Kohlbach, unpublished data).

As a structural element, sea ice affects access, both the timing and spatial extent, to other habitats such as the seafloor. This interaction between habitats has been changing in recent decades and can have profound impacts not only on ecosystems as a whole, but also at the species and even individual levels through its effects on resource distribution and availability, with downstream consequences for reproduction and population viability. Sea ice can play an important role in driving reproduction in marine-living bird species by impacting habitat availability, and importantly resource availability.

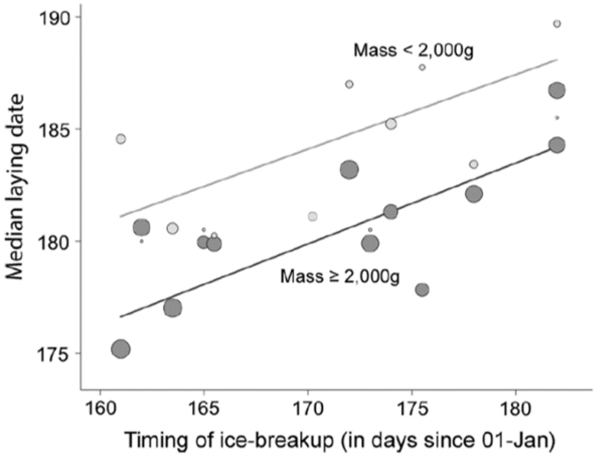


**Figure 30**. Median lay date of common eider females in response to timing of ice break up, split by body condition at arrival (source: Jean-Gagnon et al. 2018. Reprinted with permission from Springer Publishing).

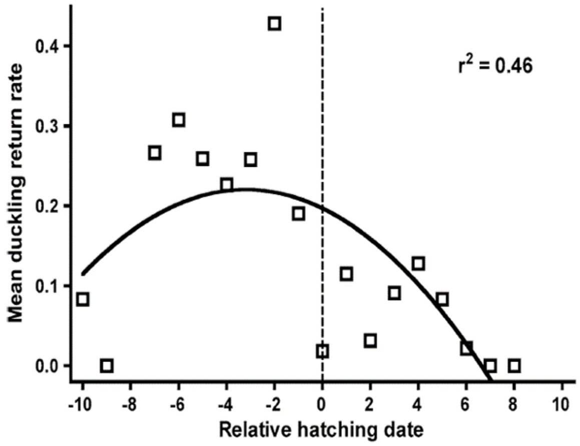


**Figure 31.** Average probability of female common eider ducklings returning to the breeding colony as adults in relation to their relative hatching date within a given year, where relative hatch date 0 = ice-free conditions (source: Love et al. 2010. Reprinted with permission from Springer

Common eiders are a species of seaduck that forages on benthic marine invertebrates (e.g., mussels, urchins), some fish species, and copepods in marine environments. After arriving on the breeding grounds, females must forage intensively to accumulate a significant amount of fat stores prior to initiating reproduction to form their eggs and to successfully complete their 24-day incubation period during which they fast. Therefore sea ice can often limit or constrain the ability of females to reproduce, especially if they arrive in already poor body condition.

Research at the nesting colony of common eiders at East Bay in the Eastern Canadian Arctic has shown that in years of later ice-breakup, fewer females are likely to breed and overall, females lay their clutches later (Jean-Gagnon et al. 2018). Additionally, females arriving in poor body condition (less than 2000 g) are more strongly affected by a late ice-breakup than are females that arrive in good body condition (2000 g or heavier), presumably because it is more challenging for them to forage enough to get into reproductive condition. These results (Figure 30) demonstrate the importance of not only arrival body condition, but also sea ice in driving the timing of reproduction, with consequences for reproductive success and output in common eiders (Love et al. 2010; Descamps et al. 2011).

Sea ice also has effects on common eider reproductive output later in the breeding season. Females that time the hatching of their ducklings just prior to ice free-conditions in East Bay have the highest recruitment of those ducklings back into the population (Love et al. 2010) (Figure 31). Within days of the eggs hatching, females escort their ducklings to the ocean to begin feeding on their own on small invertebrates in shallow waters. With less sea ice in the bay, and more available foraging habitat for the ducklings, they are able to begin foraging and preparing for the upcoming winter immediately, increasing their probability of survival.

Sea ice can have significant effects on marine birds at multiple life history stages and can affect individuals in different ways. The cumulative effects of 1) changes in ice cover and 2) individual abilities to best time their reproduction, can lead to broader scale effects on the recruitment of ducklings. Such effects on recruitment may affect the persistence of the population itself.

### 4.4.2 Under-Ice

Owing to the strong light attenuation of the snow-ice cover, as well as light absorption by ice algae, the classic view is that little primary production takes place under the ice in ice-covered Arctic regions. There are early reports of under-ice phytoplankton blooms in Hudson Bay, the Canadian Arctic Archipelago, and the Beaufort Sea (Michel et al. 1993; Fortier et al. 2002; Mundy et al. 2009). However, it is the recent evidence of a massive under-ice phytoplankton bloom in the Chukchi Sea (Arrigo et al. 2012, 2014; Palmer et al. 2014) that has challenged our current understanding of phytoplankton production in the Arctic. It is likely that under-ice phytoplankton blooms are more frequent than previously assumed, especially in the context of the changing climatic and sea-ice conditions (Fortier et al. 2002; Mundy et al. 2014).

A recent modelling study showed a rapid increase in the likelihood and extent of conditions suitable for under-ice phytoplankton blooms over the past two decades (Figure 32). Currently, as much as 30% of the Arctic Ocean is considered suitable for under-ice phytoplankton blooms in July (Horvat et al. 2017). This estimate suggests that major ecological shifts in Arctic Ocean primary production could have already taken place, and will continue in coming years as significant thinning of the sea-ice cover and extensive melt ponds allow more light to reach the water column (Horvat et al. 2017).

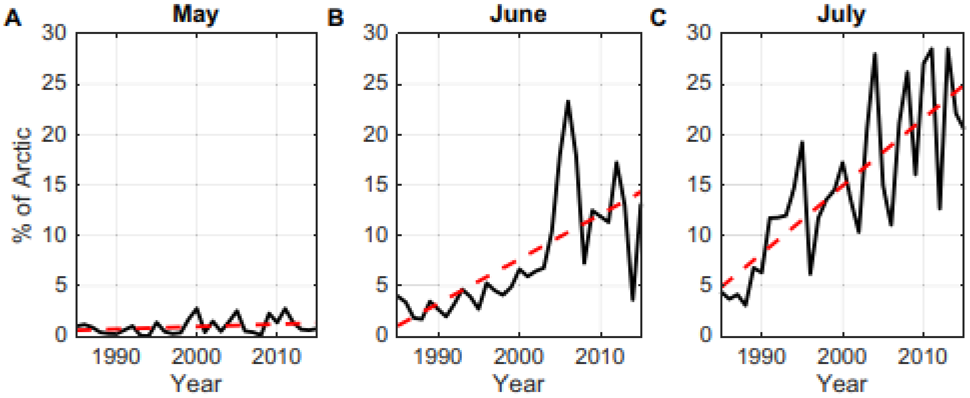


**Figure 32.** Estimates of ice-covered areas of the Arctic Ocean that are suitable for under-ice blooms (source: Horvat et al. 2017).

The bottom of the ice is also a safe haven and feeding location for fishes and invertebrates. Juvenile Arctic Cod are closely associated with the bottom ice during the ice-covered period (Kohlbach et al. 2017) and micro and macro-sized zooplankton (e.g., copepods and amphipods) also utilize this habitat. The underside of the sea ice may function similar to the benthos, except that everything is upside down. It is, however, challenging to access and adequately sample such an environment. As such, direct measurements of the ice-bottom food web are limited and recent trends for ice-bottom communities as a whole are not currently available.

### 4.4.3 Water Column

Arctic phytoplankton communities exhibit high spatial variability linked to gradients of chemical and physical (including ice) conditions from continental shelves to deep basins, and from inflow to outflow shelves (sensu Carmack and Wassmann 2006) (Section 6). The development of phytoplankton blooms is also tightly linked to seasonality as the dark winter period precludes photosynthetic activity (Section 4.5). However, as soon as there is sufficient light reaching the ocean surface in February and March, small phytoplankton cells, especially *Micromonas spp.*, form the base of a late winter food web (Pedrós-Alió et al. 2015).

Nutrient-rich Arctic shelves are typically more productive than are deep basins. In productive regions of the Canadian Arctic, phytoplankton production is dominated by large cells such as centric diatoms of genera *Chaetoceros* and *Thalassiosira*, and pennate diatoms groups such as *Cylindrotheca* and *Fragilariopsis* (Ardyna et al. 2011). Dinoflagellates and haptophytes often dominate the parts of the Arctic Ocean influenced by North Atlantic waters (Poulin et al. 2011). Recently the haptophyte *Phaeocystis* was found to dominate the phytoplankton bloom observed during the Green Edge project (http://www.greenedgeproject.info) in Baffin Bay. In contrast, primary productivity over the deep basins is often limited by nutrients and light as strong surface stratification isolates the surface layer from nutrient-rich deep waters and variable ice cover influences light conditions. As a consequence, oligotrophic conditions tend to prevail offshore, favouring small-sized phytoplankton such as the prasinophytes *Micromonas* sp. (Zhang et al. 2015).

On Canadian shelves, primary producers are influenced by oceanographic conditions which are linked to local and regional influences from water mass distribution, mixing and upwelling, combined with climatic influences and coastal-ocean interactions in the nearshore. These processes and the evolving role of sea ice in the changing Arctic ecosystem are discussed in other Sections.

Oceanographic conditions also influence the distribution of zooplankton within the water column. The vertical distribution of zooplankton species is influenced by water temperature and salinity in both the Canadian Beaufort Sea and Baffin Bay (Kjellerup et al. 2015; Smoot and Hopcroft 2017), with distinct community assemblages in different water masses. Zooplankton community assemblages in the Canadian Arctic also vary among habitat types, with different communities documented for Beaufort shelf and off-shelf habitats (Darnis et al. 2008), and across geographical regions (i.e., Labrador Sea to eastern Canadian Arctic Archipelago, Pomerleau et al. 2011). Some but not all copepod zooplankton species (e.g., *Metridia longa* in Baffin Bay, Kjellerup et al. 2015) have been documented to undergo diel vertical migrations in the Canadian Arctic. These daily migrations involve upward movements at night to feed with a return to depth during the day to avoid visual predators including marine birds and fishes. This movement can be important for energy transfer within the water column and to higher trophic levels.

Water column habitats available to Arctic fishes vary substantively with respect to salinity and temperature (i.e., highly variable with large ranges closer to shore and less so away from shore lines), key factors that affect occupancy by different species and thus local diversity. Spatial habitats are linked with depth-related zones including sea ice (surface), water column (pelagic) with varying sub-divisions by depth, and bottom (benthic) areas with varying substrate types. Fish associations with benthic habitats may also include general bottom association in the lower water column (epibenthic), direct association on the bottom (benthic) or within the substrate in some cases (infaunal) (e.g., some eelpouts in soft bottoms, wolffishes in crevices in hard bottom). There are also longitudinal and latitudinal spatial variations in habitats which, with historical factors such as colonization sources, routes and timing, have determined to a great degree the present diversity in marine fishes (Coad and Reist 2018).

The vast majority of Arctic marine fish species are benthic in general habitat usage as larger juveniles and adults (although several have pelagic eggs and larval forms) (Chernova 2011; Christiansen and Reist 2013; Coad and Reist 2018). Relatively few species use pelagic habitats primarily and, if so, tend to use upper pelagic waters. Fishes primarily associated with pelagic habitats include many anadromous species, particularly the salmonids (e.g., chars, ciscoes), as well as the clupeids (herrings). These generalizations are somewhat artificial, thus exceptions occur. For example, Greenland Halibut are generally assumed to be benthic in association, however, they feed off the bottom in the lower to mid-water areas of the water column as well (Giraldo et al. 2018). Arctic Cod are generally assumed to be closely associated with sea ice, however, they often form large pelagic schools, aggregations in mid-depths of the water column, and epibenthic associations.

In the Beaufort Sea, the diversity, distributions, and habitat associations of offshore fishes was surveyed as the Marine Fishes Project by DFO between 2012 and 2014, in partnership with Inuvialuit and the federally administered Beaufort Regional Environmental Assessment (BREA-MFP) (Majewski et al. 2016). Benthic trawl surveys conducted between 18-1001 m depths on the Canadian Beaufort Shelf and slope collected 34 species, accounting for approximately 44% (34/77) of the marine and anadromous fish species present in the Inuvialuit Settlement Region. The BREA-MFP work is similar to multi-species surveys in the western Beaufort Sea in Alaska where 32 species were recorded between depths of 40 and 470 m on the narrower Alaskan continental shelf and slope (Rand and Logerwell 2010). The majority of species caught during the BREA-MFP were relatively rare, with only eight species contributing >1% to the total abundance-based catch-per-unit-effort.

The habitats of marine fishes can be described by many different variables, including physical, chemical and biological variables. Depth, salinity, temperature, oxygen, suspended chlorophyll, benthic chlorophyll, and sediment grain size were examined singularly and in combination as explanatory variables for observed fish community structure. Fish community structure in the Canadian Beaufort Sea was most strongly correlated with water depth, and assemblages were generally delineated into depth ranges coinciding with distinct water mass habitats as illustrated in Figure 33 (Majewski et al. 2017).

Significant differences in the fish communities from east to west on the continental shelf and slope were not detected, and the species composition of the assemblages on the Canadian Beaufort Shelf (<200 m depth) do not appear to have changed substantially relative to previous work between 2006 and 2009 (Majewski et al. 2013).

These findings point towards a highly structured ecosystem, from the perspective of the fishes, likely in response to differences in the characteristics among the water masses and associated physical drivers. Accordingly, this relationship can be used to predict the potential significance of habitats and communities for conservation and management actions.

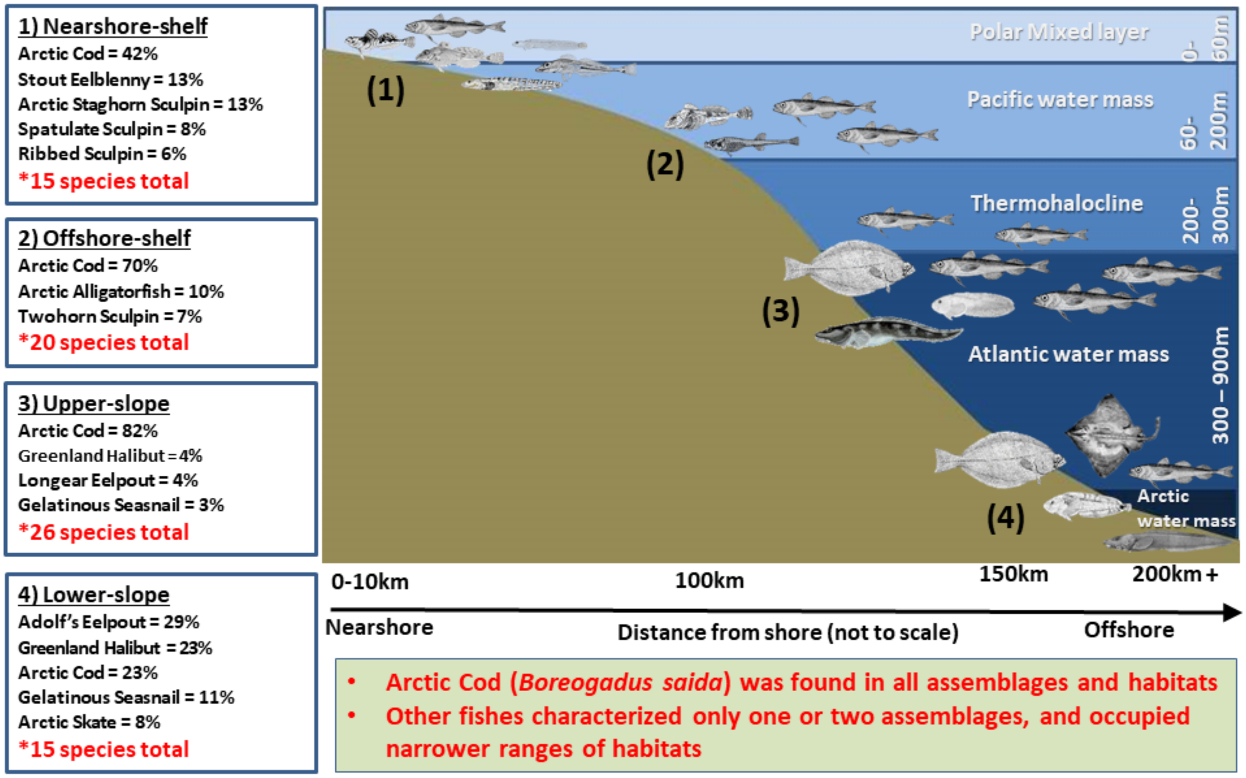


**Figure 33.** Marine fish assemblages and associated water mass habitats on the Canadian Beaufort Shelf and slope. Percent similarity values indicate the relative importance of each species in characterizing an assemblage. See Majewski et al. (2017) for more detail.

### 4.4.4. The Sea Floor

Benthic (sea floor) habitats and biodiversity have been assessed at point locations across the Canadian Arctic region with the highest level of sampling occurring in the Beaufort Sea and Baffin Bay. Few historic research-based studies have been carried out in Baffin Bay (e.g., MacLaren Marex 1978), and if so, they were mostly based on grab sampling. Over the last decade, academic-research-based projects (e.g., Link et al. 2013; Roy et al. 2015b) and programs (e.g., ArcticNet, CHONe) investigated benthos in parts of the region, mostly near the North

Water (Case Study 8). Since 2004-2005, benthic biodiversity and habitat use have been assessed annually by monitoring the by-catch of, 1) the annual multi-species, depth-stratified bottom trawl surveys implemented by DFO for Greenland Halibut stock assessment, and 2) the Northern Shrimp Research Foundation (NSRF) and DFO surveys to monitor northern and striped shrimps (*Pandalus borealis* and *P. montagui*, respectively). These surveys provide distribution and abundance information on invertebrate taxa collected in the trawls at different levels of taxonomic resolution (Siferd 2015). Due to the spatial-temporal extent and annual sampling frequency, the database on invertebrate by-catches compiled from the DFO Central and Arctic Region Multi-Species Stock Assessment Surveys (2004 to present) is the most relevant database to establish a baseline of the current state of benthic species richness, abundance and biomass in the Baffin Bay region, from which to evaluate future trends in response to climate-driven oceanographic changes. In order to eventually attain a more thorough and systematic identification of invertebrate by-catches and to develop regional reference keys, two photo-catalogues are currently in preparation for Baffin Bay and Hudson Strait.

Species richness of mega-epifauna (i.e., large invertebrates living on the seafloor, mostly sampled by trawls) from the databases of DFO Central and Arctic Region Multi-Species Stock Assessment Survey (2004 to 2016) is shown in Figure 34. Due to the few sampled stations for macro-infauna (i.e., invertebrates > 5 mm in size and living mostly in the sediments, sampled mostly by grabs and box corers), no relevant distribution patterns at the scale of Baffin Bay can be made.

Benthic invertebrates inhabit the entire seafloor of Baffin Bay; it is not a desert. All stations sampled in the region collected benthic invertebrates. Richness of benthic invertebrates is dependant on several environmental variables (e.g., depth, substrate) (Roy et al. 2014), but is also dependant on the mesh size of trawls used. It is clear from Figure 34 that the finer mesh size (12.8 mm) of trawls used during the shrimp surveys (Figure 34a) increases the richness of benthic invertebrates that can be caught compared to the trawl (30 mm) used for Greenland Halibut surveys (Figure 34b). Coral and sponge communities are particularly rich and abundant in Baffin Bay compared to the rest of the Canadian Arctic (Kenchington et al. 2011; Roy et al. 2015b), however, extensive studies from other areas are required. The observed benthos biodiversity is typically Arctic-Atlantic and highly comparable to other Arctic-Atlantic seafloors. However, fewer boreal representatives are found in the cold Canadian Western Baffin Bay than in warmer Arctic-Atlantic regions, such as in Southwestern Greenland, Iceland and the Barents Sea (Jørgensen et al. 2017).

The assumption of decreasing food supply, benthic biomass and density with depth is not necessarily straightforward for the entire Canadian Arctic region, nor for the deep Baffin Bay. Some areas harbouring productive surface waters and strong pelagic-benthic coupling, such as in the North Water and in the outflow of Lancaster Sound, can support rich and abundant benthic communities even at depths > 500 m (Roy et al. 2014).

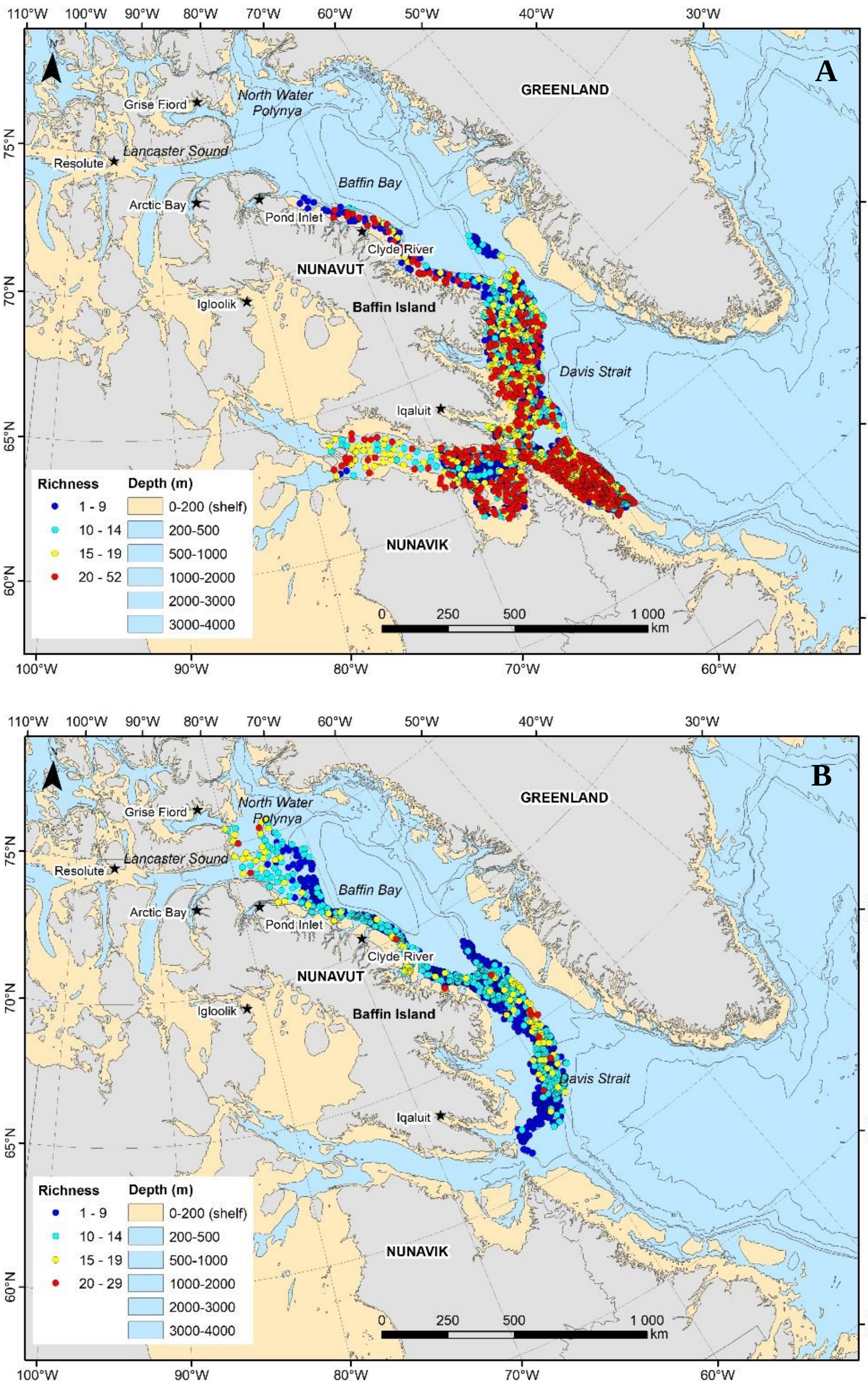


**Figure 34**. (a) Mega-epifaunal richness associated to NSRF-DFO Shrimp surveys using Campelen (12.8 mm) and Cosmos trawls (12.8 mm) (2572 stations from 2005 to 2016; 100-900 m); (b) Mega-epifaunal richness associated to DFO Greenland Halibut surveys using Alfredo trawl (30 mm) (1034 stations from 2004 to 2016; 400-1500 m). Colour level priority is given from red to blue (high to low richness) in case of overlapping symbols.

## CASE STUDY 8: The North Water – Sanctuary for High Productivity and Associated Biodiversity

During the ice-covered period, polynyas provide reliable areas of open water where marine mammals and birds can congregate during winter. The North Water in northern Baffin Bay between Greenland and Canada is the largest and best characterized polynya in the Canadian Arctic. The polynya owes its existence to an ice bridge typically forming in Nares Strait, which retains ice drifting from the Arctic Ocean, and to a combination of latent (wind-driven) and sensible (ocean-warming) heat processes.

Prior to the rapid Arctic sea-ice changes of the past two decades, the North Water, also known as Pikialasorsuaq, was considered one of the most productive regions of the Arctic (Deming et al. 2002). Pikialasorsuaq supports large populations of seabirds and marine mammals both in summer and winter (Heide-Jørgensen et al. 2013b), and human settlement on adjacent coasts dates back to 4,500 years BP (Jeppesen et al. 2018) demonstrating the importance and reliability of this resource. There are 14 species of seabirds that regularly use the polynya for breeding and the most abundant is the little auk (*Alle alle*), with more than 30 million breeding pairs (Egevang et al. 2003; Davidson et al. 2018). Breeding colonies of hundreds of thousands of thick-billed murres (*Uria lomvia*) and tens of thousands common eider (*Somateria molissima*) are also found in the region (Burnham et al. 2012; Merkel et al. 2014). Marine mammals also depend on this polynya as a refuge from ice cover and access to air. Narwhals (*Monodon monoceros*), belugas (*Delphinapterus leucas*) and bowhead whales (*Balaena mysticetus*) are species that regularly frequent polynyas and leads during the winter period. In 2009 and 2010 it was estimated that over 27,000 marine mammals inhabited the North Water in the month of May, including beluga whales, narwhal, walrus (*Odobenus rosmarus*), ringed seal (*Pusa hispida*), bearded seal (*Erignathus barbatus*), and polar bears (*Ursus maritimus*) (Heide-Jørgensen et al. 2013b). In April 2014, over 13,500 walrus, beluga, narwhal and bearded seals were seen in the region (Heide-Jørgensen et al. 2016). Marine mammals and seabirds also depend on other polynyas in the Canadian Arctic in southern Baffin Bay, Hudson Strait and Cumberland Sound (Lewis et al. 2009; Watt et al. 2016, 2017; Chambault et al. 2018).

The early opening of the North Water allows for the development of a phytoplankton bloom several months earlier than in nearby ice-covered waters of the Canadian Archipelago (Tremblay et al. 2006a; Michel et al. 2015). Efficient transfers to the pelagic ecosystem (Tremblay et al. 2006b) support a locally highly productive marine food web. A recent time-series analysis of remote sensing estimates of phytoplankton biomass in the North Water over the past two decades (1998 to 2014) shows a significant decline in the amplitude of the bloom, despite interannual variability in the observational series (Marchese et al. 2017). The high interannual variability is attributed to a fine balance between oceanographic and climatic forcings, with longer and shorter blooms during years of low and high ice cover, respectively. The recent decline in phytoplankton biomass and production is documented by *in situ* measurements (Blais et al. 2017) (Figure 35), attributed to changing sea-ice conditions and delayed formation or absence of the ice bridge in Nares Strait.

Collectively, these results indicate that Pikialasorsuaq, a region long known for its recurrent and predictable high productivity and abundance of marine resources, has been negatively impacted by climate change over the past decade. In preparation for future changes, the Pikialasorsuaq Commission (pikialasorsuaq.org) is coordinating efforts in Nunavut and Northern Greenland to recommend an Inuit strategy for safeguarding, monitoring and management of the health of Pikialasorsuaq for future generations. In 2017 the commission requested the creation of an Inuit-identified, Inuit-managed protected area in the ecologically and culturally significant area of the North Water (Pikialasorsuaq Commission 2017). An implementation framework for management options was developed in 2018.

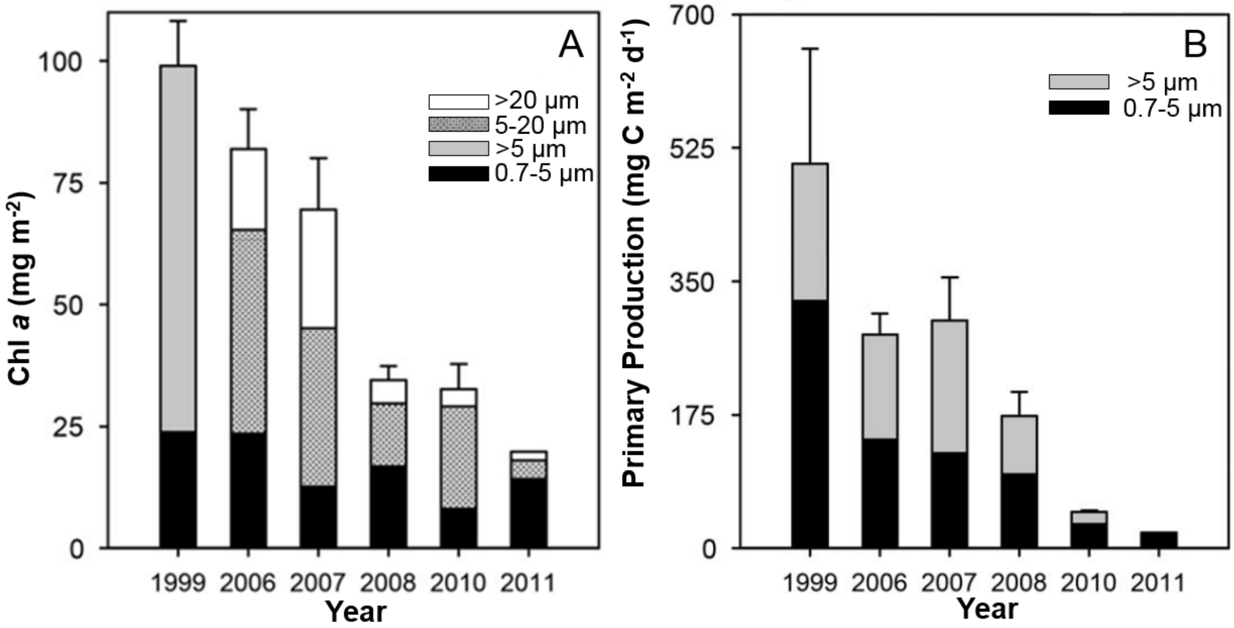


**Figure 35**. Time series of size-fractionated chlorophyll *a* (Chl *a*) biomass (a) and primary production (b) from 1999 to 2011, during fall in Baffin Bay. Data were integrated over the euphotic zone (down to 0.2% surface irradiance). In 1999 only two size fractions were measured. Values are mean ± 0.5 SE. In (b), the production by large cells is 3.2 mg C $m^{-2}$ $d^{-1}$ for fall 2011 (source: Blais et al. 2017).

## CASE STUDY 9: An Apex Predator's Response to Sea-ice Habitat Declines in Western Hudson Bay

**Figure 36.** Polar bear on shoreline of Hudson Bay (photo credit: Evan Richardson).

At a global scale habitat loss represents one of the greatest threats to species conservation and in the Arctic long-term declines in the spatial and temporal extent of sea ice are predicted to have significant impacts on ice-obligate marine mammal species. Almost two decades ago research scientists began seeing the impacts of climate change in the Arctic's most charismatic top predator, the polar bear (*Ursus maritimus*). At that time polar bears were beginning to lose body condition in western Hudson Bay in relation to reductions in sea-ice extent and the availability of their primary prey, ice-breeding seals (Stirling et al. 1999). Similar trends in the body condition of ringed seals (*Pusa hispida*) in relation to sea-ice extent have now been observed in Hudson Bay (Ferguson et al. 2017) (Case Study 4) indicating that sea ice may not only be influencing the availability of prey but also the quality of prey being consumed. These important interspecific interactions have likely played an important role in the continued, observed long-term declines in polar bear body condition at the southern limit of their range (Obbard et al. 2016; Sciullo et al. 2016).

Polar bear life history is intimately linked to the sea ice which provides a platform on which polar bear hunt, travel, mate and den. During the spring period polar bears prey heavily upon young ringed seal pups that are naïve and provide a high caloric food source. However, recent evidence suggests that ovulation and thus ringed seal pupping rates may be influenced by long-term variations in the Arctic marine environment (Ferguson et al. 2017), further bringing into question the role sea ice plays in the interspecific interactions between these two species.

As a result of reductions in sea-ice extent (Figure 37), polar bears are now spending more time on land and have begun to make use of alternative food resources. However, polar bear life history and physiology have evolved to make use of lipid rich marine mammal prey, thus terrestrial food resources, such as sea bird eggs, are not expected to maintain polar bear body condition in the face of long-term reductions in sea-ice extent (e.g., seabirds) (Case Study 13). There is some evidence to suggest that similar to ringed seals (Case Study 4), polar bear are possibly becoming more stressed in relation to long-term reduction in the availability of prey (ECCC, unpublished data). Reductions in sea-ice extent are also predicted to increase the number of human-polar bear interactions (Towns et al. 2009), potentially influencing individual survival. What does all this mean for polar bear populations?

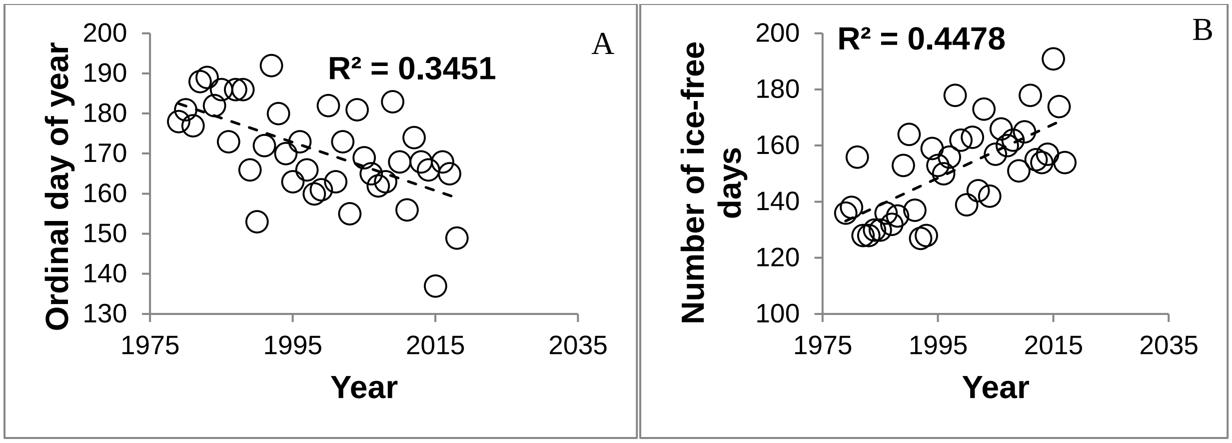


**Figure 37.** (a) Long-term declines in the date of sea-ice break-up and (b) increases in the duration of the ice-free period in western Hudson Bay Canada. Data from the National Snow and Ice Data Center, https://nsidc.org/data/NSIDC-0192).

In 2016 Lunn et al. published a long-term analysis of polar bear population demography in western Hudson Bay examining individual variation in survival in relation to changes in sea-ice dynamics. They found that survival of both young and adult female polar bears was related to changes in sea-ice dynamics that influenced the availability and quality of polar bear habitat. At the same time they were able to document a 30% decline in the size of the western Hudson Bay polar bear population from 1987-2011 (Figure 38). Subsequent aerial surveys have confirmed the population has declined to approximately 842 bears (Dyck et al. 2017).

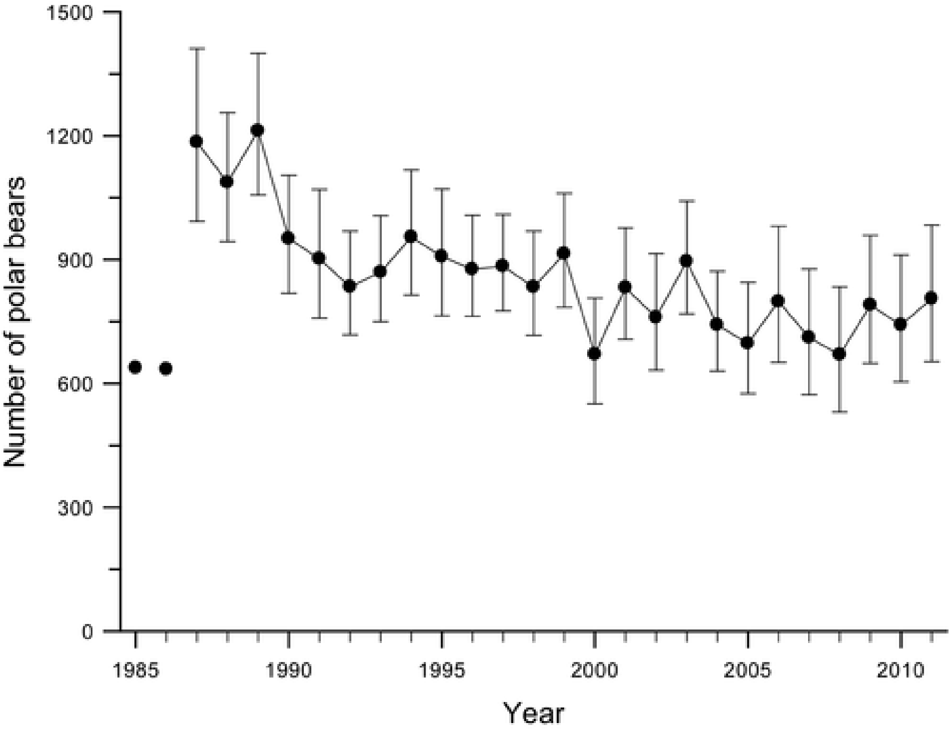


**Figure 38.** Long-term declines in the size of the western Hudson Bay polar bear population from 1987-2011 mediated by reductions in the availability of sea ice (source: Lunn et al. 2016).

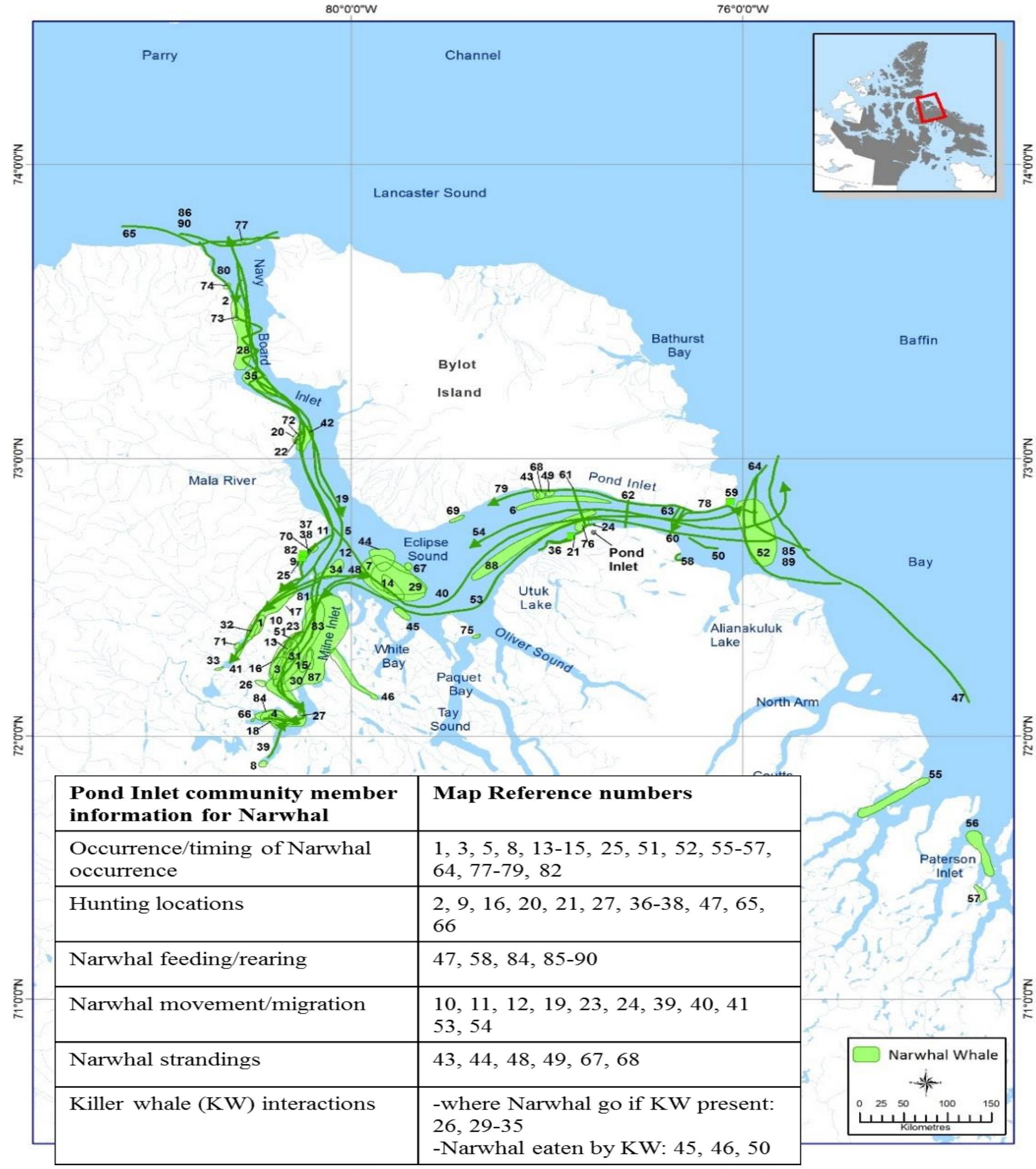
The mechanistic relationship between sea-ice dynamics, polar bear body condition, and ultimately polar survival have now been observed elsewhere. Similar declining trends in body condition initially observed by Stirling et al. (1999) in western Hudson Bay have now been documented in southern Hudson Bay (Obbard et al. 2016). More recently an aerial survey has shown a ~ 17% decline in the southern Hudson Bay polar bear population from 2011-2016 (Obbard et al. 2018). From an energetics perspective these data collectively highlight the importance of sea ice to polar bear foraging ecology and the downstream demographic responses that can result from long-term declines in body condition. Similar responses in prey populations (e.g., declines in ringed seal body condition leading to reduced survival) could have cascading effects on the long-term persistence of this species across its range.

## 4.5 A Year in the Arctic – Arctic Seasonality

How seasons are described in the Arctic depends on who you ask and what ecosystem components are being considered. For coastal communities seasonality of the Arctic Ocean is integral to daily life. These communities, deeply rooted in Inuit culture and history, rely on the Arctic Ocean for subsistence, economic opportunity, and as a way of life (Figure 39). The close relationship between coastal communities in Nunavut and seasonal changes in the Arctic Ocean are reflected in data from the Nunavut Coastal Resource Inventory. The seasons are often described in relation to the harvest of animals and the conditions associated with the use and accessibility of certain hunting grounds. An example of Inuit knowledge of narwhal near the community of Pond Inlet is described in Figure 40. The knowledge of occurrence informs seasonal events related to hunting, feeding/rearing and migration.

**Figure 39.** The lithograph titled "Nunavut Qajanartuk" depicts a year in the Arctic from the perspective of a coastal community (source: Nunavut Qajanartuk (Our Beautiful Land), Kenojuak Ashevak, 1990 Canadian Museum of History, CD 1990-001, S99-96)..

In the summer, a season defined by the absence of sea ice and the return of migrating animals, accessibility to species on the sea bed, the shoreline, and in the water column is at its peak. Summer is typically characterized as 'boating season' during which marine mammals, fishes, and aquatic plants are harvested in inlets and bays, invertebrates are collected on intertidal flats, and birds and their eggs are harvested along the coast. Fall is defined by the formation of sea ice, the shortening of daylight hours and the return of snow. Fall is typically when migrating whales and fishes are harvested as they begin their migrations to overwintering areas. Winter is characterized by the presence of sea ice, the absence of sunlight, and the harvest of winter specialists. Winter travel is typically via snowmobile over the sea ice where mammals such as seal, walrus, and polar bear are harvested. Spring is defined by the return of the sun and the slow melt and eventual breakup of the sea ice. Spring is characterized by the ability to access hunting grounds for longer periods of time, ice fishing, and the harvest of early migrants such as birds and whales.



| Pond Inlet community member information for Narwhal | Map Reference numbers |
|---|---|
| Occurrence/timing of Narwhal occurrence | 1, 3, 5, 8, 13-15, 25, 51, 52, 55-57, 64, 77-79, 82 |
| Hunting locations | 2, 9, 16, 20, 21, 27, 36-38, 47, 65, 66 |
| Narwhal feeding/rearing | 47, 58, 84, 85-90 |
| Narwhal movement/migration | 10, 11, 12, 19, 23, 24, 39, 40, 41<br>53, 54 |
| Narwhal strandings | 43, 44, 48, 49, 67, 68 |
| Killer whale (KW) interactions | -where Narwhal go if KW present: 26, 29-35<br>-Narwhal eaten by KW: 45, 46, 50 |

**Figure 40.** Traditional knowledge of narwhal occurrence near Pond Inlet (NU) collected in 2016 as part of the Nunavut Coastal Inventory initiative. Numbers represent individual knowledge contributions of community members from Pond Inlet. Arrows indicate community observed migration routes. The inset Table summarizes key categories of community observations. Comments in full are recorded in the Pond Inlet Coastal Inventory report.

In recent years, elders and active hunters from across Nunavut have noticed major shifts in seasonal patterns of biota. Participants in the Nunavut Coastal Resource Inventory have noted that winters are not as cold and the timing of sea-ice formation and breakup is altered by up to several weeks. Many communities have also noted that the weather is now largely unpredictable throughout the year. These shifts in seasonal conditions have made it difficult to safely access traditional hunting grounds and have changed the ways coastal communities harvest local biota.

For life at the foundation of the marine food web, the presence of snow-covered sea ice acts to delay seasonal progression throughout the system, with the maximum and minimum ice extent occurring at or shortly after the equinoxes. This is very different than the mid-latitude North Atlantic where the spring phytoplankton bloom occurs as surface waters stratify with solar heating close to the vernal equinox, followed by consumption of surface nutrients and the decline of the bloom. Subsequent surface mixing (e.g., during fall) can lead to an autumnal equinox bloom.

For primary producers in ice-covered seas, a sea-ice bloom does occur but it is largely limited to the bottommost centimeters of the ice. The ice-associated bloom progresses with the return of sunlight, following the dark winter period. This bottom-ice algal bloom provides the first pulse of energy to the Arctic ecosystem during spring. Snow and ice thickness and ice type influences the development and spatial variability of the ice-associated primary production. Continued spring growth and accumulation of algae in the ice bottom eventually results in nutrient demand exceeding supply from the underlying water column, leading to nutrient limitation and bloom termination. At the ice surface, melt onset also marks a transition to late spring with ensuing bottom-ice melt causing the post-bloom biomass to slough from the ice bottom, where it provides a pulse of organic matter to the pelagic (water column) and benthic (sea floor) ecosystems.

As the snow cover melts, melt ponds appear on the ice surface greatly increasing light transmission to the under-ice environment while ice melt rapidly stratifies surface waters. These conditions lead to commencement of a phytoplankton bloom close to the peak insolation of summer solstice. As previously discussed (Section 4.4.2), under-ice phytoplankton blooms can develop under the melting ice cover, possibly light limited relative to open-water conditions. As sea-ice retreats, the ice-edge bloom follows the spatial distribution of sea-ice, with regional differences. It is not yet known if this ice-edge bloom is ubiquitous to the Canadian Arctic region or if light or nutrients are limiting factors in some regions. Phytoplankton growth rapidly depletes surface nutrients as the ice progresses to break-up, resulting in a subsurface chlorophyll maximum as algae concentrate along the nutricline (i.e., depth characterized by a rapid increase in nutrient concentrations), balancing light from above with nutrient access from below. The subsurface chlorophyll maximum persists during the open-water period until fall when the rapidly decreasing solar angle induces light limitation. As air temperatures decrease and surface waters cool, strong fall storms can break down surface stratification and mix nutrients into the surface, potentially leading to a second pulse of surface primary production also referred to as the fall phytoplankton bloom (Ardyna et al. 2014). With the formation of new ice in the late fall, there is a potential for a short-lived period of ice algal growth that is terminated by the onset of polar darkness. Although polar darkness inhibits photosynthetic processes, microbial communities persist and remain active. The dark winter is not synonymous with an inactive Arctic Ocean.

Zooplankton are present throughout the year in Canadian Arctic waters. They reproduce in tune with the ice algae and/or phytoplankton bloom so that young stages can feed in surface waters.

*Calanus* zooplankton, the most important zooplankton group in the Canadian Arctic with respect to biomass and energy transfer, efficiently graze ice-algae and phytoplankton during the bloom period, rapidly building fat reserves that allow them to survive non-feeding periods (i.e., diapause) during winter. Many species of copepods undergo seasonal vertical migrations and the depths to which migration occurs is documented to be species specific. For example, *Calanus hyperboreus* can migrate hundreds of meters to the deep Atlantic Layer in the Canadian Beaufort Sea (Darnis and Fortier 2014). The seasonal vertical migrations represent a significant active transport of carbon and lipid-rich resources to lower water column layers during the fall/winter period (Darnis and Fortier 2012), with overwintering adults returning to surface waters in response to spring primary productivity.

Seasonal movements of fishes are explicitly evident for anadromous species and also occur in some marine species. As rivers open in the spring, char that have spent the winter in fresh water are able to migrate to nearshore marine habitats to forage on abundant marine resources, maximizing their opportunities for growth before they are forced to return in the fall. Nearshore and shallow habitats that were scoured by ice during winter or the spring breakup are recolonized by marine fishes and invertebrates capitalizing on the increased productivity. Even Greenland Halibut, despite their deep water habitats, show seasonal movements in relation to sea ice, with some moving between fiord habitats in the winter to deeper habitats, often along the shelf break, in summer (Section 6.3).

Marine mammals fall under two broad categories; residents spend the entire year in the Arctic whereas migrants only visit the Arctic in the months of June-September. For most residents, the seasons are marked by migrations related to habitat preference and need (Appendix A), and movements depend on the ice melt and freeze-up dates which change annually.

There are three resident species of whales (narwhal, beluga and bowhead whales), and three resident pinnipeds (ringed seals, bearded seals (*Erignathus barbatus*), and walrus) that inhabit the Arctic year round, while many other species migrate to the Arctic in the summer months (Appendix B). The resident cetaceans, such as narwhal and beluga, undergo seasonal migrations to polynyas and moving sea ice in the winter (approximately December to March), and back to estuaries, fiords and inlets in the summer (arriving on their summering grounds in July and staying until approximately September). Bowhead whales have a large summer distribution and exhibit directed seasonal movements into areas with unconsolidated pack ice in the winter (Chambault et al. 2018) (Figure 41). Some years, for reasons unknown, whales leave their summering grounds late in the season and if temperature and ice conditions change rapidly, can become entrapped in the ice. It is unknown how common entrapment events are, but in 2008 and 2015 two large entrapment events of over 1000 and 600 narwhal occurred in the Eclipse Sound stock. It was deemed the whales were too far from open water to escape the entrapment and humane harvests of approximately 600 and 250 whales occurred, respectively (DFO 2018a). Large entrapment events have potential to negatively impact narwhal stock abundance if they increase in frequency (DFO 2018a).

The resident pinnipeds are present in the Arctic year round with a circumpolar distribution (Appendix B). Bearded seals generally prefer ice habitat that is in constant motion and produces natural openings and areas of open water, such as leads, fractures, and polynyas for breathing, hauling out on the ice, and access to water for foraging (Cameron et al. 2010). To remain associated with their preferred ice habitat, bearded seals generally move north in late-spring and summer as the ice melts and move south in the fall as sea ice forms (Cameron et al. 2010). Mature ringed seals tend to prefer landfast ice with stable ice, rough surface to allow wind drift, and relatively heavy snowfall to build lairs in winter, whereas, immature ringed seals stay near to polynyas and open-water leads or seasonally migrate to moving ice near the floe edge. Walrus have a large distribution and there is limited evidence of concerted seasonal movements (COSEWIC 2017).

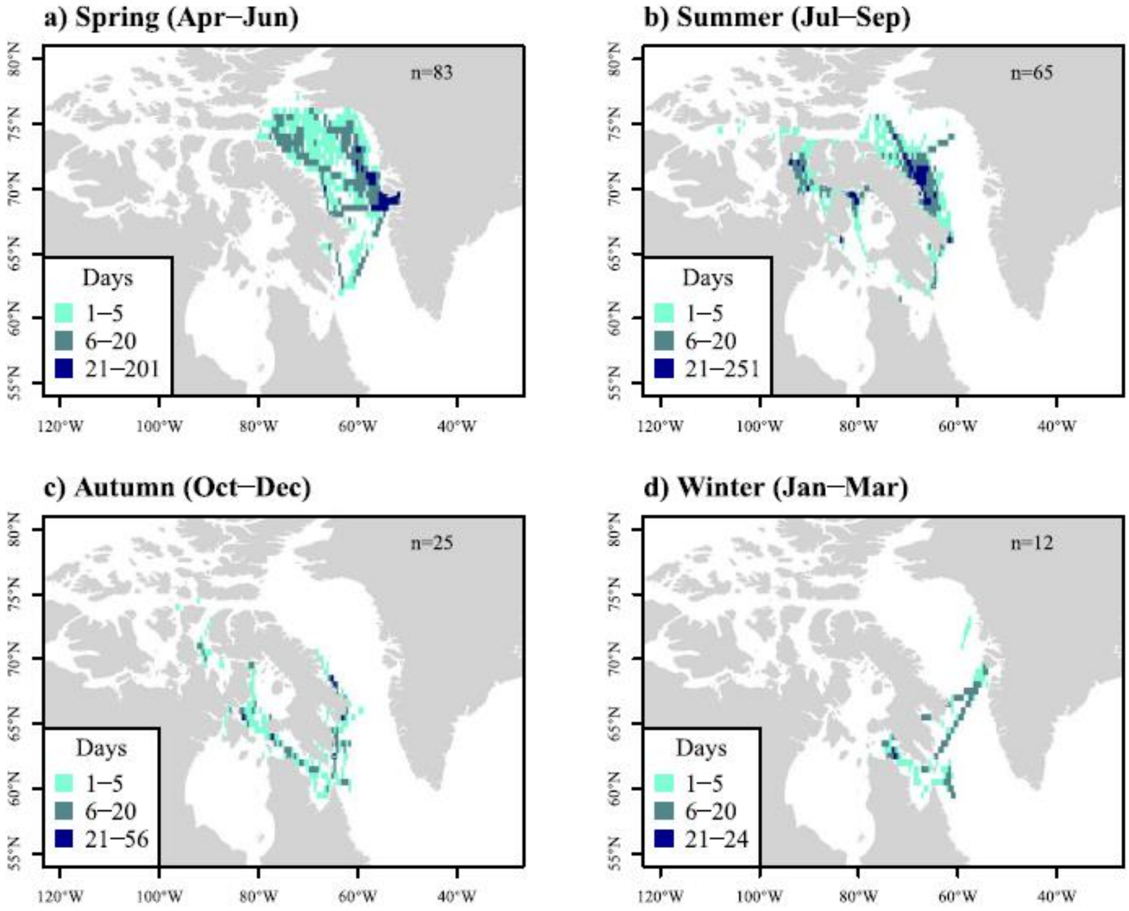


**Figure 41.** Example of seasonal habitat use (days spent in an area) for bowhead whales from the Eastern Canada-West Greenland population in spring (a), summer (b), autumn (c) and winter (d) (source: Chambault et al. 2018).

## CASE STUDY 10: Changing Phytoplankton Phenology: From Shelves to Basins

The timing of events in the annual cycle (i.e., phenology) affects the functioning of the entire marine ecosystem. The spring to early summer phytoplankton bloom is often considered as the single most important event in the seasonal cycle of primary production in the Arctic, aside from the bloom of ice algae. The transfer of primary production from the short-lived phytoplankton bloom to upper trophic levels depends not only on the temporal and spatial coupling between grazers and the timing of bloom occurrence, but also on the taxonomic composition of the bloom. In the warming Arctic, earlier sea-ice retreat and later freeze-up are changing the phenology, of the phytoplankton bloom. Predictions for a second fall bloom due to longer open-water seasons (Kovacs and Michel 2011) are now documented throughout the Arctic and on Canadian shelves (Ardyna et al. 2014; Michel et al. 2015).

The loss of thick multiyear ice and the overall thinning of Arctic sea ice is also cause for a marked increase in the prevalence of light conditions conducive to under-ice blooms. Over the past decades, earlier and extensive sea-ice melt has resulted in conditions suitable for the development of under-ice blooms, such that nearly 30% of the ice-covered Arctic Ocean has become favourable for under-ice phytoplankton blooms in July (Horvat et al. 2017). One of the important consequences of under-ice blooms is that they consume a substantial fraction of surface nutrients at the expense of primary production in the marginal ice zone following ice retreat (Palmer et al. 2014). While both ultraviolet radiation and zooplankton grazers have little effect on under-ice primary production, they do reduce the magnitude of primary production in open waters, with important implications for the production that is transferred to pelagic or benthic food webs. The shift in the timing of primary production can also affect food-web transfers through a mismatch with grazer life cycles that can have cascading implications on higher trophic levels.

Superimposed on these changes in seasonality, one also observes a shelf-to-basin displacement of the ice edge. Because the location of the ice edge relative to topography is a key parameter for upwelling and mixing (Carmack and Chapman 2003), knowledge of the spatio-temporal distribution of the ice edge is crucial to understand and predict changes in the magnitude and type of primary producers and the food webs that depend on them in the changing Arctic. A schematic of changes in the phenology of primary production on the shelves and basins, due to climate warming, is presented in Figure 42 and described below.

On productive Arctic shelves, the spring ice break-up typically triggers a short and intense ice edge bloom, dominated by large diatoms such as *Chaetoceros* spp. and *Thalassiosira* spp. These large phytoplankton store energy in lipid form and are very efficient at transferring energy to harvestable resources, compared to smaller phytoplankton. In areas still ice-covered, ice algal or under-ice phytoplankton blooms can develop when sufficient light is transmitted through the ice cover. Following these events, the nature of a summer phytoplankton bloom changes drastically from that of an ice-edge bloom. Since the bloom occurs at depth, it forms a sub-surface chlorophyll maximum (SCM) with different species. As nutrients become depleted, small phytoplankton cells replace the diatoms and low light-adapted species such as *Micromonas* sp. take precedence as solar irradiation declines and winter sets in.

In recent years, ice edge blooms have developed offshore. Although dominated by diatoms, the offshore blooms are one order of magnitude less productive than blooms occurring on the shelf, owing to the lower initial surface nutrient inventory in the basin (Coupel et al. 2015). Concomitantly, on the shelf, the spatio-temporal occurrence of productive hot spots is likely to change since it depends on the balance between mixing that provides nutrients and light availability, which is also linked to the location of the ice edge. At the shelf break, upwelling-favourable wind conditions can generate productive fall blooms depending on ice conditions and available daylight.

Regional differences in the timing and extent of the open-water surface area have important implications for phytoplankton bloom phenology (Barber et al. 2015). Phytoplankton blooms in the Atlantic-influenced Barents Sea start as early as late April, whereas in the Canadian sector, phytoplankton blooms usually develop after mid-June (Mundy et al. 2014) or mid-July (Arrigo et al. 2012). Overall, complex sea-ice dynamics influence the timing, location, magnitude and composition of primary producers on Arctic shelves and deep basins. Our overall understanding of phytoplankton phenology in relation to ice dynamics is being challenged by the rapid on-going changes, and the effects of the trophic cascade remain to be understood.

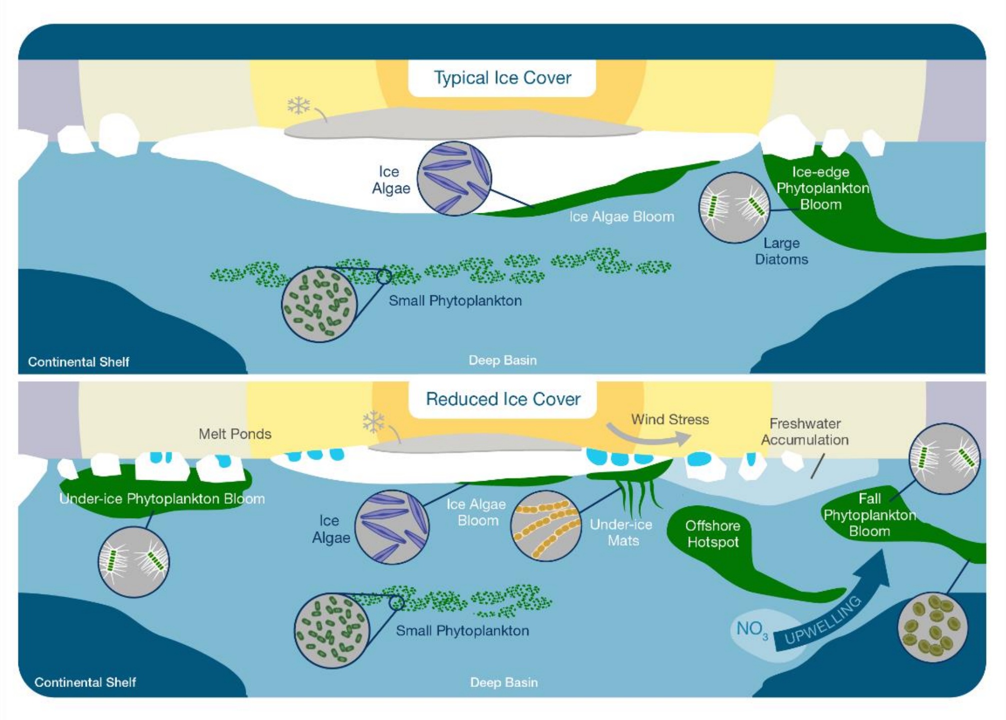


**Figure 42**. Annual events (phenological changes) in sea-ice and water column primary production under typical (top panel) and reduced (bottom panel) ice-cover conditions on Arctic shelves and basins.

## 4.6 Biodiversity

Biodiversity assessments for the Arctic Ocean have been conducted by the Conservation of Arctic Flora and Fauna (CAFF) Working Group of the Arctic Council, providing a baseline from which to assess change (CAFF 2013, 2017). Key findings of the 2017 CAFF report indicate that biodiversity in the Canadian Arctic is and will continue to be affected by, 1) northward expansion of Arctic species, 2) seasonal increases in the number and diversity of southern species in Arctic waters (e.g., killer whale, salmon, Case Study 14), and 3) the availability of food resources. The report also highlights the serious need for long-term monitoring of biodiversity and ecosystems in the face of ongoing cumulative environmental changes. Species richness was not specifically addressed in the 2017 Biodiversity report but previous assessments for the Arctic as a whole report 2000 phytoplankton taxa, >1000 ice-associated protists, >50 ice-associated metazoans, ca. 350 zooplankton species, >4500 benthic protozoans and invertebrates, ≥160 macro-algae (e.g., kelp), 243 fishes, 64 seabirds, and 16 marine mammals (Bluhm et al. 2011).

Species continue to be discovered (Table 3) in the Canadian Arctic and many regions have not yet been explored with respect to species richness at multiple trophic levels. For example, in some regions of the eastern Canadian Archipelago, it is estimated that up to 59% of mega-benthic taxa, are yet to be discovered (Roy et al. 2015b). Table 3 provides a summary of recent studies contributing to our understanding and assessment of marine biodiversity in the Canadian Arctic region.

### 4.6.1. Adaptation and Resilience

The adaptation capacity of Arctic marine species has been the focus of recent studies in an effort to identify the resilience of Arctic ecosystems. Ecosystem resilience refers to the ability to respond to disturbances and reorganize while undergoing changes to maintain critical functions. An understanding of resilience is important given that climate change is in part responsible for rapidly re-shaping the dynamics of marine Arctic ecosystems. Large-scale (temporal and spatial) modeling of data gathered through multi-species scientific surveys has shown a gradual shift in the distribution of marine organisms allowing them to cope with increasing physiological (e.g., increased temperature) and behavioural (e.g., shifting predator-prey interactions) stressors brought on by climate change in Arctic ecosystems (Cheung et al. 2010; Fossheim et al. 2015; Miller et al. 2018). In addition to these quantitative advances, mechanistic explanations for species-level adaptation capacity (e.g., Arctic Cod) have been assessed (Drost et al. 2016) and species-specific characteristics such as temperature, salinity, pH, and dissolved oxygen tolerance limits have been reviewed in a recent effort to develop a physiological database for Arctic and sub-Arctic species (Steiner et al. 2018). This database contains information on 17 species, with Arctic Char being the only species of commercial interest (Steiner et al. 2018). Genomic tools are also being developed to determine the acclimation and adaptation potential of individuals by identifying candidate genes whose expression are directly correlated with a coping mechanism for climate change (Franks and Hoffmann 2012). For example, Arctic Char genetic markers are being developed to monitor thermal stressors and the recovery potential under stressful physiological conditions (Quinn et al. 2011). Information is emerging on the capacity of Arctic species to adapt to change. However, further research is required to predict long-term resilience of Canadian Arctic marine ecosystems.

**Table 3.** Recent assessments and studies informing biodiversity in the Canadian Arctic region.

| Species/Group | New knowledge | References |
|---|---|---|
| Single-cell marine eukaryotes (phytoplankton) | 1229 species in Canadian Arctic, singled-celled organisms make up a significant part of total species diversity. | Poulin et al. 2011 |
| Single cell ice eukaryotes (ice algae and protists) | 540 species in Canadian Arctic, high contribution of diatom species. | Poulin et al. 2011 |
| Marine fishes | All 221 known marine fish species (58 families) in the Canadian Arctic are described in a comprehensive compendium including species-specific distributions (occurrences).<br>Trawl surveys (2012-2017) in the Beaufort Sea have identified ca. 16 new marine fish occurrences.<br>Trawl surveys (annual since 2004) in Baffin Bay and Davis Strait support ongoing monitoring of benthic biodiversity. | Jørgensen et al. 2011; Majewski et al. 2016; Coad and Reist 2018 |
| Geographic distribution of Canadian Arctic Benthos | 774 benthic taxa identified from museum collections (1920-1980s).<br>527 benthic taxa identified from field collections (2007-2011). | Roy et al. 2015b; Roy and Gagnon 2018 |
| Monstrilloid copepods | New species identified in the Kitikmeot region. | Delaforge et al. 2017 |
| Siboglinid tubeworms | First documented living chemosynthetic community in the western Arctic Ocean. Associated with active mud volcanoes on the continental slope of the Canadian Beaufort Sea. | Paull et al. 2016 |
| Benthic sedentary polychaetes | Four new records and one new species from the Canadian Archipelago. | Løpez et al. 2017 |
| Assessment of benthic diversity in Arctic ports | Benthic invertebrate surveys for non-indigenous species and habitat suitability for potential invasive species related to shipping. | Goldsmit et al. 2014; Goldsmit et al. 2018 |
| Cryptophytes (Baffin Bay) | New family (Baffinellaceae), genus and species described. | Daugbjerg et al. 2018 |
| Marine amphipods | 100 putative Canadian Arctic species identified by DNA barcoding. | Tempestini et al. 2018 |

## CASE STUDY 11: Biodiversity of Fishes in the Canadian Marine Arctic

About 221 recognized species in 138 genera and 58 families of fishes are presently known to occur in the marine waters of the Canadian Arctic (Coad and Reist 2018) (Figure 43). This includes 24 species in six families of anadromous or sea-run fishes. More than 32,000 distinct species of fishes are thought to exist globally (Nelson 2006), of which about 15,800 are marine and over 225 diadromous (i.e., both anadromous and catadromous species). Thus, the biodiversity present in Canadian Arctic Marine waters is overall comparatively low. In comparison to all fishes found in Canada, the Arctic marine ichthyofauna represents about 25% of the families and 15% of the species present in total (i.e., the entire Canadian freshwater and marine ichthyofauna totals about 1,439 species in 233 families). Exact numbers of species in the Arctic are uncertain due to taxonomic and distributional uncertainties, variable abundances and often clumped distributions of taxa, as well as rapid rates of change in distributions due to increasing environmental variability/change accompanied by limited ongoing sampling. Accordingly, the present 'state of knowledge' for marine fishes as summarized in Coad and Reist (2018) is incomplete and likely out-dated thus ongoing documentation of changes and new occurrences is required.

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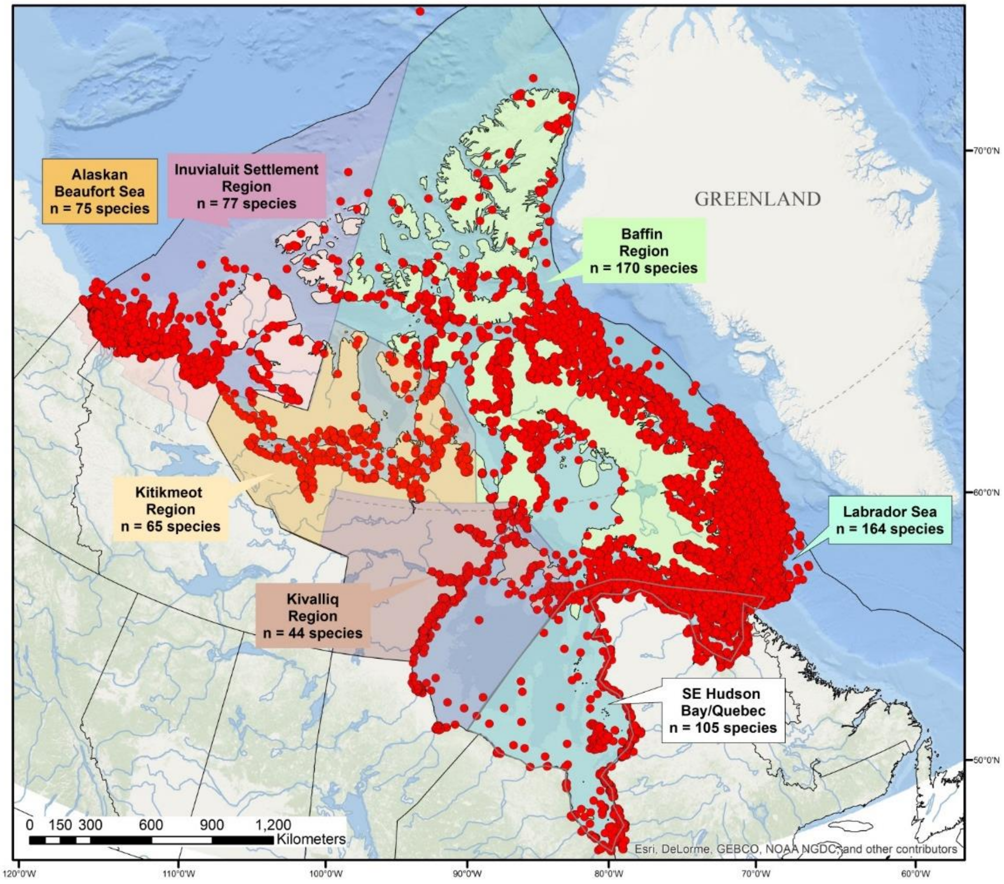

**Figure 43.** Number of marine and anadromous fish species per region in the area of consideration. Red dots indicate documented occurrences of all marine fish species.

What kinds of fish live in the Canadian Arctic Ocean? Around 20 species of jawless (i.e., hagfishes (1) and lampreys (1)) or cartilaginous (i.e., chimaeras (3), sharks (5), skates (9), sturgeons (1)) fishes occur, and the remaining 201 species from 49 families are ray-finned (Coad and Reist 2018). The most numerous and geographically widespread species is Arctic Cod (*Boreogadus saida*). In contrast, a deep-sea, Arctic-endemic (i.e., only occurs in the Arctic) species, the Arctic Brotula (*Bythites fuscus*), found between Baffin Island and northwestern Greenland, is known from only three specimens. The ecological roles and significance of many of these rarely occurring species, particularly those in deeper waters, remain uncertain. It is generally assumed that higher diversity confers greater stability on the structure and function of ecosystems emphasizing the general importance of high diversity. Accordingly, despite the rarity of many of the species and the low diversity of some families in the Arctic, appropriate conservation and management efforts are required.

Occurrences of species throughout the Canadian marine Arctic are not evenly distributed. Rather, geographical disparities in occurrence are biased by proximity to adjacent seas and oceans, as well as by geographically varying abiotic factors such as currents and water mass structure (Majewski et al. 2017), and physical barriers (e.g., Bouchard et al. 2018). Additionally, historical factors such as the timing and pattern of deglaciation and post-glacial uplift have affected fish access and colonization of the Canadian Arctic. Accordingly, in sub-areas from west to east then south, the numbers of species present are as follows (Figure 43): 1) Inuvialuit Settlement Region (Northwest Territories) – 77; 2) Kitikmeot (Nunavut) – 65; 3) Baffin (Nunavut) – 170; 4) Kivalliq (Nunavut) including western Hudson Bay and Ontario and Manitoba coasts – 44; 5) Southeast Hudson Bay (and Quebec) – 105. The species' complements within each region noted are not mutually exclusive, thus, these numbers represent sub-sets of the 221 total for the entire area.

In addition to the 221 species known from Canadian waters, about 21 species occur extralimitally (i.e., in adjacent marine waters) in Alaskan waters of the Beaufort and Chukchi seas but have not yet been recorded in Canadian western Arctic waters. Similarly, around 100 species occur in adjacent Greenlandic and northwestern Atlantic waters but have not yet been recorded in Canadian eastern Arctic waters. The majority of these occupy deeper waters, thus documenting their occurrences may be challenging and require specialized efforts. These, however, are possible future additions to the known diversity of fishes in the Canadian Arctic (Coad and Reist 2018). Recent work suggests some species may be extending their ranges into Canadian waters either through migratory vagrant occurrences (i.e., distributions extralimital to known reproductive ranges) and perhaps also colonizing (e.g., Pacific salmons (*Oncorhynchus* spp.) in the western Arctic, Dunmall et al. 2013). Ongoing monitoring is required to document such occurrences and determine whether reproduction (i.e., colonization) has occurred for these in Canadian Arctic waters. As new occurrences are documented it is important to differentiate between new information regarding species that were already occurring in the area versus those that are newly occurring species. Thus, although several species recently found in the Canadian Beaufort Sea represent new records for Canada (n~16), they most likely result from increased effort in under-sampled or newly sampled areas rather than recent colonizations (Majewski et al. 2016).

Baffin Bay and Davis Strait in the eastern Arctic is an area of very high diversity (170 species). Additional areas of high fish diversity appear to be present where distinct habitats meet or where different water masses intersect (Majewski et al. 2017). Further work is required to better characterize such areas ecologically and to understand their significance in maintaining biodiversity. The northern-most location known for any species in our area of consideration is a single record for Glacial Eelpout (*Lycodes frigidus*) northwest of Ellesmere Island (Coad and Reist 2018). Undoubtedly there are other fishes distributed under the polar pack ice, however, limited sampling restricts our knowledge of high Arctic fishes.

Based upon post-glacial processes (e.g., dissolution patterns of glacial ice masses and freshwater inputs during the late Pleistocene, and the present-day oceanographic patterns), the Boothia Peninsula appears to represent a delineating boundary between western and eastern zoogeographic zones (Coad and Reist 2018). Thus, 136 species (61.5% of the Canadian Arctic total) in the Arctic occur only east of the Boothia Peninsula; 30 (13.6%) only in the western Arctic; and, 54 species (24.4%) are present in both areas. These zoogeographic differences are relevant in terms of ecosystem structure, function and stability as well as the potential human uses marine fishes may serve.

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and the International Union for the Conservation of Nature (IUCN) have assessed many (but not all) of the marine fish taxa of Arctic Canada. COSEWIC findings for taxa are: not at risk – 2, data deficient – 6, special concern – 6, threatened – 4, and, endangered – 3 (Coad and Reist 2018). IUCN assessments are: data deficient – 4, lower risk/least concern – 2, least concern – 34, near threatened – 3, vulnerable – 2, and, endangered – 2. The Canadian National General Status Working Group also conducts a status assessment of a wide range of species every five years. The most recent results were published in 2016 (CESCC 2016). In the western Arctic, marine and anadromous fish species were assessed as follows: secure – 8, apparently secure – 3, vulnerable – 2, imperiled – 1, and the remainder were unrankable (CESCC 2016; Sawatzky et al. 2018). Results for the eastern Arctic include: secure – 15, vulnerable – 6, imperiled – 4, and the remainder were unrankable (CESCC 2016; Sawatzky et al. 2018). The large number of 'data deficient' and 'not assessed' taxa documented in these sources indicates the need for substantive work to fills gaps in our knowledge.

Uneven and/or absence of effort to capture marine fishes in certain areas or habitats (or with particular gear types such as deep-water trawls) limits our knowledge base. Inadequate monitoring in space and time exacerbates this situation. Accordingly, the determination of whether a species newly captured in the area is the result of previous dearth of knowledge or whether it represents change (i.e., vagrant occurrence or colonization) may be problematic. Similarly, the determination of ecological relevance, responses to drivers or stressors, and assessment of status cannot be adequately accomplished. Accordingly, appropriate design and delivery of monitoring programs which are comprehensive in space (location, habitats) and time (frequency) are required throughout the Canadian marine Arctic.

## 5.0 Ecosystem Variability

Variability is an inherent condition of Arctic ecosystems and is therefore a key condition describing the state of a system. Understanding variability is essential to properly identify/predict change and to managing Arctic resources. Variability challenges our ability to make generalized statements about the Arctic Ocean.

*Participants noted that Capelin have arrived to the area in large numbers in the last 5-7 years. There are so many that they blacken the water. They believe that sea run Char are now feeding on this abundant species and that is the reason for the change in flesh colour and taste (Nunavut Coastal Resource Inventory – Pangnirtung 2013)*

*The ice seems to be thinning all the time, I think. But every year it changes, I mean it's different (Jobie Attitaq, 2004, Arctic Bay NU). [Quoted from Archer et al. 2017].*

The fact that Arctic ecosystems vary over time and by location is well known by Indigenous Peoples. Inuit knowledge documents variability for multiple ecosystem components including sea ice (Case Study 5), the condition of coastal fishes, presence/absence of species (e.g., jelly fish) and migration patterns (Brown and Fast 2012; Brewster et al. 2016; Byers et al. 2019). Although ecosystem variability is part of the natural state, it is often a concern because we cannot adequately infer the cause of observed variability or identify the point at which variability becomes a discernable change. The variability of key Arctic ecosystem components (e.g., sea ice, carbon pump) is linked to variables such as water temperature, wind, and ocean circulation. These are in turn affected by overlying drivers including, inherent climate variability generated by the naturally chaotic nature of our climate system as well as external global forcings (e.g., greenhouse gases, ozone, etc.), and other local/regional stressors (Section 1.3). With the current state of knowledge for Arctic ecosystems and the climate system, it is challenging to identify causation for variability and therefore the security/stability of Arctic ecosystems, especially resources of subsistence, cultural and economic importance, cannot be predicted with a high degree of certainty.

The climate of the Arctic as a whole has dramatically changed over the last decades (Section 1.3). The change and variability in climate have been caused by external forcing (e.g., greenhouse gas emissions), but also from natural interaction among the components of the climate system (i.e., complex interactions among the atmosphere, the marine and continental cryosphere, and ocean systems) (IPCC 2013). Section 5.1 provides an overview of key modes of climate variability that ultimately affect all components of the marine ecosystem. These modes of natural, climate variability are influential at time scales of days to multiple decades.

For the Canadian Arctic Ocean we cannot describe ecosystem variability in a unified way for all ecosystem components. Differences in data collection do not allow us to do so. As such, in the following sections temporal trends are presented for the ocean environment where long-term data sets allow for the assessment of the mean and associated variability over recent years. Ecologically significant spatial variability/change is presented for primary producers and regionally specific examples of variability are presented for fishes and marine mammals. Case studies that follow provide examples of ecosystem-level variabilities for the Beaufort Sea and northern Hudson Bay.

## 5.1 Atmospheric Variation in the Arctic

There is no shortage of evidence of sea-ice response to the atmosphere in the Arctic. For example, unusual conditions of wind and air temperature in the western Arctic (Stroeve et al. 2008), in association with increased Bering Strait inflow (Woodgate et al. 2010) and reduced cloudiness (Kay et al. 2008) apparently created the extreme loss of Arctic sea ice seen in 2007 (Figure 4). In 2012 an intense storm in the central Arctic, acting on already thin sea ice, was the cause the most extreme minimum ice extent in the Arctic to date (Zhang et al. 2013).

The energy to drive the ocean's circulation originates in the gravitational influence of the sun and moon (tides), in differences in solar heating, evaporation/precipitation and freezing/melting across the Earth, and in the wind. The input of tidal energy varies principally on half-daily and daily cycles which are regular and predictable; its variation over decadal intervals is not of concern. The atmosphere, however, not only influences other components of the Earth's environment – land, sea, ice and snow – but is influenced by them. Such two-way interactions can generate chaotic and cyclic behaviour in both elements. In interactions where one element is the ocean, which has great mass and heat capacity and is therefore slow to respond, the cycles may span decades. El Nĩno which originates in the tropical Pacific Ocean, is perhaps the best known of these cycles.

The natural oscillation of the atmosphere most influential in the Arctic is the northern annular mode (NAM) (Thompson 2019) more commonly termed the Arctic Oscillation (AO). Its effect is to move air back and forth between mid-latitudes (30-40°N) and the north polar cap on a time scale of years. This transfer raises or lowers air pressure in the respective regions of action and thereby changes the strength and pattern of wind, because wind depends on difference in air pressure. The geographic footprint of the Arctic oscillation is shown in Figure 44. When the oscillation is causing air to shift southward from the blue to the red-yellow areas, air pressure at mid-latitude rises and Arctic air pressure drops. The resulting increased difference in pressure between south to north causes west wind to strengthen (east wind to weaken). Some years later, the oscillation causes air to shift northward, causing air to accumulate in the Arctic and west winds to weaken (east wind to strengthen). In the western Canadian Arctic, where wind normally blows from the east or north-east, this half of the cycle strengthens the Beaufort Gyre.

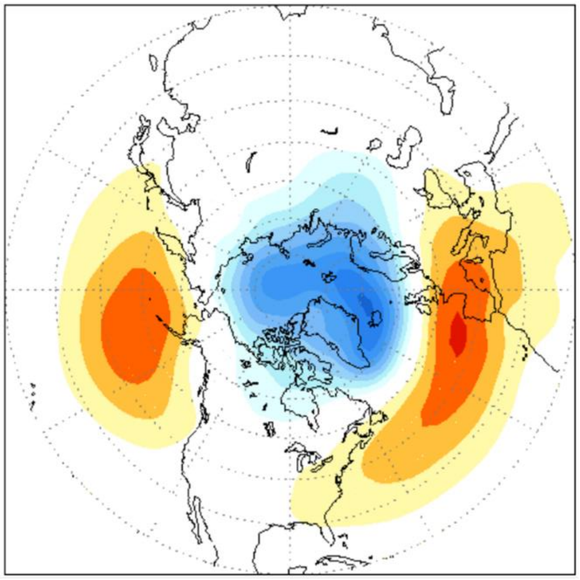

**Figure 44.** Geographic pattern of the Arctic Oscillation. Note that this so-called Arctic phenomenon actually fills the top half of the northern hemisphere. http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.loading.shtml

The Arctic Oscillation accounts for about 20% of month-to-month variation in wind and air pressure north of 20°N. The stage and strength of the oscillation at any time is represented by an index, which by convention is positive if air pressure at mid-latitude is higher than normal (with Arctic air pressure lower than normal). A positive index therefore corresponds to a weaker Beaufort Gyre, and vice versa. Values of the index derived from weather observations since 1950 are displayed in Figure 45. Grey-shaded panels on the figure denote periods of interest in the Beaufort region, and are discussed further in Section 5.2. There is no obvious correspondence between the index and these shaded intervals. The correlation may be weak because the area over which the index is calculated (that north of 30°N) is so much larger than the Canadian Arctic region. Indeed, Proshutinsky et al. (2015) have noted that the Arctic Oscillation's centre of action in the North Atlantic is quite remote from North American Arctic.

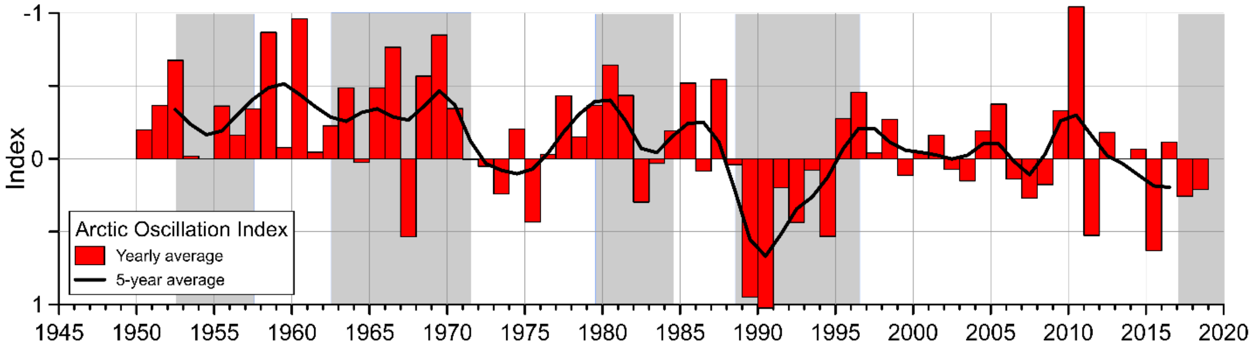

**Figure 45.** Variation of the Arctic Oscillation index over time. For ease of interpretation (and later comparisons), the index is plotted with negative values up-going. Grey-shaded panels denote periods of interest in the Beaufort region.
http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii

Wang et al. (2009) described a second but less influential pattern of sea-level-pressure variation across the Arctic, the Dipole Anomaly (DA). This pattern associates high air pressure over the Canadian Arctic region with low air pressure over eastern Siberia and vice versa. The wind associated with the DA, when pressure is high in the Canadian Arctic region, comes from the south. Not only does it push sea ice from the Chukchi Sea across the Arctic to the Atlantic, effectively clearing ice north-westward from the Canadian Arctic region, but it brings warmer air into the Arctic from the Pacific.

The North Pacific index of atmospheric variation (Trenberth and Hurrell 1994) is representative of a geographic area closer to the Canadian Arctic region than is the Arctic Oscillation index and closer in size, being based on monthly average sea level pressure over the region 30°N-65°N, 160°E-140°W. Its possible relevance to the Canadian Arctic region lies in its role as the southern end of a "see-saw" that perturbs the north-south difference in sea-level pressure across Alaska, which in turn influences the strength of east wind across the southern Beaufort Sea.

Values of the North Pacific index are shown in Figure 46. The NPI time series bears some resemblance to that of the Arctic Oscillation index (Figure 45), in particular peaks in 1958, 1969, 1980 and 1987 and a dip in 1990. This seems reasonable because the NPI describes one of the action centres of the Arctic Oscillation. However the two time series are clearly not identical.

Again there is no obvious correspondence between North Pacific index and the shaded intervals descriptive of variability in the Beaufort Gyre.

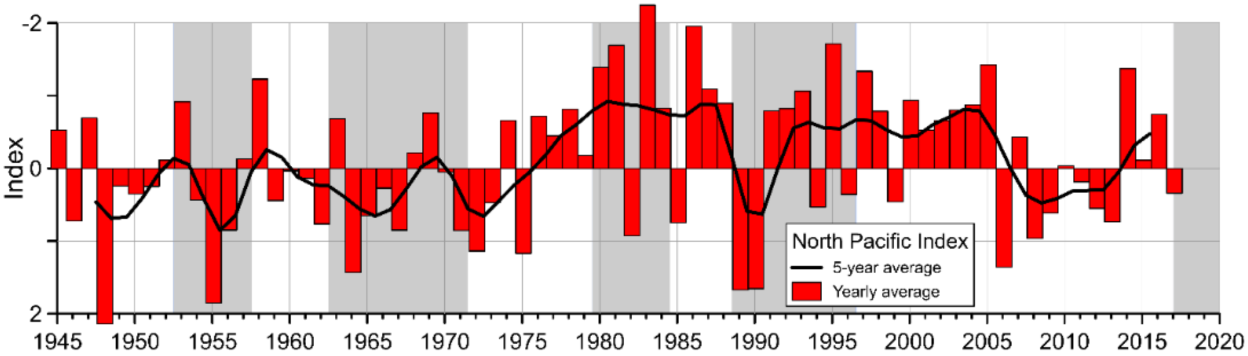

**Figure 46.** Variation of the North Pacific index over time. For ease of interpretation (and later comparisons), the index is plotted with negative values up-going. Grey-shaded panels denote periods of interest in the Beaufort region. https://climatedataguide.ucar.edu/climate-data/north-pacific-np-index-trenberth-and-hurrell-monthly-and-winter (Trenberth and Hurrell 2019).

Another index, the North Pacific Oscillation (Linkin and Nigam 2008), has been used to characterize atmospheric variation over a much larger area in the North Pacific, 15°N-80°N, 130°E-120°W. It provides a somewhat different viewpoint of variability in the North Pacific. Although this domain incorporates Arctic latitudes, it also covers the tropics. Zhang et al. (2019) have identified a connection between the North Pacific Oscillation index in spring and September sea-ice extent in the Beaufort Sea. The connection appears to be mediated by the index's influence on easterly winds over the Beaufort, which drives ice offshore, exposing the ocean to warming sunshine which in turn promotes the melting of sea ice.

In summary, both the Arctic Oscillation index and the North Pacific Oscillation index are insightful in two respects. First, they reveal the sizeable multi-annual variability in wind and air pressure that is characteristic of the climate of the north temperate and polar regions of the Earth. Second, they reveal that this variability is cyclic, in the sense that it moves back and forth between extremes, but that its period is irregular, seen in these short records that vary between 2 and 20 years.

## 5.2 Variation in the Ocean Environment

Variation in environmental conditions over time challenges our capability to provide a reliable description of the present state of the Arctic (see Section 1.1). Here we strive to describe a “state of the Arctic” that is an average of conditions over 5 years (autumn 2012 to autumn 2017), enough time to embrace some inter-decadal variation but not so much as to lose timeliness.

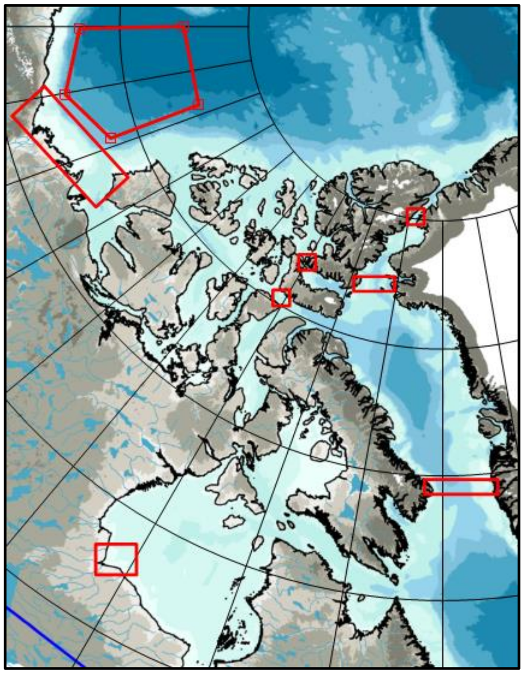

**Figure 47.** Polygons (red) delineating parts of the Canadian Arctic region where observations are adequate to describe some aspects of the state of the ocean's environment.

With the exception of sea-ice extent, which has been carefully monitored for half a century, ocean data are sparse in space and over time in the Canadian Arctic region. Again excepting sea-ice extent, there are only a few areas where we have sufficient information to document the present state of the ocean (Figure 47):

- Canada Basin, systematically observed from 2003 to the present: annual geochemical mapping in August, September or October; year-round observations from 3 oceanographic moorings.
- Beaufort shelf / Amundsen Gulf, systematically observed from 1990 to the present: year-round observations from 2-10 oceanographic moorings; annually occupied geochemical stations.
- Canadian Polar Shelf, where a comprehensive observing program established in the late 1990s became financially unsustainable by 2012: year-round oceanographic moorings and repeated geochemical surveys.
- Baffin Bay (north), observed systematically since 1998: data are primarily biogeochemical.
- Davis Strait, systematically observed year-round since 2004.
- Hudson Bay: ongoing studies are largely biological.

None of the initiatives listed above have embraced the coastal zone, nominally inshore of 10 km, although Inuit knowledge may be available near some communities. The large area outside the mapped polygons clearly reveals the inadequate scope of marine monitoring in Canadian waters.

### 5.2.1 Canada Basin

The area in the Canada Basin under annual scrutiny since 2003 is delineated by the shaded keystone in Figure 48. Approximately one third of this area lies within the Canadian EEZ. Lines mark the end-of-summer ice edge for 1980-2000 (blue) and for record-setting ice retreats in 2007 (magenta) and 2012 (green).

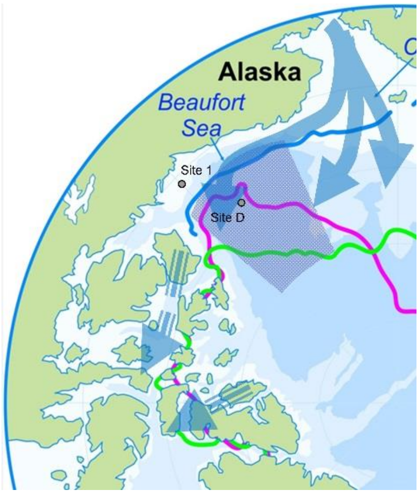

**Figure 48.** Location of the Beaufort Gyre Exploration Project in the Canada Basin (shaded keystone). Arrows are presumed pathways of Pacific Water movement. Coloured lines mark end-of-summer ice edges (2012 in green, 2007 in magenta, 20-year mean in blue). Dots mark ice-monitoring locations (Site D and 1).

Ice draft (the submerged part of its thickness) has now been monitored year-round at 3-4 sites within the keystone for 15 years. Krishfield et al. (2014) discuss the observations acquired up until the autumn of 2013 and more recent data are available (http://www.whoi.edu/page.do?pid=66559). Updated time series for observations at the BGOS-D site (Site D, Figure 48) are displayed in Figure 49. In contrast to conditions in earlier decades, the open-water fraction (Figure 49a) here in late summer exceeded 50% in 8 of the 12 summers of observation; there was more than 75% open water for a prolonged interval in 4 of these summers. During at least half of the 11-year period, areal coverage by ice more than 1.2-m thick (1.1-m draft) was less than half. Figure 49b reveals a seasonal cycle in average ice draft, from about 0.3 m in September to 2.0 m in late May (open areas are included in the average as ice of zero draft); such a wide seasonal range is characteristic of a seasonal sea-ice zone and atypical of this location formerly beneath multi-year pack ice. The curve for

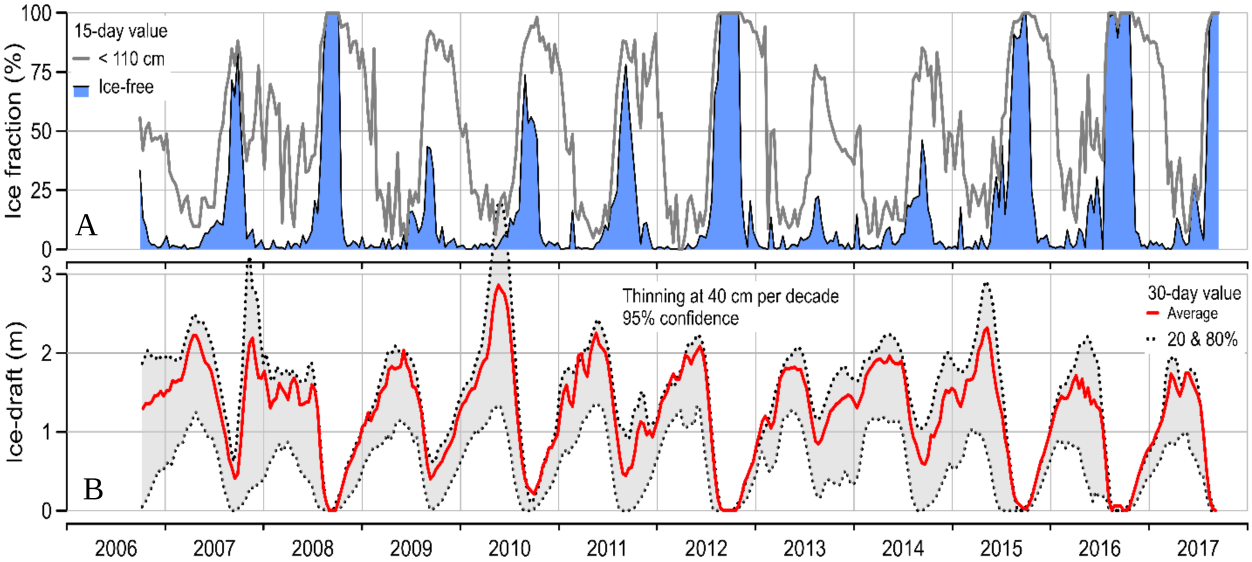

**Figure 49**. Variation of pack ice measured by ice-profiling sonar at Site D (Figure 48) of the Beaufort Gyre Observatory. a) displays the extents of open water and of ice less than 1.1 m in draft; b) displays average ice draft and its percentiles.

the 80th percentile reveals that ice with draft more than 2.5 m – typically pressure ridges and old ice – has recently been uncommon at this site. Average ice draft has, with 95% confidence, decreased at 40±20 cm per decade since 2003.

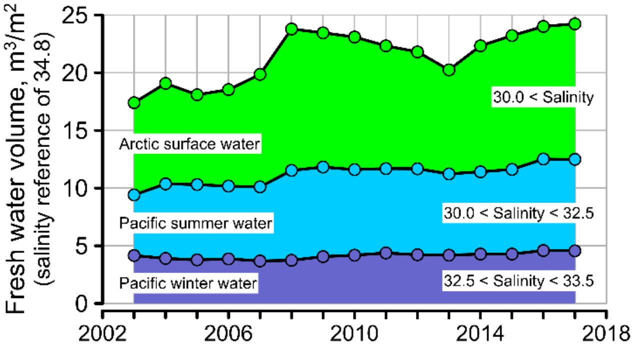

**Figure 50.** Volume of diluting fresh water within various seawater masses found in the Beaufort Gyre. Data from Proshutinsky et al. (2019).

During this same period of moderating ice conditions, the volume of fresh water diluting seawater of nominal 34.8-salinity has been increasing within the Beaufort "gyre" – the clockwise rotation of water in the Canada Basin. There is now one third more fresh water stored in the gyre than in 2003. Moreover, since the increase in fresh water has been greater at shallow depths than deeper down, the vertical stratification (stability) of the ocean – or its resistance to mixing (Davis et al. 2016) – has increased too. Much of the increased fresh water near the top of the ocean (green in Figure 50) has been provided by Arctic rivers. Fresh water deeper in the ocean (blue in Figure 50) has come via the Pacific Water inflow via Bering Strait.

The increased pooling of fresh water in the Beaufort Gyre reflects in part the recent pattern of prevailing wind in the Arctic. The alternation at 5-10 year intervals of wind over the Canada Basin between patterns of clockwise and counter-clockwise circulation (Thompson 2019) is described in Section 5.1. Proshutinsky and Johnson (1997) have demonstrated that this variation of wind over the Arctic generates alternating phases of clockwise and counter-clockwise water circulation in the Canada Basin, which they named the Arctic Ocean Oscillation. Annual hydrographic mapping of the gyre has revealed that a positive phase of this cycle (clockwise circulation) initiated in the late 1990s has persisted much longer than seen before. Indeed the Arctic Ocean Oscillation was positive for a 19th year in 2017 (Figure 51).

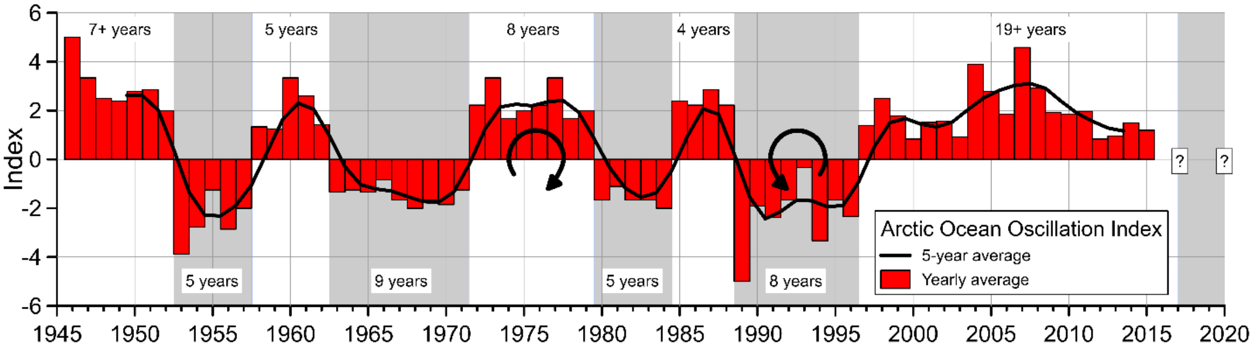

**Figure 51.** Variation of the Arctic Ocean Oscillation Index displaying the intervals of alternating direction of rotation since 1945. The grey band at the right is conjectural. Data from Proshutinsky et al. (2015).

Observations since 2003 reveal that marine productivity within the Canada Basin has moved to a state consistent with reduced access to nutrients (Stanley et al. 2015). The reduced access results in part from an increase in the consumption of nutrients through an increase in primary production. This in turn reflects the increase in available light at the sea surface because there is less shadowing by sea ice now in summer. The dissolved nutrients necessary for growing marine plankton in the Arctic must be replenished from the submerged Pacific Water layer because necessary sunlight is at the surface; it is mixing of the upper ocean that brings these elements together. However as noted above, upper ocean mixing has weakened in the Canada Basin as fresh water has accumulated near the surface.

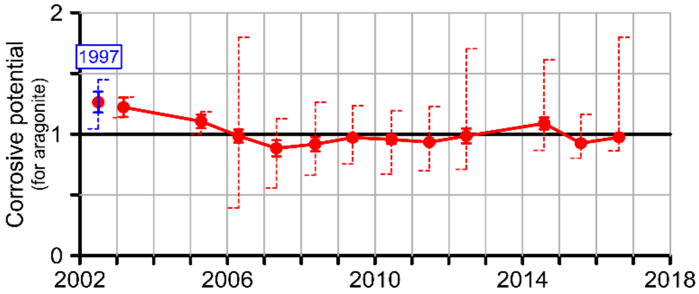

**Figure 52.** Values of an index Ω in surface seawater of the Canada Basin. Ω represents the corrosive effect of seawater on hard-shelled organisms, here for a limestone called aragonite. The threshold for damage is 1. Dashed lines span each year's range of variation across the basin. Unpublished data courtesy of Y. Zhang.

An increase in the acidity of near-surface seawater is an emerging source of stress on the ecosystem that has been discovered via sustained observation in the Canada Basin. The increase in acidity results in part from increasing carbon dioxide in the atmosphere, which is gradually dissolving in the World's oceans to form carbonic acid. Within the Canada Basin in particular there is an additional effect from melted sea ice and river water, which are both naturally more acidic than seawater and which, as noted above, have been accumulating in the surface waters of the Canada Basin during the last two decades. Near the surface and within the cold layer centred at about 120-m depth, seawater acidity has increased enough to dissolve the hard shells of some marine organisms. The corrosiveness of surface seawater in the Canada Basin, represented by quantity Ω, specific to each type of carbonate ion in shells, is shown in Figure 52 for aragonite. Values of Ω less than one threaten shelled marine organisms.

### 5.2.2. Mackenzie shelf, Amundsen Gulf

The Mackenzie shelf/Amundsen Gulf marine area is the best known in the Canadian Arctic region. Locations within this area have been under continuous year-round observation since 1990 using autonomous instruments on submerged moorings and annual ship-based surveys.

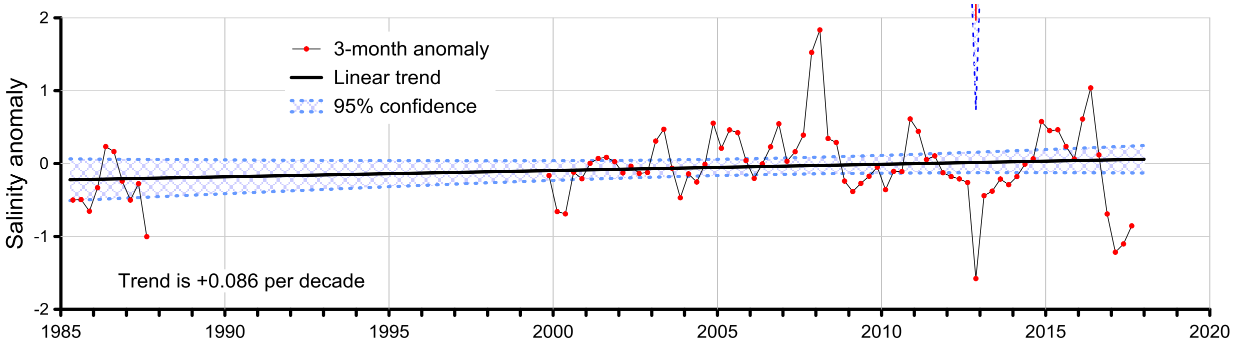

**Figure 53.** 3-month anomaly in seawater salinity near the seabed of the Mackenzie shelf of the southern Beaufort Sea (source: DFO, unpublished data).

The continuous records we hold are those of ocean variables most readily and reliably observable by autonomous instruments. They provide indications of variability and change in the ocean but are far from being comprehensive in an ecological context.

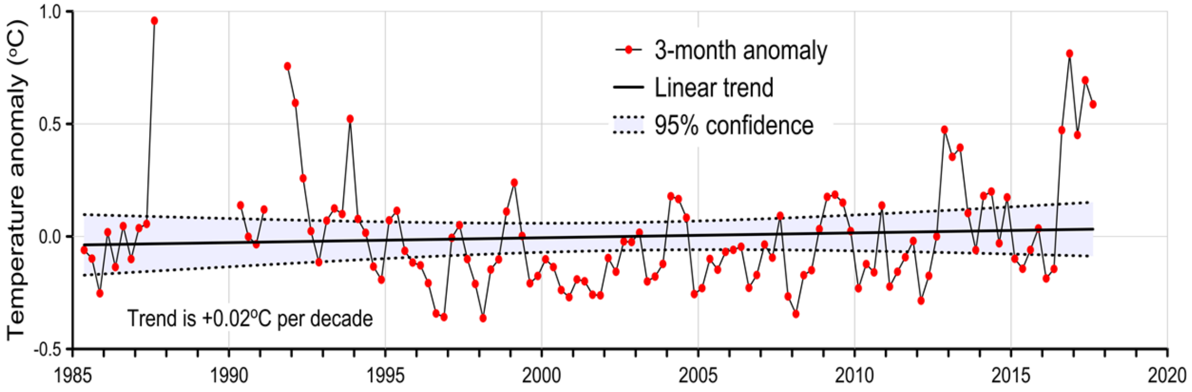

**Figure 54**. 3-month anomaly in seawater temperature near the seabed of the Mackenzie shelf (source: DFO, unpublished data).

The longest records document salinity and temperature 3 m above the seabed (53-m depth) at the middle Mackenzie shelf. Average salinity here is about 32.5, lower in summer and higher in winter; the full range since 1985 has been 27.0 to 36.5. Because such variability masks progressive change, we examine seasonal anomalies – the differences between seasonal average values for a particular year and the average for that season over all years. Figure 53 displays the time series and its trend, an increase by 0.26 in three decades. An increase, equivalent to having less fresh water on the shelf than in earlier times, is consistent with a transfer of fresh water from the shelf to the Beaufort Gyre, where it has been accumulating over the last 15 years. The trend is too small relative to natural variation (that is, it is not different from zero with 95% confidence) to be judged a substantive change in the ocean regime here.

Temperature near the seabed at the middle of the Mackenzie shelf is typically near -1.5°C, a few tenths above freezing. Since 1985 it has varied between -2 and 1.5°C. The time series of seasonal anomalies in temperature (Figure 54) reveals a weak trend, one 50th degree per decade, that is also too small relative to variation to be judged a substantive change in the ocean regime here. At this location and depth, the Arctic Ocean is clearly not getting warmer.

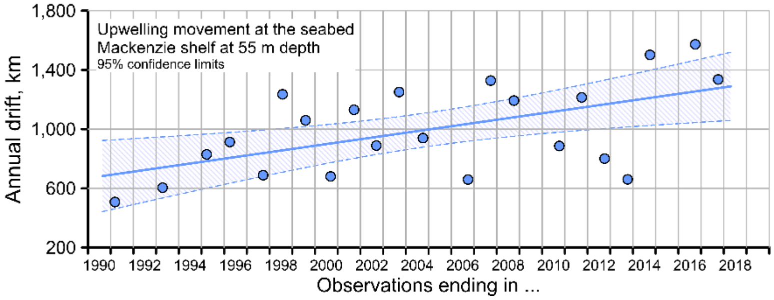

**Figure 55.** Upslope distance travelled annually by bottom water on the middle Mackenzie shelf. The doubling of this movement over the last quarter century is statistically significant with 95% confidence (source: DFO, unpublished data).

Also at this location we have measured ocean current just above the seabed every hour of every day since 1990. By adding each small hourly movement over the span of a year we calculate an annual distance and direction of water movement across the seabed. The component of this flow that is directed towards the coast represents the movement of water from deeper to shallower areas. If sufficiently intense and prolonged, such upslope movement ("up-welling") is capable of raising nutrient-rich water Pacific Water from below 100-m depth on the continental slope into the sunlit zone on the inner shelf. Figure 55 shows that this up-welling component has doubled during the last quarter century; this change is large enough in relation to variation to be judged, with 95% confidence, a substantive change in the ocean regime here. The measured increase in the up-welling of deeper more saline water is consistent with the increase in shelf-water salinity already documented. Also, since upwelling favourable winds in the southern Beaufort Sea are easterly, and easterly winds are associated with high air pressure over the Canada Basin, up-welling onto the shelf is consistent with the afore-mentioned prolonged anti-cyclonic phase of the Arctic circulation. Moreover, since concentrations of dissolved nutrients increase with depth in the upper 150 m, stronger up-welling can be presumed to be beneficial to the marine food web on the shelves of the southern Beaufort Sea.

Sea ice on the Mackenzie shelf has been monitored in detail since 1991. This area differs from the central Arctic Ocean in having always had ice-free summers – it is part of the Arctic's seasonal ice domain. As in the case of seawater salinity and temperature, variation and change in ice are most easily seen as anomalies relative to a long-term average. We use monthly anomalies for sea ice because its properties vary widely during the year.

Figure 56 displays ice-concentration anomalies measured by submerged sonar at mid-shelf. Data from cold months are plotted using black dots; wintertime anomalies are very close to zero throughout the record – no change in ice concentration at this time of year. Data from the warmer half of the year are plotted in red; summertime anomalies also are typically close to zero, indicating consistently ice-free seas here in summer now as in the past. The remaining feature is a double peaked anomaly in most years, indicating anomalous conditions in June and October, between winter and summer; the peaks are positive (more ice than the long-term average) in the early years and become negative more recently. They demonstrate that ice reduction in the seasonal sea-ice zone has occurred via lengthening of the summertime ice-free period at both ends. The overall trend of 4.6% per decade is not so large relative to natural variation to be judged a change in regime and is appreciably smaller than the loss of (old) ice in the central Arctic Ocean.

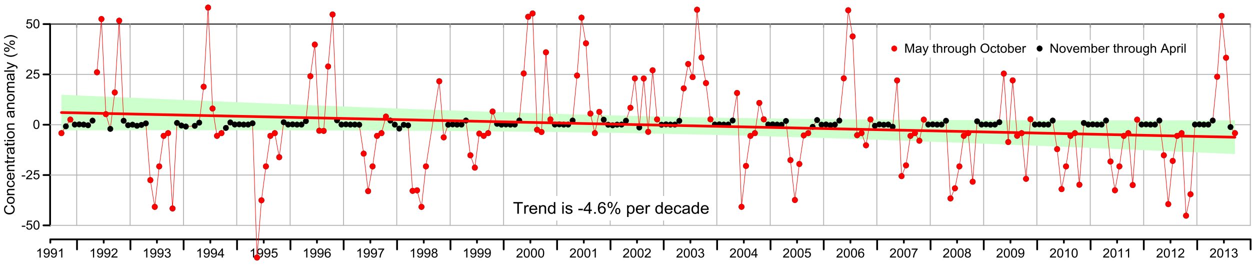

**Figure 56.** Monthly anomaly in sea-ice fractional coverage, or ice concentration, at the middle Mackenzie shelf. Ice concentration here has decreased by 4.5% per decade on average over the last quarter century. 95% confidence limits in green (source: DFO, unpublished data).

This change also is consistent with the prolonged clockwise phase of Arctic circulation and the persistent east wind across the southern Beaufort that it has generated in spring and fall (Proshutinsky and Johnson 1997). Such wind now pushes ice faster to the west, establishing an

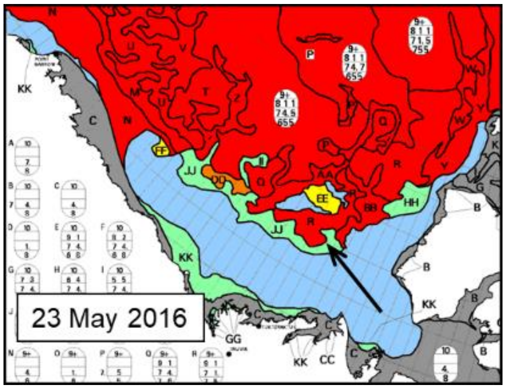

**Figure 57.** Ice chart from mid-May 2016, showing a broad expanse of open water in the south-eastern Beaufort Sea. Easterly winds (arrow) typically clear this area of ice in late winter, long before snow and ice begin to melt.

ice-free sea surface earlier in spring and later in fall (Figure 57). DFO's ice-tracking data from the mid-Mackenzie shelf show an increase of this annual westward push by 150 km in the last 25 years.

The submerged depth (viz. draft) of pack ice has also been monitored at Site 1 (Figure 48) at the middle of the Mackenzie shelf since 1992 (Melling and Riedel 1995, 1996; Melling et al. 2005). Figure 58 displays the areal fraction of open water and that of open water plus new, thin and medium ice (A) and monthly mean values of average ice draft (B), including open water as "ice" of zero draft. It is interesting to compare the observations from mid-Mackenzie shelf (Site 1, Figure 58) with those from the Site D (Figure 49) in the (former) old-ice zone, 460 km to the north-northwest. Figure 49a (Site D) and Figure 58a (Site 1) look very similar, except that the annual period of open water is more reliable and lasts longer on the shelf. A typical monthly maximum ice draft on the shelf (Site 1) in late winter is 3 m, 50% larger than the value observed farther offshore (Site D). The principal reason for the greater value on the shelf is the greater volume of ice in pressure ridges there. The 80th percentile, a measure of ice ridging, ranges between 4 and 7 m on the shelf in contrast to values not much more than 2 m farther north. There have been winters of very light ice at Site 1, particularly those of 1997-1998 and 2007-2008; these coincide with conditions of strong persistent east wind which continually pushed younger ice out of the south-eastern Beaufort Sea. The trend in mean ice draft, calculated from monthly draft anomalies (not shown), is a slow thinning by about 6 cm per decade, much smaller than the 40 cm per decade observed at the Canada basin site. The small trend on the Mackenzie shelf is

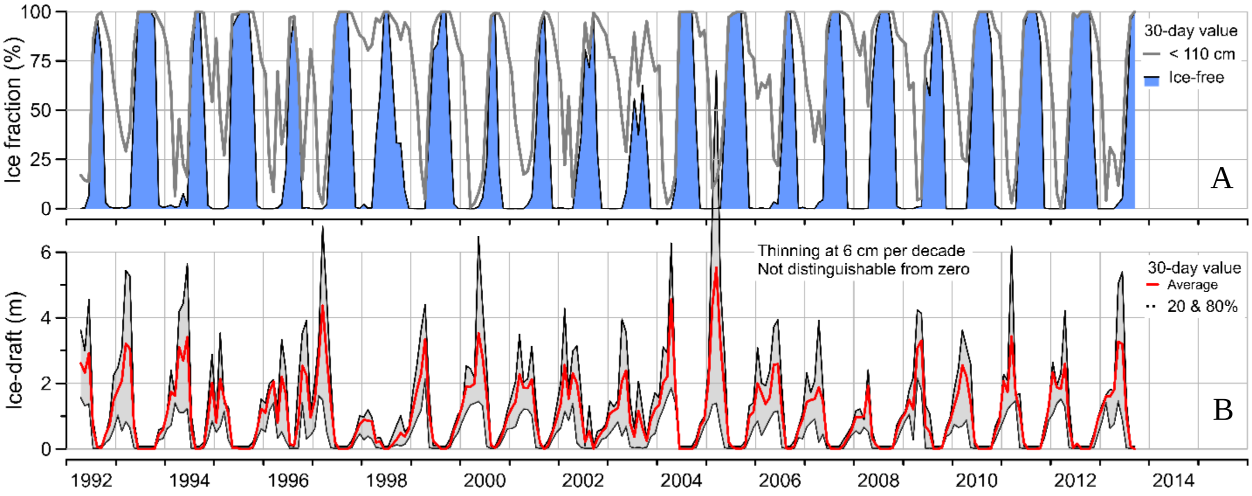

**Figure 58.** Variation of pack ice measured by ice-profiling sonar at Site 1 of the DFO Beaufort Observatory (mid-Mackenzie shelf). a) displays the extents of open water and of ice less than 1.1 m in draft. b) displays average ice draft and its percentiles (source: DFO, unpublished data).

not different from zero with high confidence. Insight provided by this unique data record suggests that seasonal ice on continental shelves is responding differently to climate change than is old ice over its central deep basins.

Sea-ice changes have a variety of ecological implications. Decrease in ice (extent, thickness, mobility) is beneficial to some forms of life, improving ease of access, light availability and safety from predators for example. It is detrimental to others, reducing ease of access and safety from predators and shrinking habitat. The use of sea ice by marine mammals is summarized in Appendix A.

### 5.2.3. Canadian Polar Shelf

Because there has been only minimal support for sustained observing of the Canadian Polar shelf, we are not aware of the state of the ocean over most of this vast area. Knowledge of variation and change is sparse compared with that in the Beaufort Sea. However, we do have long systematic records of ice conditions thanks to Earth observing satellites and the Canadian Ice Service. The multi-year ice on the Canadian polar shelf has particular interest because it, in combination with an adjacent part of the Canadian exclusive economic zone, will likely form much of a future “last ice area” (http://www.dfo-mpo.gc.ca/oceans/conservation/higharctic-hautarctique/index-eng.html), the presumed remnant of the present polar ice pack after further decades of climate warming. Melling (2002), Howell et al. (2008) and Howell et al. (2015) provide information on multi-year-ice dynamics in this area.

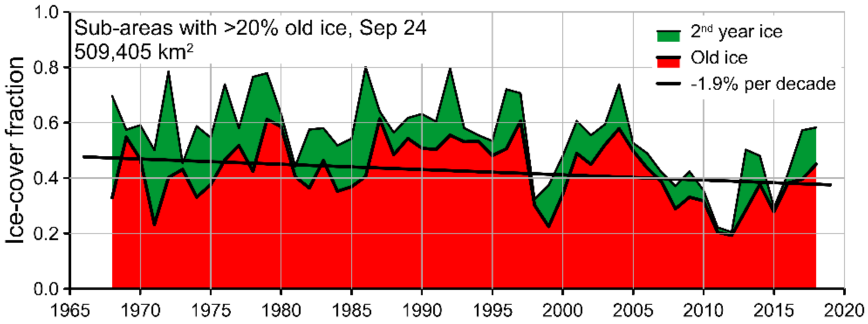

**Figure 59.** Fraction of multi-year ice (red) within sub-areas of the Canadian polar shelf where its fraction averages 20% or more. The green area represents first-year ice on September 24, to become second-year ice on October 1 (source: IceMap, Canadian Ice Service 2019).

A half-century of ice-cover observations by the Canadian Ice Service allows a long-term view of ice variation and change over the Canadian polar shelf. Figure 59 displays ice-type fractions computed over sub-areas with at least 20% multi-year ice (High Arctic, Nares Strait, Parry Channel (west), M’Clintock Channel, Larsen Sound, Victoria Strait). The chosen date reveals ice that has survived summer’s thaw. Old ice covers about half the sea surface here and the dominant signal is decadal variation. There has been a small decrease in the amount of multi-year ice here (less than 10% over 50 years), which statistics suggest is likely fortuitous; it is largely attributable to prolonged dips during the second half of the record (1998-2000 and 2008-2013).

Data from two sources illustrate variation and change in the thickness of ice over the Canadian polar shelf. Canadian weather agencies have measured the thickness of nearshore fast ice at locations across Canada since the late 1940s (Brown and Cote 1992; Flato 1996; Dumas et al. 2005; Howell et al. 2016). Three stations, Eureka, Resolute Bay and Cambridge Bay, near 80°, 75°, and 69°N, respectively provide a view along a north-south Arctic transect (Figure 60). The larger panels to the left display yearly values (red dots), a 5-year running average and a trend line. The trends are both positive and negative, small (between -3.8 and +1.7 cm per decade) and not statistically distinguishable from zero. The trends in pack ice thickness on the Beaufort shelf and Canada Basin are 1.5-3 and >10 times larger, respectively, than on the Canadian Polar shelf. The scatterplots of ice thickness versus snow depth (Figure 60) illustrate a strong negative correlation between the two variables, suggesting that varying air temperature is of secondary importance to winter’s ice growth in this area (Dumas et al. 2005).

The thickness of multi-year fast ice in the western Canadian High Arctic was systematically mapped during winters of the 1970s via drilling during seismic surveys (Melling 2002). However, it was not until 2003 that DFO began to take a second look, by placing ice-profiling sonar in the straits (Nares Strait, Penny Strait, Byam Martin Channel) via which ice exits the "last ice area". Instruments in Nares Strait during 2003-12 have provided the longest recent time series; 25-km-mean values of thickness spanned 3-6 m with an overall average of 4.5 m (DFO, unpublished data). Although there are no comparative data here from past decades, the recent values are consistent with the spatial pattern of ice thickness in the Arctic Ocean in the 1960s to 1980s (Bourke and Garrett 1987), suggesting little change.

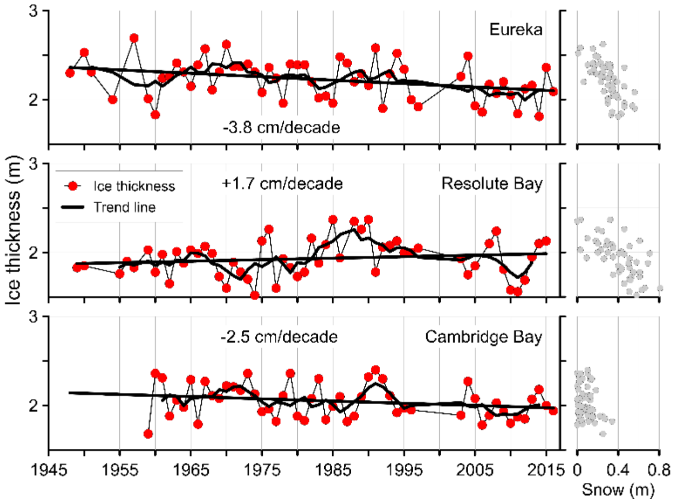

**Figure 60.** End-of-winter thickness of fast ice at 3 stations on the Canadian polar shelf since the late 1940s. The scatter plots to the right show that years with thinner ice tend to be those with deeper snow (source: Canadian Ice Service, unpublished data).

Observations made in Byam Martin Channel in 2011 are compared against those from the 1970s (Melling 2002) in Figure 61. The recent data (shaded area) reveal a distribution of ice volume versus thickness that equals or exceeds that in the 1970s (coloured traces). It is clear that in 2011 at least, multi-year ice was much like that of earlier decades. Data from 2011 form part of the series from four recent summers plotted in Figure 62. The overall means for each summer (about 3 m) are close in value and comparable to ice measured in the 1970s. In Byam Martin Channel evidence of a dramatic thinning of multi-year ice during the last 2-3 decades is lacking.

The monitoring of seawater movement across the shelf between the Arctic and the Atlantic is the oceanographic issue on the Canadian polar shelf that has received most attention. Movements from the Arctic to the Atlantic deliver dissolved nutrients to the productive oceans of the eastern Arctic and temperature marine regions of Canada; they carry fresh water that may inhibit mixing of surface and sub-surface waters so that nutrient delivery to the photic zone may be restricted; Arctic fresh water in large enough quantities has the potential to block climatically important deep convection in the Labrador Sea. Seawater movement from the Atlantic to the Canadian polar shelf via the West Greenland Current brings heat that inhibits sea-ice formation, promotes early ice clearance in eastern Baffin Bay and contributes to melting of tide-water glaciers in Canada's High Arctic.

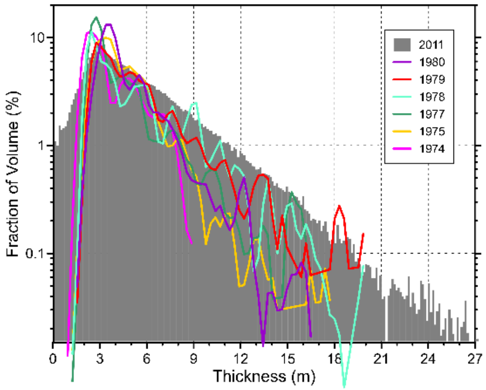

**Figure 61.** Volume fractions of pack ice at each ice thickness in Byam Martin Channel. Coloured curves are for the 1970s; the shaded area is for 2011 (source: DFO, unpublished data).

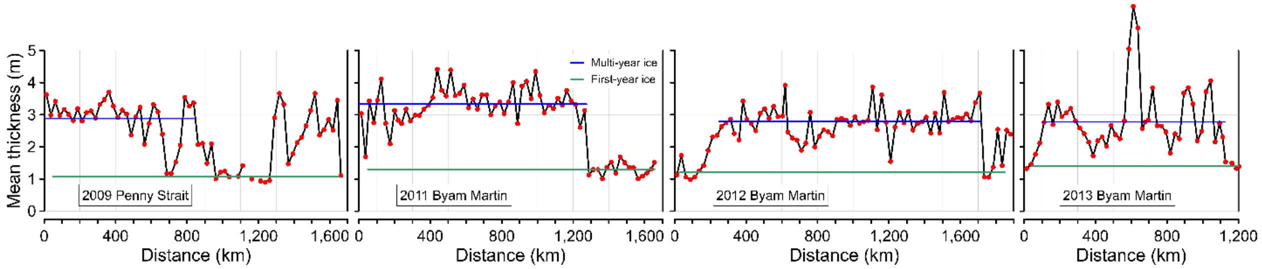

**Figure 62**. 25-km-mean thickness values of ice at the southern edge of the "last ice area" during 4 recent summers. Zones of both first-year and multi-year ice were observed. The overall mean thickness for multi-year ice was about 3 m (source: DFO, unpublished data).

First attempts to measure Canadian Arctic through-flow were made in Barrow Strait near Resolute Bay in the early 1980s. Efforts were resumed in western Lancaster Sound in the late 1990s with new sonar and compass technology helping to reduce the challenges. Even so, only observations of ocean current, temperature and salinity have been sustained.

The net eastward movement of seawater through Lancaster Sound (Peterson et al. 2012) is displayed in the top frame of Figure 63; the unit (milli-Sverdrup or mSv, is 1000 $m^3$/s, equivalent to 31 $km^3$/y). There is a clear annual cycle with strongest flow in summer and a weak downward trend (red line) that is not statistically significant. The black dashed line is the trend during 2003-09 to be discussed below. The lowest annual mean value occurred during 2007-08 coinciding with the highest value of the Arctic Oscillation index. The overall mean rate of flow was 460 mSv. This observatory was closed in 2011, although effort is presently underway to re-establish it.

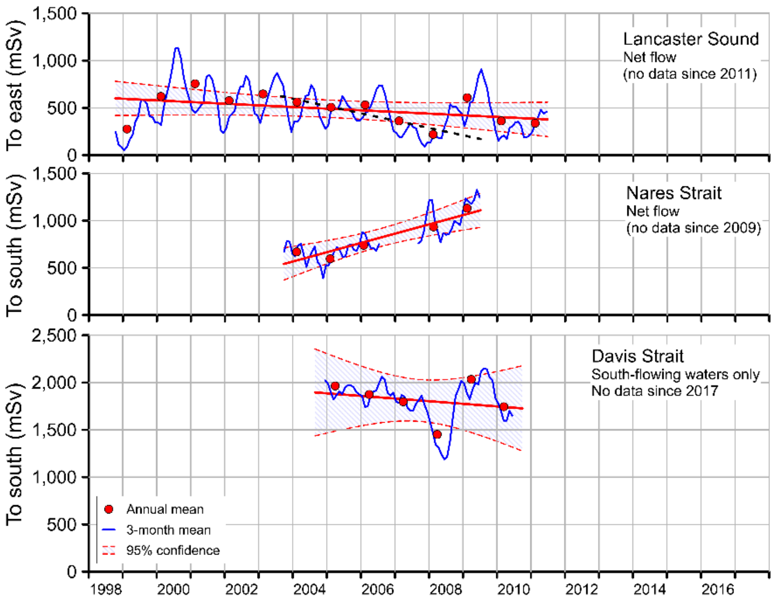

**Figure 63.** Measured flow of seawater from the Arctic to the Atlantic through Lancaster sound, Nares Strait and Davis Strait. The first two flows feed the third. The unit is the milli-Sverdrup, equal to 1000 $m^3$/s.

An observatory to measure flow southward from the Arctic to the Atlantic through Nares Strait was established in mid-2003. It operated in its full configuration for 6 years and in a cut-back form until 2012, when it was closed. The middle frame of Figure 63 displays seasonal and annual means of net southward water movement during the first 6 years (Münchow 2016). Seasonal variation is not as pronounced in this channel, but a trend to stronger flow is statistically significant. Note that the increase in Arctic through-flow through Nares Strait during 2006-09 was synchronous with and about the same magnitude as the decrease in outflow through Lancaster Sound (see black dashed trend line in the top frame). The overall mean rate of flow was 815 mSv.

An observatory spanning Davis Strait was activated in 2004, a year later than in Nares Strait. This observatory was active until 2017, but the record presently available ends in mid-2010 (Curry et al. 2014). The installation was placed to capture the bulk of Canadian Arctic through-flow on one cross-section. Observations are displayed in the bottom frame of Figure 63. This plot accommodates larger values of flow; it also differs from the two above in that only the Arctic water (salinity less than 33.7 and south-flowing) has been considered. The strong anti-clockwise circulation around Baffin Bay of more saline water of the West Greenland Current, not part of the through-flow, has been ignored. As in Nares Strait, seasonal variation is not a strong signal. As in Lancaster Sound the modest downward trend measured over 6 years is not statistically significant. The overall mean rate of flow was 1815 mSv, appreciably larger than the sum of contributions (1275 mSv) from Nares Strait and Lancaster Sound. However, each of the three mean values was evaluated over a different interval of time. Even when the 300 mSv flow via Cardigan Strait and Hell Gate (DFO, unpublished data) is included, there remains an appreciable residual (240 mSv) that awaits explanation.

Upstream and downstream impacts of these Arctic-Atlantic transfers of seawater will vary with the rates of transport. Oceanographers are striving for the best possible observed values, so that the reliability of climate prediction models in representing the Canadian Arctic through-flow can be evaluated. Once this is accomplished, the validated models can be used to predict the size and ecological impacts of its future changes.

### 5.2.4. Baffin Bay

Ship-time allocated to the maintenance of the observatory in Davis Strait has enabled annual collection of ocean chemical data along the cross-section where instrumented moorings were installed. The trace chemical of special interest because of its impact on seawater acidity has, as in the Canada Basin, been carbon dioxide. Because carbon dioxide is more soluble in cold water, the impact on Arctic waters and calcifying organisms holds special interest.

The upper frame of Figure 64 displays values of a quantity Ω related to seawater's potential to corrode carbonate shells (Azetsu-Scott et al. 2010). Values of Ω less

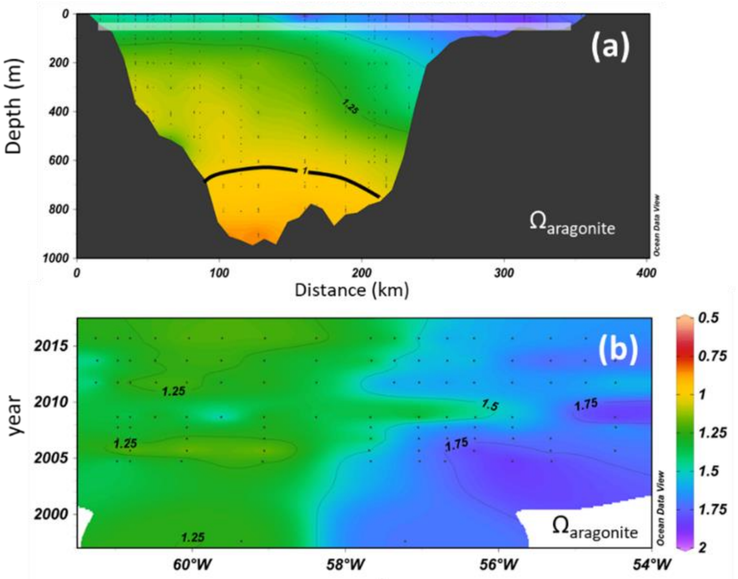

**Figure 64.** (a) Average ocean acidity across Davis Strait during 1997-2015, in terms of the saturation state, Ω, for aragonite, a form of limestone; (b) Time variation of Ω at 50-100m. Shells and skeletons of organisms start dissolving in seawater with Ω less than 1 (source: DFO, unpublished data).

than one (yellow and red), potentially harmful to shelled organisms, prevail near the seabed. Slightly higher values (green and blue) near the surface are in the stressful range. The lower frame displays Ω at 50-m depth during 2005-2016. Values in the Arctic outflow, on the Canadian side, are marginally damaging whereas those on the Greenland side are less alarming. The plotted data do not indicate that conditions are deteriorating rapidly on the Canadian side although inter-annual variation is evident.

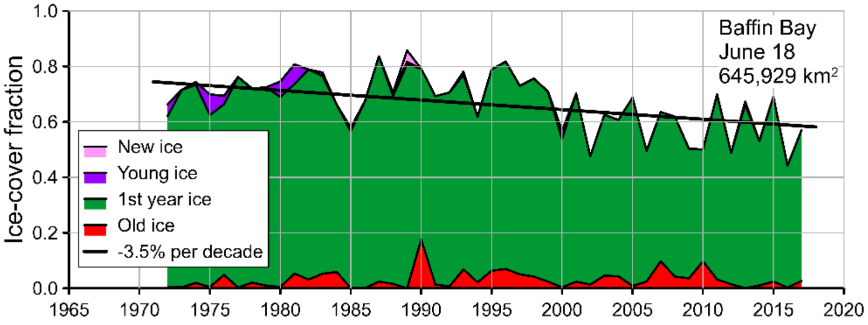

**Figure 65.** Fractional coverage by ice type of Baffin Bay in mid-June. The downward trend in ice extent on this date (significant at 95% confidence) indicates that pack ice here is now clearing earlier in spring (source: IceMap, Canadian Ice Service 2019).

The ice cover of Baffin Bay is predominately seasonal, ranging between almost complete coverage on April 1 to only a small area of ice in the north-west in mid-September. It is therefore most useful to examine ice extent in the shoulder seasons when the cover of ice is shrinking (spring) or expanding. At these times, a trend in ice extent is equivalent to a change in the length of the ice-covered season. Figure 65 displays the fractional coverage by ice type of Baffin Bay in mid-June. Apart from small areas of old ice in the north-west, the dominant ice type is thick first-year ice. Coverage by thick first-year ice on this date has decreased at an average rate of 3.5% per decade during the last 47 years. However, since conditions appear to have been stable here until the late 1990s, much of the change has occurred since then. The downward trend indicates that pack ice is now clearing earlier in spring than in the past.

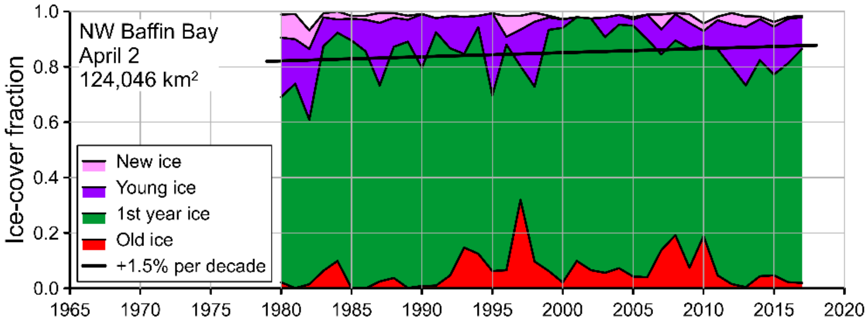

**Figure 66.** Fractional ice coverage of north-western Baffin Bay in early April. A weak upward trend in the extent of thick first-year ice on this date implies a weak downward trend in the size of the North Water (source: IceMap, Canadian Ice Service 2019).

A polynya is an area of the sea surface in winter with ice cover much thinner than on the ocean around it. The North Water (Case Study 8), a large polynya in northern Baffin Bay, is an important ecological feature of the Canadian Arctic region. Its existence is attributable to the influence of prevailing winds flowing out of Smith Sound, Lady Ann Strait and Lancaster Sound, which are locally intensified through confinement by the high ground of bordering islands (Melling et al. 2001; Samelson et al. 2006). Polynyas are dynamic features that expand and contract on weekly time scales as areas of exposed sea surface freeze and winds change. However, the presence of open water, new ice and young ice in north-western Baffin Bay in early spring provides a metric of North Water's occurrence and variation over time

(Figure 66). An observed weak upward trend in the extent of thick first-year ice here implies a weak downward trend in the size of the North Water (not statistically significant). So, except for a high level of inter-annual variation this feature appears to have been stable at this time of year.

### 5.2.5. Hudson Bay

Sustained, systematic observations of Hudson Bay are scarce. As in other parts of the Canadian Arctic region, the data on sea-ice cover form the most useful record of past conditions and the likelihood of change. As in Baffin Bay, it is useful to examine the ice cover in mid-June for possible evidence of change in the length of the ice season and in early April in north-western Hudson Bay, to determine if the flaw lead opened by strong offshore winds at this time of year has grown larger over time.

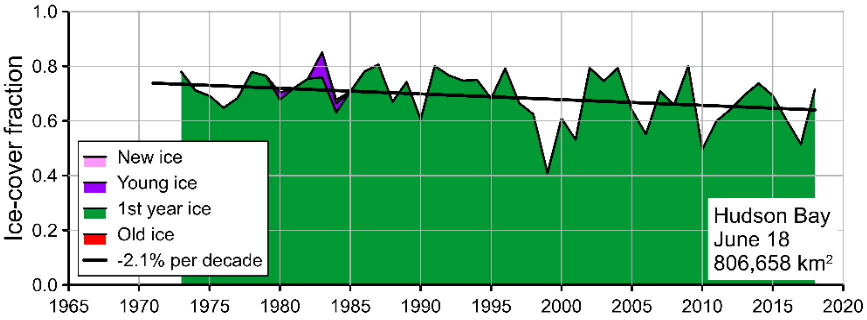

**Figure 67.** Fractional coverage by ice type of Hudson Bay in mid-June. The weak downward trend in ice extent on this date is not statistically significant (source: IceMap, Canadian Ice Service 2019).

Figure 67 displays the ice cover fraction by ice type of Hudson Bay in mid-June. A substantial fraction of ice has already melted by this date, including all younger ice forms, leaving almost entirely thick first-year ice. The downward trend in ice extent (-2.1% per decade) has low significance but as in Baffin Bay, it reveals a trend to earlier clearance of ice in spring. Because sea ice circulates counter-clockwise around Hudson Bay, ice clears first from the north-western area of the bay, in response to north-westerly wind. Indeed, an examination of the ice record for this area in mid-June (not shown), reveals this trend towards earlier clearance more strongly; ice cover has decreased at a rate of -4.4% per decade for this week, or by 20% over the 45-year length of the record.

The ice record for north-western Hudson Bay in early April (Figure 68) resembles that for the North Water, in terms of both its decadal variations and its trend, which suggests a weak trend towards a narrower flaw lead. This trend runs counter to the sizeable negative trend of -4.4% per decade in the same area only 2.5 months later. This difference may indicate that atmospheric change has yet to have a strong influence on the ice coverage of Hudson Bay in the depth of winter.

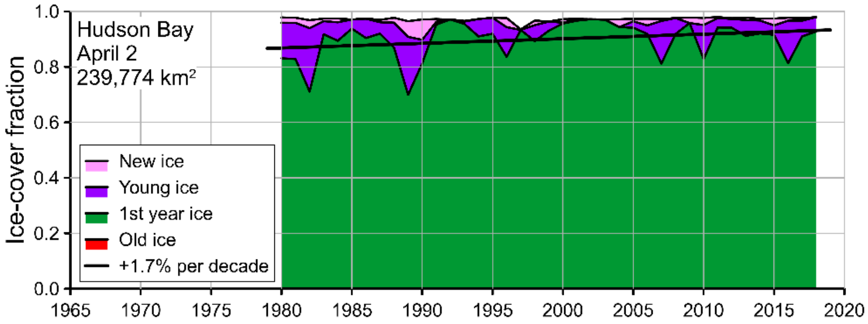

**Figure 68.** Fractional ice coverage of north-western Hudson Bay in early April. A weak upward trend in the extent of thick first-year ice on this date implies a weak downward trend in the width of the flaw lead (source: IceMap, Canadian Ice Service 2019).

### 5.3 Regional Responses in Primary Production: Northward Expansion and Hot Spots

The phytoplankton bloom is an important event in annual phenology of Arctic Ocean ecosystems as it supports a large part of the primary production that feeds higher trophic levels of the marine food web. The transfer of primary production from the short-lived phytoplankton bloom to upper trophic levels largely depends on temporal coupling between grazers and the timing of bloom occurrence. In the Arctic, due to the short productive season, many species have adapted to the sudden and intense burst of food supplied through the phytoplankton bloom, leading to a tight temporal connectivity that ensures efficient transfers from primary producers up to marine mammals.

Primary producers, as their name accurately points out, produce organic matter from elements in the water column (nutrients, Section 4.2) using solar energy as a fuel source through photosynthesis. This means that primary producers need both sunlight and nutrients in order to produce the organic matter that supports all trophic levels in the marine food web. Primary producers set the limit for higher trophic-level production, within the Arctic, as in other oceans, as there cannot be more production than what is supported by primary-produced organic matter.

Because snow-covered sea ice strongly attenuates light and its transmission to the water column, changes in sea-ice conditions have consequential effects on phytoplankton production. In the Canadian Arctic, remote sensing estimates of annual primary production show an increase by more than 40% between the period 2002-2004 and 2010-2014 (Figure 69).

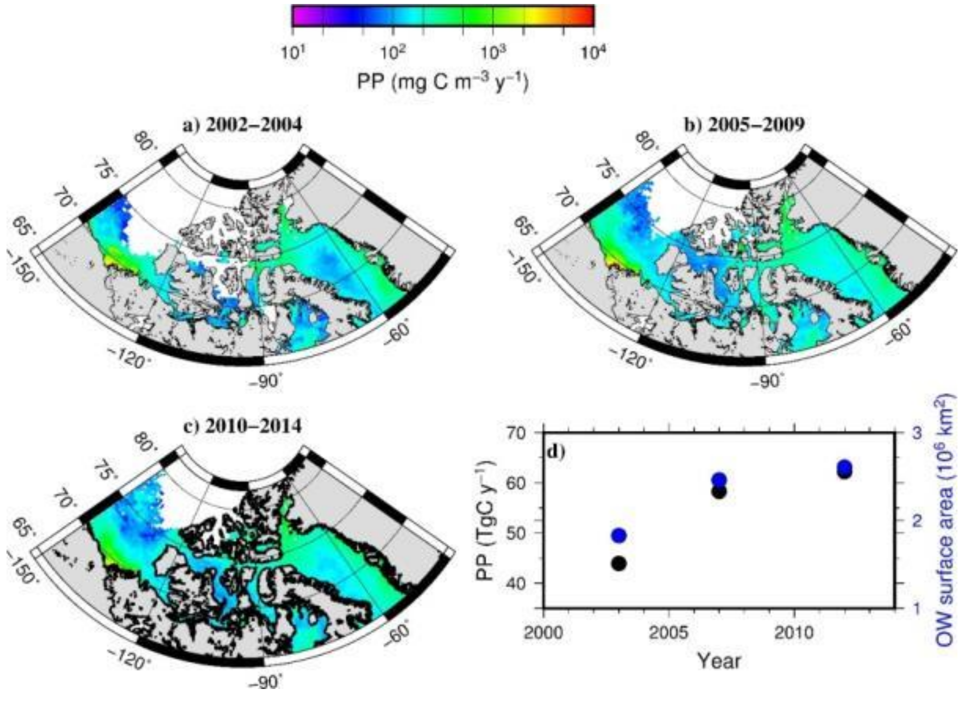

**Figure 69.** Averaged primary production in the Canadian Arctic derived using MODIS L3 images for three periods: a) 2002-2004, b) 2005-2009 and c) 2010-2014. Panel d) corresponds to the total mean annual primary production for the three periods (black symbols) and the maximum surface area of open waters (OW) for each period (blue symbols) (data source: Takuvik, DOI: 10.5884/12513).

For these estimates, the Canadian Arctic is defined as the region bounded between 65° and 85°N and between 40° and 110°W. The increase in primary production in Canadian waters is attributed to a longer open-water season and an increase in the areal coverage of open water for a given period (e.g., Section 5.2.4). There is a strong correlation between the maximum surface area of open waters and annual primary production as estimated from satellite imagery.

In addition to the increase in annual open-water primary production over the last decade, the phytoplankton bloom is also progressing northward. In the Beaufort Sea, remotely observed phytoplankton blooms reached near 80°N during the period 2010-2014 whereas surface blooms were only observed up to ca. 75.5°N during the 2002-2004 period. Ice-edge blooms are also documented in high-latitude regions where they were not previously observed (Figure 70). At the pan-Arctic scale, despite strong regional variability, ice-edge phytoplankton blooms have progressed northward at a rate of 1 degree of latitude per decade between 2003 and 2013, reaching 82°N (Renaut et al. 2018).

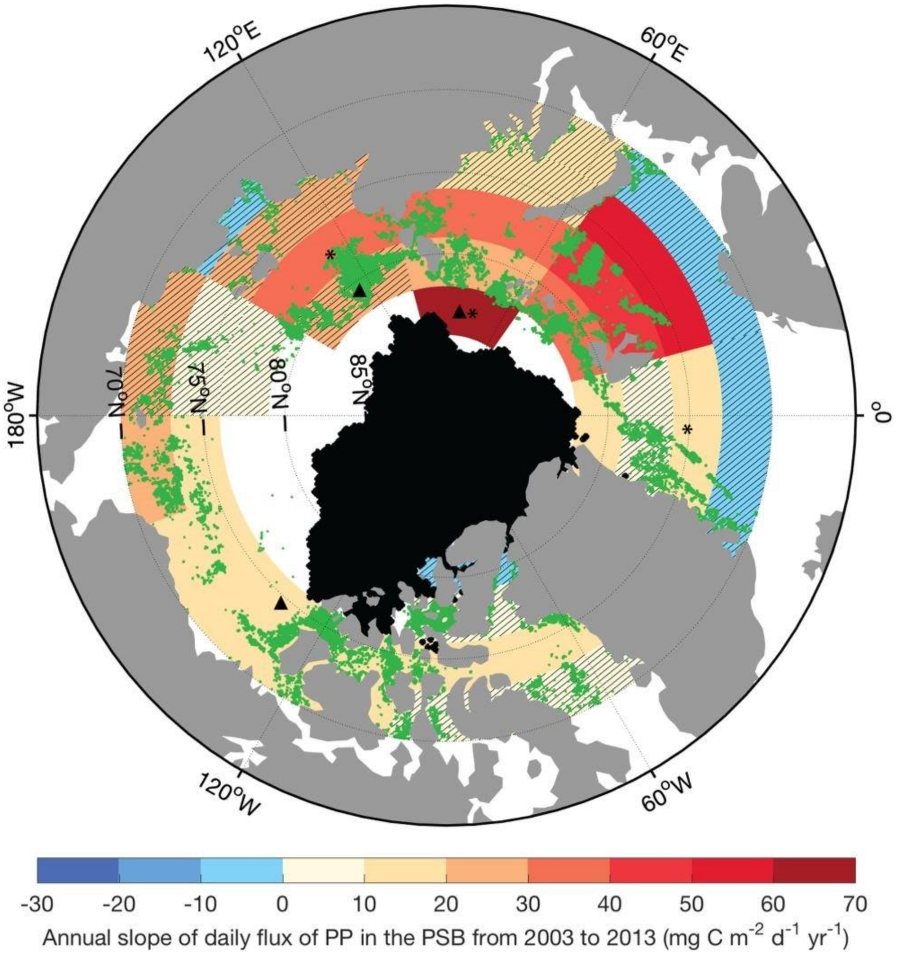

**Figure 70.** Estimates of annual trends in primary productivity (PP) during the phytoplankton spring bloom (PSB) period determined from satellite ocean colour data between 70° and 90°N. Note green pixels corresponding to new phytoplankton spring blooms observed since 2010. Color bands indicate if annual PP has been decreasing (blue tones) or increasing (orange/red tones) during the study period (2003-2013). Striped bands denote areas without significant trends in primary productivity. Black areas have no data due to the presence of sea ice. White areas are not included in the analysis or do not have enough observations. (source: Renaut et al. 2018).

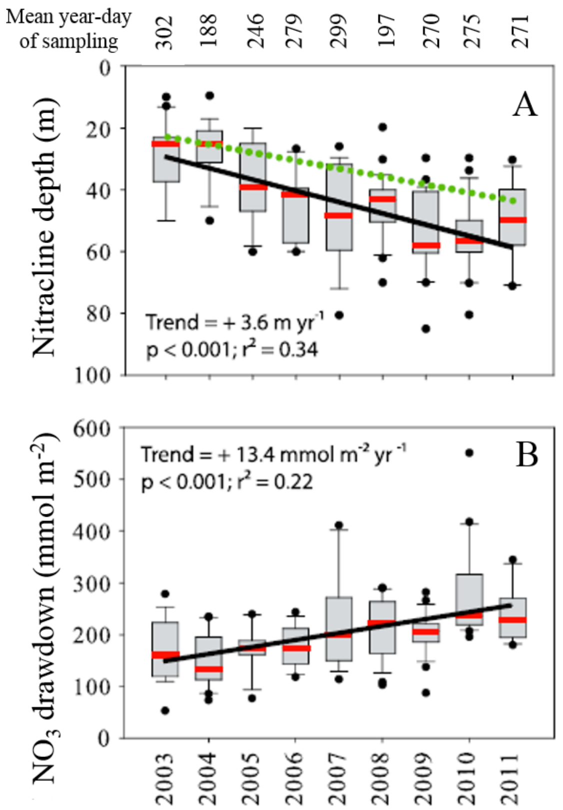

**Figure 71.** Trends in a) depth of nitracline and b) $NO_3$ drawdown in the Beaufort Sea from 2003 to 2011 (source: Bergeron and Tremblay 2014).

Region-specific changes in sea ice result in regionally different effects on primary production. A pan-Arctic remote sensing analysis points to a range of changes in primary production, from a decline to significant increases across the different Arctic shelves (Arrigo and van Dijken 2015).

In the Canadian Arctic region, there is strong regionality in responses. On the Beaufort Sea shelf (Section 5.2.2), the changing sea-ice cover allows for more light to penetrate deeper in the water column, providing suitable conditions for phytoplankton growth. The resulting effect is an increase in nitrate drawdown and annual productivity as phytoplankton cells can access a deeper nutrient reservoir (Bergeron and Tremblay 2014) (Figure 71).

In contrast, in offshore regions such as the Canada Basin there is evidence that the Beaufort anticyclonic gyre is driving freshwater accumulation, from melting ice and riverine input, in the area (Section 5.2.1, Figure 50) impeding the phytoplankton capacity to access the deep nutrient reservoir, thereby limiting primary production (McLaughlin et al. 2010; Coupel et al. 2015). The strengthening of the surface stratification also hampers the resupply of nutrients during winter. Consequently, winter nitrate concentrations can be one order of magnitude lower over the basins than on the shelf (Codispoti et al. 2013), setting the stage for lower primary production. Similarly, a decrease in primary production linked to sea-ice declines and associated changes in surface stratification and mixing has been observed in Baffin Bay (Bergeron and Tremblay 2014) and the North Water Polynya (Case Study 8).

Regional processes also affect the composition of phytoplankton communities and thereby food web transfers. As the surface mixed layer deepens on the shelf, phytoplankton communities dominated by species adapted to low light conditions thrive, favoring nano-sized flagellates (Coupel et al. 2015). In contrast, in the nutrient-depleted upper layer of the offshore basins, smallest phytoplankton cells (pico-sized) dominate as they are more efficient at low ambient nutrient concentrations (Li et al. 2009). These changes in the structure of marine ecosystems are fundamental to the fluxes of energy and materials towards harvestable resources as different phytoplankton groups do not equally contribute to food-web transfers.

Overall, these changes in the magnitude and distribution of primary producers are anticipated to cascade throughout marine food webs, benefiting species that can take advantage of the longer open-water period rather than "specialists" such as Arctic Cod, seals and polar bear that are finely-tuned to the sea ice and its associated food chain to meet their energy requirements (Case Studies 4 and 9). Regional processes influencing the location of productive hot spots, the composition of phytoplankton species also have cascading effects throughout the food web, with largely unknown consequences on local, regional and global resource inventories.

## 5.4 Fish and Invertebrates Variability

### 5.4.1 Anadromous Fishes

Anadromous fishes are one group that may be well positioned to take advantage of the documented trends toward longer open-water seasons and regional changes in productivity in the Arctic Ocean. These species make seasonal use of coastal habitats, migrating from upstream freshwater winter refuges and spawning/rearing areas to marine waters shortly after ice break-up in spring. Here they spend the short Arctic summer feeding and taking advantage of the high productivity in brackish waters created by the discharge of tributaries ranging in size from the numerous small lake outlets that characterize much of the Baffin Island coastline in the east (Moore 1975; Loewen et al. 2010) to larger rivers such as on the Kivalliq coast, the Yukon North Slope (Firth, Babbage, Big Fish rivers), and Hornaday and Mackenzie Rivers to the west. The large rivers can require species to migrate extensive distances (Sprules 1952). For example, Inconnu (*Stenodus leucicthys*), a species with one of the longest migrations, has been shown to undertake seaward migrations of up to 1,800 km (Stephenson et al. 2005).

Nearly all of the anadromous species in the north (most of which are salmonids) support important subsistence and commercial, as well as limited, recreational fisheries. Arctic Char and Dolly Varden (*Salvelinus malma*), in particular, are highly prized and regular annual subsistence harvests occur near many communities. Fisheries are typically at locations where large numbers of fish congregate along the coast or en-route during fall upstream migrations. In some cases, overwintering stocks of Arctic Char are harvested through lake ice (e.g., Kuujua River Arctic Char in Tatik Lake, Harwood et al. 2013; various stocks in Baffin Island lakes, Mulder et al. 2018). A limited fall harvest of Dolly Varden also occurs on the Big Fish River at spawning/overwintering fish holes using traditional seining methods. These annual harvests provide ideal opportunities for community-based monitoring for demographic traits and catch rates. Some of the longest time series of stock assessment data for Arctic fishes have been obtained through such programs involving anadromous chars collected by community harvesters (e.g., Rat River Dolly Varden, Hornaday River and Kuujjua River Arctic Char, Table 4). These long-term data sets allow for the examination of temporal trends and can provide a window into the potential effects of environmental variability in both the freshwater and marine habitats utilized by these species.

Following are examples of stock trends where links to the recently changing ocean environments have been documented:

In the Cumberland Sound region of the eastern Arctic, Ulrich (2013) documented a shift between 2002 and 2011 in the Arctic Char summer diets from primarily invertebrates to Capelin. This diet shift showed some evidence of having a positive effect on growth rates of Arctic Char in the populations examined, however, long-term consequences of this diet shift on Char population trends are unknown. Although Capelin are not new to the Arctic, records exist back to the 1820's (Coad and Reist 2018), Inuit knowledge (e.g., Nunavut Department of Environment 2013) and marine mammal and fish diet studies (e.g., Ulrich 2013; Yurkowski et al. 2017, 2018) suggest that, within the last 10-20 years, Capelin have become more prevalent in some coastal ecosystems. To date, there has been no direct assessment of Capelin abundance within the Canadian Arctic.

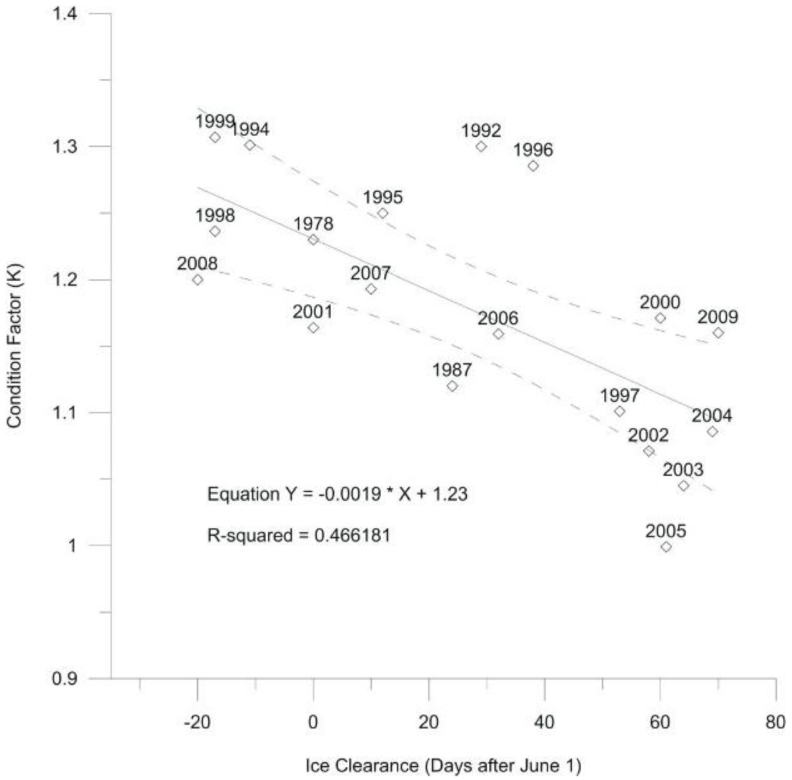

**Figure 72.** Relationship between Kuujua River Arctic Char body condition and ice clearing in the Beaufort Sea (source: Harwood et al. 2013).

Long-term harvest monitoring of the fall return migration of the Kujjua River Arctic Char stock to Tatik Lake, Victoria Island, revealed variability in mean annual body condition that was correlated with the timing of spring sea-ice retreat in the Beaufort Sea (Harwood et al. 2013, 2015a) (Figure 72). Earlier ice retreat was associated with improved fish condition. These results are generally consistent with harvest-based observations of increased growth rates, body size and a trend toward higher abundance over the last decade in this stock (Harwood et al. 2013, 2015a; DFO 2016a), as well as other nearby Arctic Char stocks such as in the Hornaday River (DFO 2015). A similar relationship of improved somatic condition with earlier ice clearing in the Beaufort Sea was also noted from long-term harvest monitoring of Dolly Varden Char in the Rat River (Harwood et al. 2009). These scientific findings are consistent with Inuit knowledge that in recent years larger and fatter Dolly Varden are being caught at coastal fishing locations (Byers et al. 2019). Observed changes in condition are thought to be associated with improved environmental productivity (Harwood et al. 2015a). At the same time, earlier loss of sea ice may also allow these species to migrate to the sea earlier and feed for an extended period of time. Shifts in coastal feeding opportunities and associated growth can be expected to have implications for life history trajectories and, by extension, dynamics of populations, as demonstrated by recent studies on growth and reproduction in northern Dolly Varden populations, where growth has been shown to be a key driver of migratory behaviour and spawning frequency (Morrison 2017; Gallagher et al. 2018a).

While these long-term data sets provide the opportunity to examine effects of harvest and environmental factors, they are rare for anadromous fish stocks in the Canadian Arctic. Only a small number of key fisheries (Table 4) are regularly monitored, yet there are an estimated 195-400 harvested anadromous stocks across the Canadian Arctic (Tallman et al. 2013, 2019). Among the monitored stocks, only a few have data sets extending >5 y making it difficult to apply typical stock assessment approaches for estimating population trajectories and evaluating stock status (Table 4), particularly in association with variabilities in envrionmental parameters. An alternative approach to traditional assessments was provided by Roux et al. (2011, 2019). Using productivity-susceptibility analysis they analyzed the vulnerability to harvest of 95 Arctic Char stocks in Nunavut (Figure 73). Among key harvested stocks, the most comprehensive information on population trends is available for subsistence fisheries on Arctic Char and Dolly Varden in the Western Arctic. Several of these stocks went through previous periods of decline due, in part to overharvest, but environmental changes in riverine habitats have also been implicated (Howland et al. 2012; Byers et al. 2019). However, more recent assessments indicate stable or increasing trends in abundance (Table 4), and in some cases, increasing size at age. Improvements in stock status appear to be linked with strong co-management of these fisheries and associated implementation of community fishing plans with voluntary quotas that have been utilized over the past decade.

Although population trends are generally positive and fish growth seems to be increasing in the western Arctic, patterns of coastal movement and associations with sea-ice conditions are complex and not well understood. For example, harvesters report that catches of Dolly Varden on the Beaufort Sea coast have declined in recent decades, but are uncertain if this is due to smaller Char populations or to a change in coastal migration patterns with Char swimming farther offshore beyond netting locations (Byers et al. 2019). It is thought that a recent lack of sea ice close to shore and reports of siltier coastal conditions due to coastal erosion may be impacting use of nearshore migration corridors by Dolly Varden (Byers et al. 2019). Recent scientific studies of Dolly Varden using satellite telemetry also provide indications of offshore habitat use (Courtney et al. 2018). However, it is unclear whether this is a recent change in behaviour since earlier studies of coastal habitat use are unavailable.

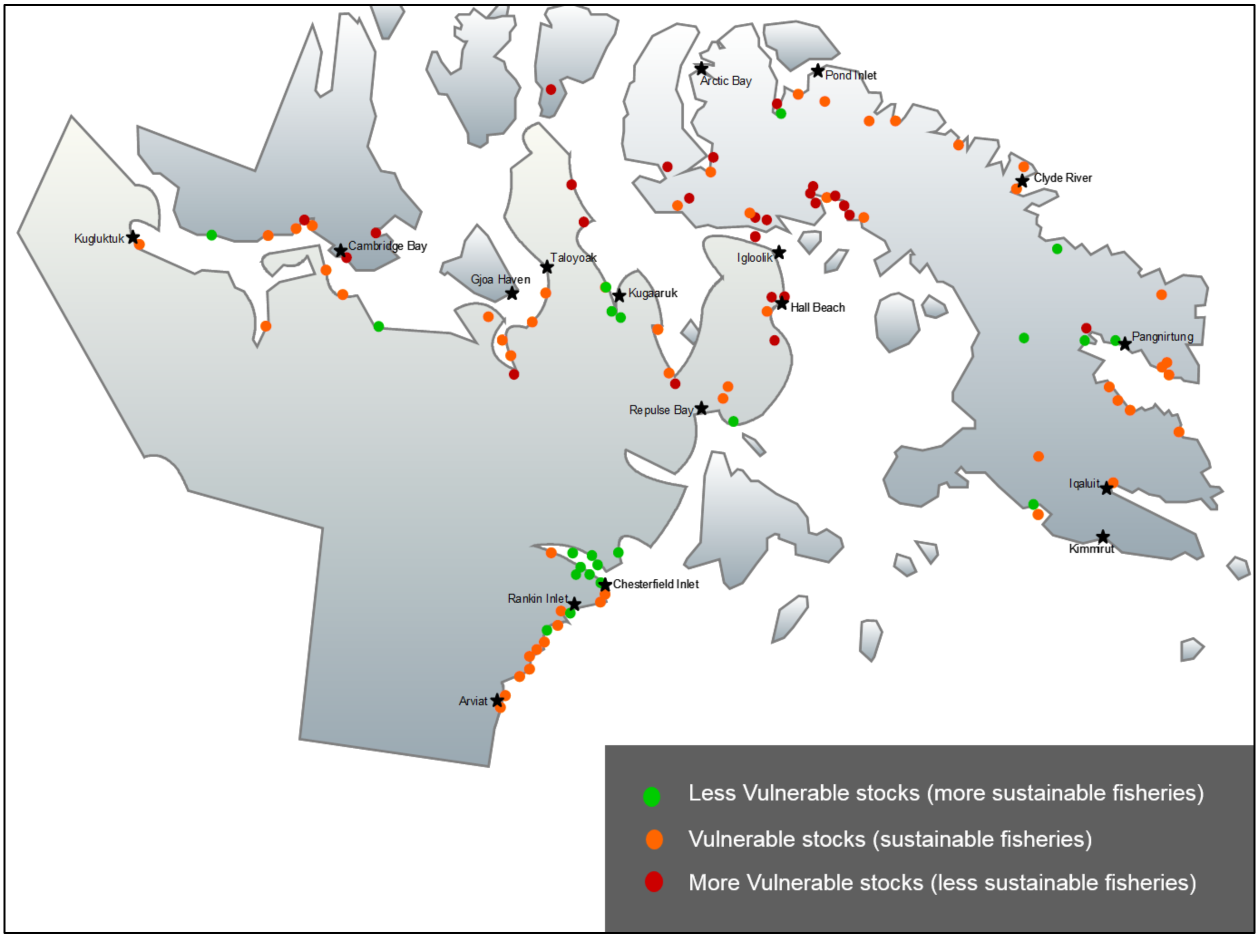

**Figure 73.** Relative vulnerability to harvest of Arctic Char stocks in Nunavut using Productivity-Susceptibility Analysis (data from Roux et al. 2011; Tallman et al. 2019).

**Table 4.** Abundance estimates, biological indices and trends of key harvested anadromous fish stocks in the Canadian Arctic.

| Common Name | Stock | Summer Coastal Feeding Distribution | Bio-logical Indices | Abund-ance Estimates | Time Frame (Years) | Population Trend/ Status | References |
|---|---|---|---|---|---|---|---|
| Dolly Varden | Rat River | Eastern Beaufort Sea (Herschel Is.to Shingle Pt.) | Yes | Yes | 1995-2014 | Previous declines, currently stable/ increasing | Sandstrom et al. 2009; Roux et al. 2012; Howland et al. 2012; DFO 2017a; Harris et al. 2017; Gallagher et al. 2019 |
| Dolly Varden | Big Fish River | Eastern Beaufort Sea (Herschel Is.to Shingle Pt.) | Yes | Yes | 1972-2011 | Previous declines, currently stable/ increasing | Gallagher et al. 2011, 2013; Howland et al. 2012; DFO 2013a; Harris et al. 2017 |
| Dolly Varden | Babbage River | Eastern Beaufort Sea (Herschel Is.to Shingle Pt.) | Yes | Yes | 1990-2014 | Stable/ increasing | DFO 2017b; Harris et al. 2017; Gallagher et al. 2018b |
| Arctic Char | Hornaday River | Darnley Bay | Yes | Yes | 1990-2013 | Previous declines, currently stable/ increasing | DFO 2016a; Gallagher et al. 2017; Zhu et al 2017 |
| Arctic Char | Kuujua River | Prince Albert Sound/Minto Inlet | Yes | No | 1991-2015 | Previous declines, currently stable/ increasing | Harwood et al. 2013; DFO 2016b |
| Arctic Char | Lauchlan River | Cambridge Bay | Yes | Yes | 1985-2018 | Increasing | DFO 2013b; Day and Harris 2013 |
| Arctic Char | Halovik River | Cambridge Bay | Yes | Yes | 1985-2018 | Decreasing | DFO 2013b; Day and Harris 2013 |
| Arctic Char | Jayko Lake | Cambridge Bay | Yes | Yes | 1985-2018 | Decreasing | DFO 2013b; Day and Harris 2013 |
| Arctic Char | Ekalluk River | Cambridge Bay | Yes | No | 1985-2018 | Stable | DFO 2013b; Day and Harris 2013 |
| Arctic Char | Paliryuak River | Cambridge Bay | Yes | No | 1985-2018 | Stable | DFO 2013b; Day and Harris 2013 |

| Common Name | Stock | Summer Coastal Feeding Distribution | Bio-logical Indices | Abund-ance Estimates | Time Frame (Years) | Population Trend/ Status | References |
|---|---|---|---|---|---|---|---|
| Arctic Char | Kipisa Lake | Cumberland Sound | Yes | No | 1998-2003 | Stable | DFO 2005 |
| Arctic Char | Iqaluit Lake | Cumberland Sound | Yes | No | 2005-2011 | Stable | DFO 2005 |
| Arctic Char | Sylvia Grinnell River | Frobisher Bay | Yes | Yes | 1947-2018* | Increasing | DFO 2013c |
| Arctic Char | Millut Bay | Cumberland Sound | Yes | Yes | 2008-2014 | Stable | Y. Janjua, unpublished data |
| Arctic Char | Naulinarvik | Cumberland Sound | Yes | No | 2010-2018 | Stable | C. Lewis, unpublished data |
| Arctic Char | Kanayuktuk Ikpit | Cumberland Sound | Yes | No | 2003-2012 | Stable | Y. Janjua, unpublished data |
| Arctic Char | Irvin Inlet | Cumberland Sound | Yes | Yes | 2008-2014 | Stable | Y. Janjua, unpublished data |
| Arctic Char | Iqalujjuaq | Cumberland Sound | Yes | Yes | 2008-2014 | Stable | Y. Janjua, unpublished data |
| Arctic Char | Ijaruvung | Cumberland Sound | Yes | Yes | 2008-2014 | Stable | Y. Janjua, unpublished data |
| Arctic Char | Anaktuayuit | Cumberland Sound | Yes | No | 2008-2014 | Unknown | |
| Arctic Char | Arvtuajuk | Cumerland Sound | Yes | No | 2010-2018 | Unknown | |

*note the time series is intermittent – the longest consecutive period is 5 years.

### 5.4.2 Commercial Marine Fishes

The Greenland Halibut stock in Baffin Bay and Davis Strait (Northwest Atlantic Fisheries Organization Subarea 0; NAFO SA 0) is assessed annually using data from bottom trawl surveys conducted by DFO. The biomass and abundance indices for the NAFO SA 0 stock showed overall increasing trends from 1999 to 2016 but declined markedly in 2017 (Treble and Nogueira 2018). Length frequencies in the survey data have been variable across years; multiple modes have been observed in some years (e.g., 27 and 45 cm in 2017) but in general individual cohorts cannot be tracked reliably through time. The number of large fish caught in the survey increased from 1999 to 2004 and from 2008 to 2014. Overall the Greenland Halibut stock in NAFO SA 0 has been stable for a number of years and the fishery has never experienced a sustained significant decline (Figure 74). Greenland Halibut are extremely challenging to age given they experience very little seasonal change in water temperature or food availability in their deep water habitats (typically >400 m). The lack of age data makes it difficult to implement many stock assessment models that require a population age structure to produce reliable results. Ongoing research is seeking to improve ageing methods for Greenland Halibut and better understand Greenland Halibut ecology and population dynamics to support population models that are less reliant on a robust population age structure.

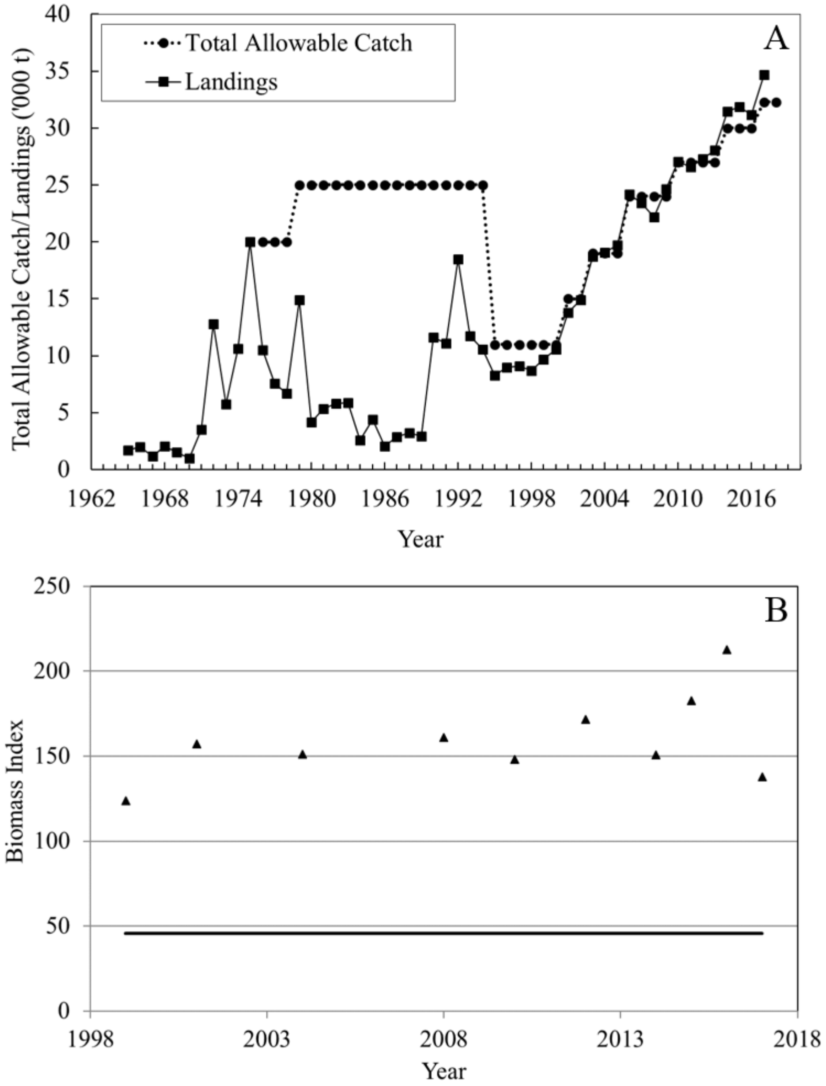

**Figure 74.** Greenland Halibut Total Allowable Catch and annual total landings (‘000 tonnes) (a), and biomass index (b) in Baffin Bay and Davis Strait combined. Lower limit for the biomass index within the period of the Integrated Fishery Management Plan indicated by dotted line in b.

In addition to the offshore commercial fishery for Greenland Halibut in NAFO SA 0, a winter community-based commercial Greenland Halibut fishery has occurred in Cumberland Sound since 1986. Despite a strong start, interest and effort in the fishery diminished through the 1990s and early 2000s because the fishery operated from the sea ice, and the sea-ice extent steadily declined, forcing fishing to occur in increasingly shallower habitats that had consequently lower catch rates (Hussey et al. 2017). Stock status has been monitored by collecting data from a subsample of the commercial catch (by monitoring demographic characteristics and catch rates), but fishery-independent assessments have not been conducted. Since 2011 the fishery has rebounded to the point where the entire 500 t quota was caught in 2018; this followed the discovery of deeper water habitats that were not apparent on existing hydrographic charts and are well back from the floe edge. This deep water habitat has had higher winter Greenland Halibut catch rates.

The success of the Cumberland Sound Greenland Halibut fishery near the community of Pangnirtung has led to fishery development efforts at other communities. Exploratory fishing for Greenland Halibut has occurred at Qikiqtarjuaq, Clyde River and Pond Inlet, all on eastern Baffin Island. The development of new commercial fisheries in these communities would increase the pressure on the NAFO SA 0 Greenland Halibut stock as these fisheries would exist in inshore waters directly adjacent to the offshore fishery, and would harvest from the same population.

In addition to monitoring populations targeted by current and developing commercial fisheries, regular assessments are conducted of all species on the SARA registry or that are listed by COSEWIC. Assessments of wolffishes, grenadiers and redfish in NAFO SA 0 have concluded that the various populations are stable despite direct and indirect fishery interactions.

### 5.4.3. Commercial Shrimp stocks

Northern Shrimp and Striped Shrimp have been assessed on an annual basis since 2006 in Davis Strait (Eastern Assessment Zone corresponding to Shrimp Fishing Area 2) and 2007 in Hudson Strait (Western Assessment Zone corresponding to Shrimp Fishing Area 3, Figure 75). Fishable (carapace length greater than 17 mm) and female spawning stock biomass (SSB; all female shrimp regardless of size) indices form the basis of the assessment. As a general rule, Northern Shrimp are 4.5 times more abundant than Striped Shrimp in the Eastern Assessment Zone while the opposite is true for the Western Assessment Zone, where Striped Shrimp are 2.8 times more abundant than Northern Shrimp.

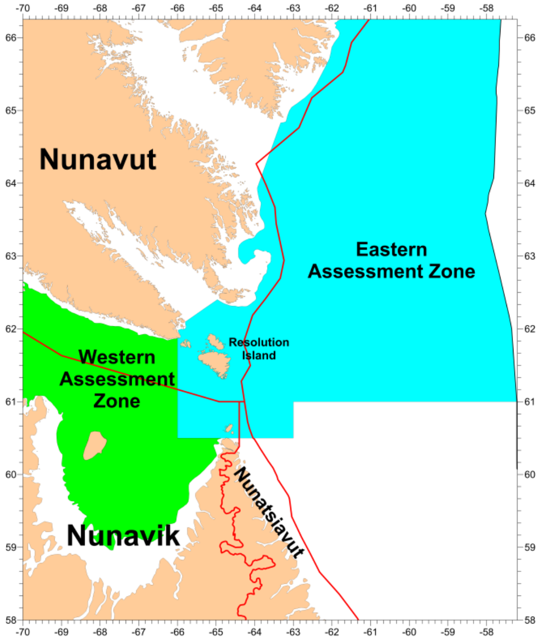

**Figure 75.** Eastern and Western Assessment Zones for commercial shrimp species in the Baffin Region of the Canadian Arctic. Boundaries of the Nunavut, Nunavik and Nunatsiavut land claims areas are shown in red.

The shrimp fishery, which began in the late 1970's (Figure 76), is operated with 100% observer coverage allowing for by-catch to be monitored closely (e.g., increase in Arctic Cod, by-catch in recent years). Since the implementation of a precautionary approach to shrimp management in 2006/2007 in the Eastern Assessment Zone, the Northern and Striped Shrimp stocks have found themselves below the upper stock reference point in 8% (1 out of 12 years) and 50% (6 out of 12 years) of the time, respectively. This indicates that the Northern Shrimp stock in the Eastern Assessment Zone is generally considered healthy while the Striped Shrimp stock is more variable. Efforts are underway to develop an ecologically-relevant precautionary approach framework for the Western Assessment Zone for both species of shrimp.

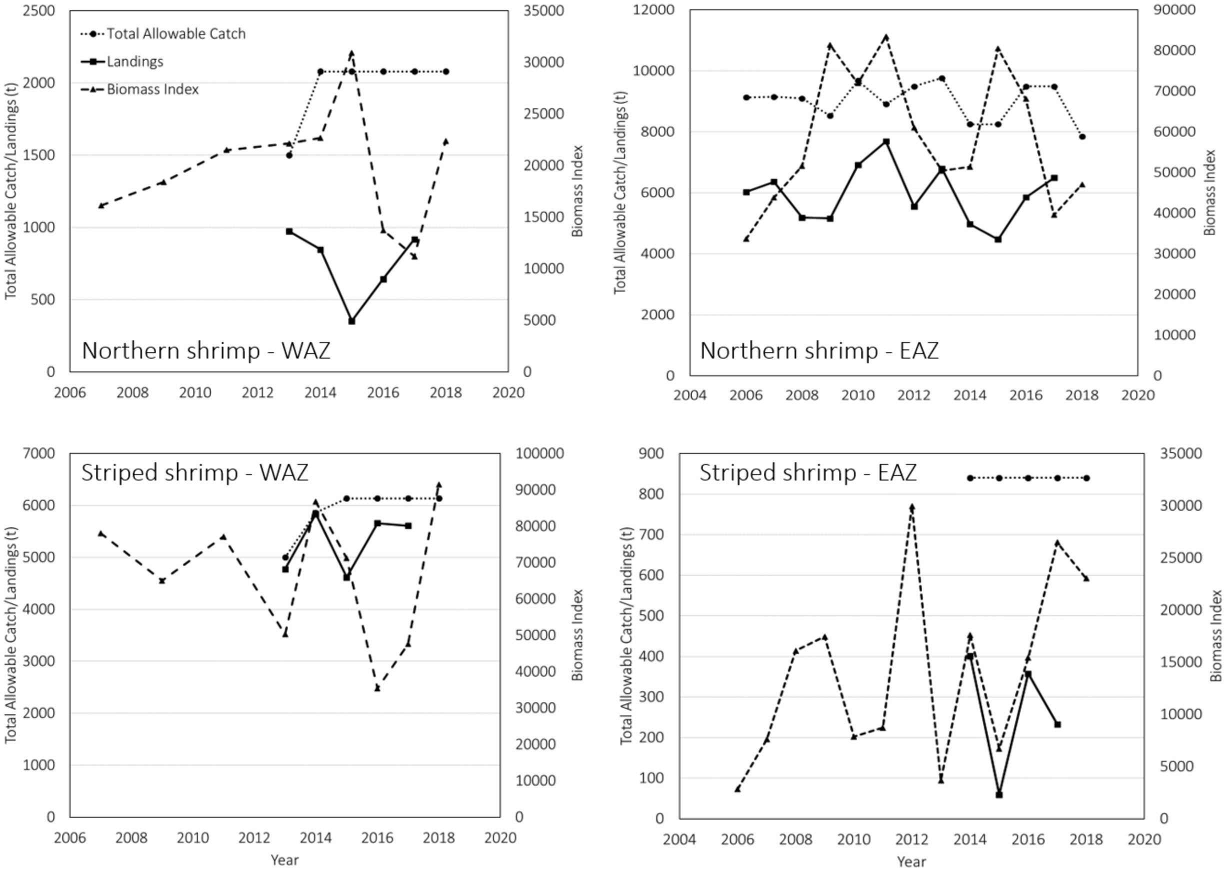

**Figure 76**. Total Allowable Catch, annual total landings, and biomass index for Northern and Striped Shrimp harvested in the Western (WAZ) and Eastern (EAZ) Assessment Zones of Baffin Bay.

## 5.5 Stability of Marine Mammal Populations: Observations and Trends

Coastal Arctic communities are in the best position to observe marine mammals on a seasonal and annual basis. Local harvest data and Indigenous knowledge of fishes and marine mammals represent the longest ecological records for the Canadian Arctic (Case Studies 17 and 18). Inuit knowledge from Tuktoyaktuk (NT), the community with largest modern harvest of beluga, reports variability in the timing of beluga arrival in spring, with a notable early arrival of the whales in 2016 (2–2.5 weeks earlier than previous years) (Waugh et al. 2018). Recent collections of Inuit knowledge also inform variability in species occurrences. Interviews with Hall Beach community members in 2017, as part of the Nunavut Coastal Inventory, describe the occurrence of multiple species, examples of which are shown in Figure 77. The distribution ranges are based on personal sightings and locations where species are normally harvested and the information recorded also includes observations of temporal/seasonal variability. Similar information now exists for multiple Nunavut communities.

Inter-annual variability and long-term trends for marine mammal abundance are challenging to assess from both Inuit and scientific information. Comprehensive surveys are regularly done for stocks with management concerns (e.g., narwhal, walrus). However, for stocks that have fewer management concerns (e.g., ringed seals) no survey rotational plan is in effect. For some marine mammal stocks, it has been over a decade between population assessments (e.g., Beaufort Sea beluga, High Arctic beluga, and High Arctic walrus). Current population trends associated with marine mammal populations are for the most part unknown in the Canadian Arctic (Appendix B). Bowhead populations are the only resident cetacean known to be increasing in abundance (Schweder et al. 2010), following declines due to historical whaling practices. The only other trends known for marine mammals are for polar bears with stable populations occurring in Davis Strait, Foxe Basin and northern Beaufort Sea. The Kane Basin population is increasing whereas populations in both the southern Beaufort Sea and southern and western Hudson Bay are likely declining (Durner et al. 2018).

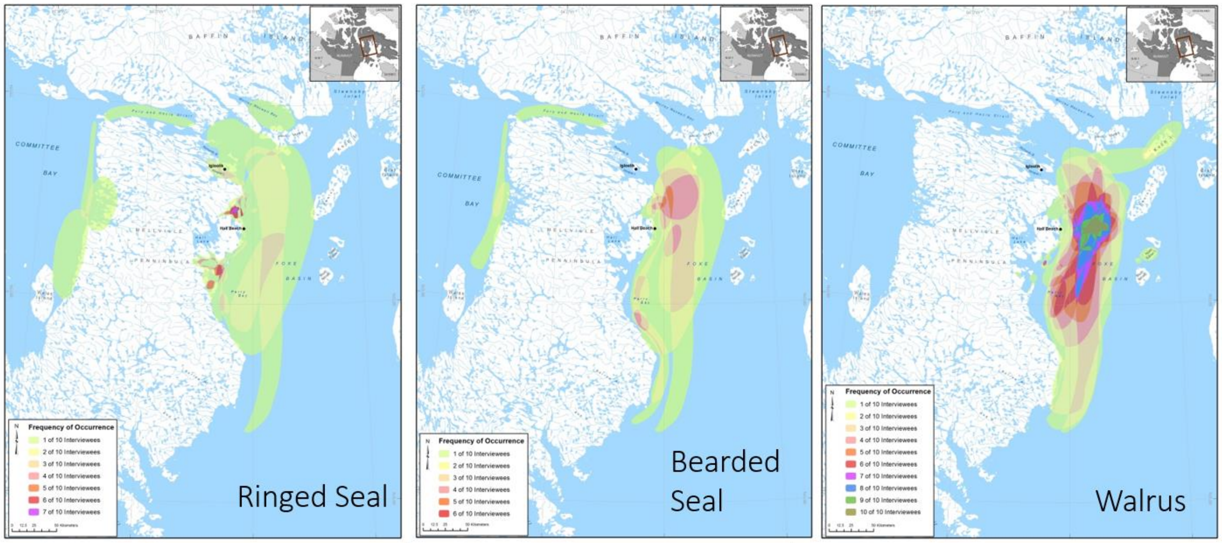

**Figure 77.** Heat maps of marine mammal occurrence observation near Hall Beach (NU). Observations represent year-round knowledge for the resident species (data source: Nunavut Coastal Inventory).

## CASE STUDY 12: Ecosystem Variability in the Southern Canadian Beaufort Sea

In the past 15 years, considerable research attention has focused on the Beaufort Sea marine ecosystem. Federally administered research including the Northern Coastal Marine Studies program (DFO, 2003-2009), ArcticNet (2003-), the Beaufort Regional Environmental Assessment (BREA, 2011-2015), and the current Canadian Beaufort Sea – Marine Ecosystem Assessment (CBS-MEA, 2017-) have established biological baselines for the offshore marine environment and, for the first time, are beginning to build time series of biological data associated with both physical and chemical habitat characteristics. Results indicate extensive spatial and interannual variability for several key ecosystem components, presenting the challenge of identifying natural variability in an environment that is also rapidly changing in relation to climate change. Such challenge also applies to other regions of the Canadian Arctic, many of which are poorly studied.

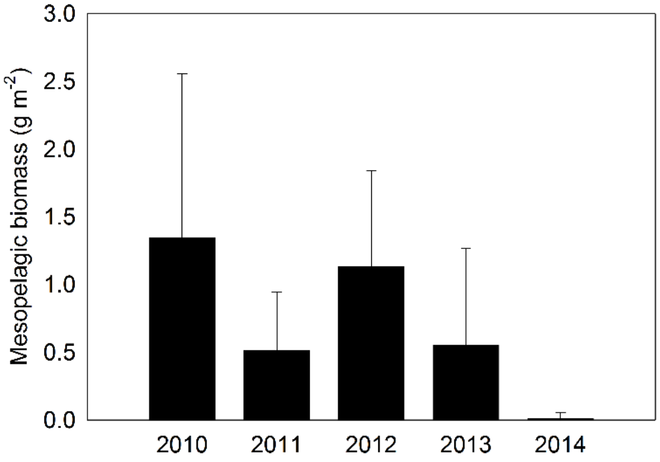

**Figure 78**. Mesopelagic biomass of Arctic Cod in the southern Canadian Beaufort Sea, calculated from hydroacoustics data. (source: M. Geoffroy, unpublished data).

Arctic Cod (*Boreogadus saida*) are an important component of the Beaufort Sea marine forage base, and play important roles both as grazers and as prey for fish, seals, whales and birds (Mueter et al. 2016). Joint hydroacoustic surveys conducted aboard the CCGS *Amundsen* and F/V *Frosti* between 2010 and 2014 indicated substantial interannual variability in the biomass of Arctic Cod in both young-of-year (age-0) and adult life-stages, with a sharp decline in biomass of adult cod observed in the 2014 sampling year (Figure 78). This decline was preceded by a general decline in the abundance and biomass of age-0 cod between 2010 and 2013. A subsequent analysis incorporated these data along with ship-based acoustic data sets from across the Canadian Arctic and determined that the biomass of age-0 cod in August and September was negatively correlated to ice breakup week and positively correlated to sea-surface temperature (Bouchard et al. 2017), suggesting bottom-up control for some trophic levels, such as pelagic fish.

Concurrent with the low biomass of adult Arctic Cod in the Canadian Beaufort in 2014, remarkable observations occurred in other aspects of the ecosystem, including coastal areas. Over 30 beluga whales (*Delphinapterus leucas)* were harvested near Ulukhaktok, which was the

**Figure 79**. Beluga whale with mouthful of Sand lance (photo courtesy of Loseto et al. 2018a).

only harvest of this magnitude on record for that community (Loseto et al. 2018a). Observations from monitoring programs in the Mackenzie Estuary and Darnley Bay indicate that beluga stomachs are typically empty upon harvest (Harwood et al. 2015b). The diet of Eastern Beaufort Sea belugas has mainly been inferred from biotracer studies (Loseto et al. 2009), investigations of habitat use during tagging studies (Hauser et al. 2017b), and aerial surveys (Hornby et al. 2016, 2017). These studies all pointed to Arctic Cod as a primary prey species for beluga in offshore marine waters. The belugas harvested at Ulukhaktok in 2014 were unique in having numerous prey items in their stomachs, but did not appear to be feeding substantially upon Arctic cod. Instead, Sand lance (*Ammodytes* sp.) (Figure 79) was the numerically dominant prey item in guts, along with squid (inferred by beaks) and other fish species to much lesser extent (Loseto et al. 2018a). Beluga harvested in the Inuvialuit Settlement Region in 2014 had lower body condition indices values than those harvested the previous three seasons, suggesting that annual variability in prey availability may be associated with inter-annual variation in condition of beluga whales (Choy et al. 2017).

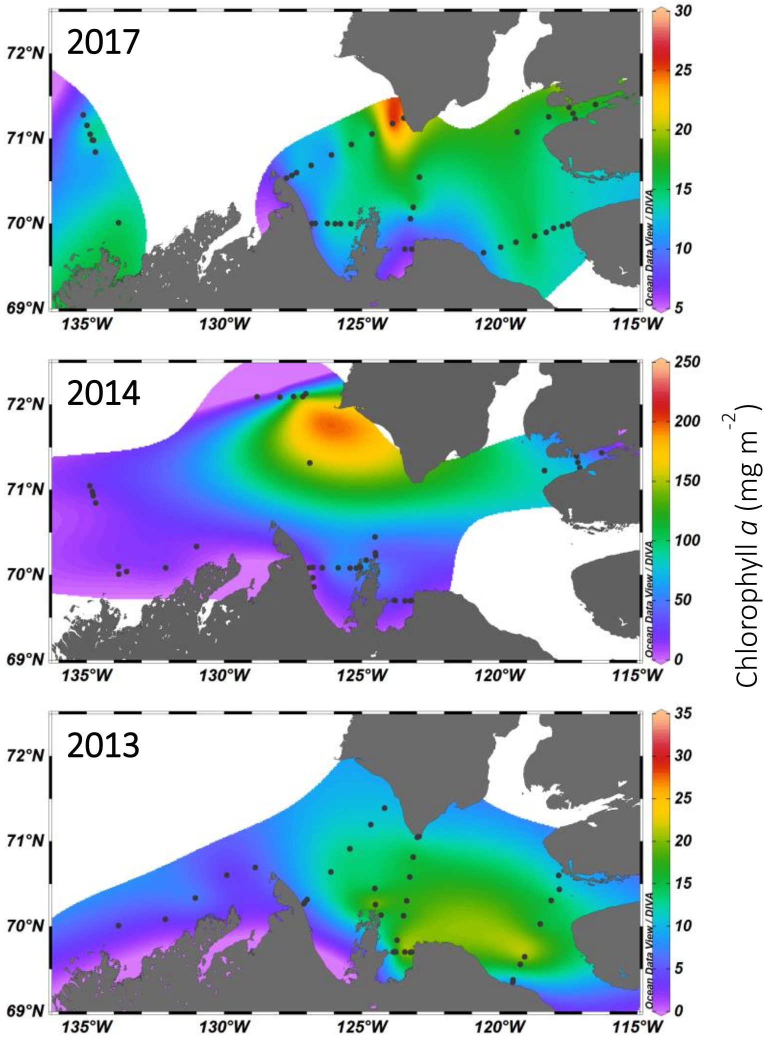

**Figure 80.** Beaufort Sea chlorophyll *a* concentrations, integrated for the euphotic zone, in 2013, 2014 and 2017. Maps created with Ocean Data View, Schlitzer, R., https://odv.awi.de, 2018.

Gut contents of Arctic Char (*Salvelinus alpinus*) harvested in Ulukhaktok in 2014 and 2015 indicated that the diet of char can be highly variable, and may be linked to the availability of preferred prey. As with beluga, Sand lance was prevalent in the diet of Arctic Char, as were marine amphipods. These results contrast with samples collected in Ulukhaktok in 1977 and 1978 that contained predominantly Arctic Cod (E. Lea, unpublished data).

Apparent inter-annual variability in the Beaufort Sea ecosystem was also indicated by primary production estimates. Despite an apparent low biomass year for Arctic Cod in 2014, and concurrent shifts in distribution and diet of subsistence species, the biomass of primary producers, indicated by chlorophyll *a* concentrations, reached values six times higher than in 2013 or 2017, with highest biomass accumulation in the southwest Banks Island area (Figure 80, C. Michel, unpublished data). These results suggest that ample resources were available to support strong secondary productivity, at least at localized scales.

Results and observations from the open-water season in 2014 provide a distinct example of interannual variability that occurred at multiple trophic levels, and was observed at both offshore and coastal environments. Variability affects subsistence harvests within the area, creating benefits and uncertainties for different communities (Loseto et al. 2018a). Given the limited number of years of sustained, ecosystem-level observations in the Canadian Beaufort Sea, it is not possible to label 2014 as an ecological anomaly. Further work is required to understand the drivers of the observed ecosystem changes, acknowledging that the drivers may have initiated the changes in seasons or years prior to the 2014 open-water season. It is expected that variability and the occurrence of anomalous events will likely become more common as the earth warms (IPCC 2014). Consequently, ecosystem monitoring required to understand the drivers of ecosystem variability, including physical and biological couplings, is essential to predicting local and down-stream effects of climate change in the Beaufort Sea, and other Arctic regions, and for informing adaptations strategies in the Inuvialuit Settlement Region.

## CASE STUDY 13: Ecosystem Interactions Influence Observed Variability in Northern Hudson Bay – Sea Ice, Eggs, and Bears

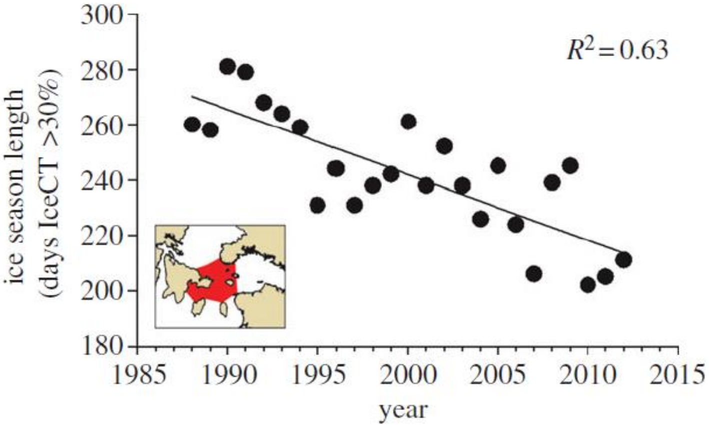

**Figure 81.** Sea-ice duration decrease in Northern Hudson Bay from 1988 to 2012 (source: Iverson et al. 2014).

Overall, there has been a decrease in the total amount of sea ice and number of days with solid sea ice in the Northern Hudson Bay and South Baffin Area from 1988 to 2012 (Figure 81). With longer ice-free periods, polar bears (*Ursus maritimus*) have less time available to forage for seals and struggle to meet their energetic demands. As a result, there have been increased instances of polar bear presence at seabird colonies (common eider (*Somateria molissima*) and thick-billed murre (*Uria lomvia*)) by more than seven-fold. This is due to bears shifting their diet towards seabird eggs in an attempt to fulfill their nutrient requirements (Iverson et al. 2014).

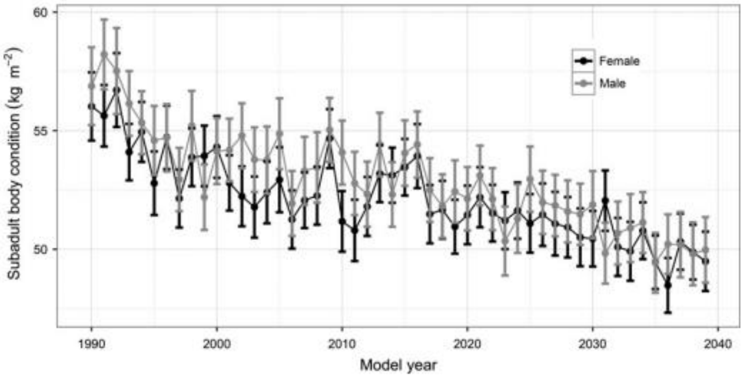

**Figure 82.** Across years, subadult body condition of polar bears is predicted to decrease in both males and females (source: Dey et al. 2017).

With changing ice conditions projected to continue, the adverse effects on polar bears and seabirds are also likely to continue. Modeling work has been done which incorporates Inuit Knowledge of changes in bear conditions over time and predation events of seabird colonies together with empirical field data. The models use foraging behaviour of polar bears and response behaviour to predation pressure from common eiders to predict the impacts of continued loss of sea ice. These models not only reproduced the empirical results found by Iverson et al. (2014), indicating that as sea ice decreases, reliance of polar bears on seabird eggs as a food source will increase (Dey et al. 2017). Results also indicate that polar bear body condition during the ice-free period will continue to decline annually across the population (Figure 82). In response, common eiders are predicted to move closeer to mainland areas with greater dispersion of nests in response to increasing predation. These behavioural responses of common eiders may increase their exposure to land-based predators (e.g., Arctic fox (*Vulpes lagopus*)) and influencing the livelihood of Indigenous peoples that collect eider eggs and down.

Although the changes of sea ice may have negative effects on the nesting behaviour of common eiders, these changes in climate are predicted to increase breeding propensity and clutch size in female eiders, positively influencing population size by allowing individuals access to resources for a longer period of time, gaining more in body condition and thus investing more in reproductive attempts (Dey et al. 2018). With increased predation rates from polar bears, however, population sizes of common eiders are predicted to remain stable over a 50-year period (Figure 83).

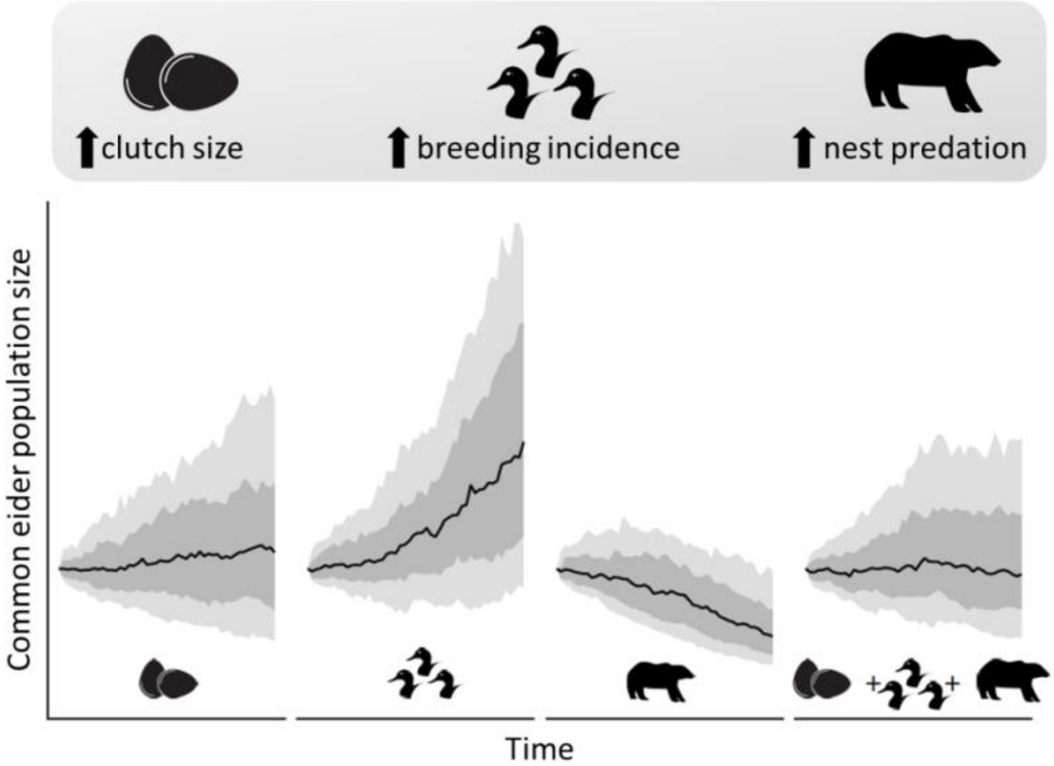

**Figure 83.** Multiple effects of climate change on common eiders (adapted from Dey at al. 2018).

## 6.0 Neighbourhood Connections

Different ‘currencies’ track connectivities between and within oceans. Common currencies used to describe physical connectivities include water masses, carbon and nutrients. Biological connectivities are described by highly mobile and migratory species that move around, and enter and exit the Canadian Arctic region. Biological connectivity demonstrates how the Canadian Arctic provides a critical service to ecosystems in other oceans. An understanding of physical and biological connectives is needed to measure the accumulation and cycling of energy within ecosystems including imported and local production. The following sections discuss these physical and biological tracers of connectivity and also demonstrate how the presence and co-location of species can identify existing and changing connections that affect how the ecosystem functions.

### 6.1 Inflows and Outflows

The layers of water masses in the Arctic are illustrated in Section 4.1.3 – Arctic water above Pacific above Atlantic. Section 4.1.3 also provides an overview of the general circulation of these water masses around the Arctic, showing how Canada’s three oceans are connected to each other. Pacific-derived water attracts special interest because of its wealth of dissolved nutrients. Pacific water reaches the Arctic via Bering Strait, following a downward slope of the sea surface to the north. Prevailing wind slows the inflow, more strongly in winter than in summer. Beyond the strait, the flow diverges to follow several paths across the shallow Chukchi shelf, and ultimately slips into the Arctic Basin at depth between the Arctic water, which is less saline, and Atlantic water, which is more so. It subsequently spreads across the central Arctic to form a vast submerged pool extending as far as the Lomonosov Ridge near the North Pole.

Two paths are open to Pacific water leaving the Arctic. One passes around the northern end of Greenland to join the East Greenland Current in Fram Strait, thereby bypassing Canadian waters; the other crosses the northern Canadian Polar shelf via channels through the Queen Elizabeth Islands or via Nares Strait. There are no obstructions to water flow via the Greenland route. However, shallow water at sills limits outflow via the Canadian Polar shelf to depths less than 80-220 m, depending on the pathway.

Observations reveal that the rates of Pacific-water outflow via various pathways vary over time. Data shown in Section 5.2.3 reveal that decreasing Canadian Arctic through-flow via Lancaster Sound in the 2000s was offset by increasing through-flow via Nares Strait. Similar patterns of compensation are suspected in relation to the East Greenland out-flow. Statistical analysis of fluctuations of flow via Lancaster Sound demonstrates that variation in the strength of the Beaufort Gyre are implicated (see discussion of the Arctic Ocean Oscillation in Section 5.2). In summary, nutrients in Pacific water reach Canadian waters at changing rates, via changing pathways, and likely after varying delays from the time of entry through Bering Strait. These varying factors are likely contributors to inter-annual variation in dissolved nutrient inventories and ecosystem productivity in Canadian Arctic waters.

## 6.2 Nutrients: Sources, Depletion and Downstream Effects

The strong connection between the Canadian Arctic and Pacific-derived waters has several consequences for nutrient availability and biological productivity. In oxygen minimum zones of the North Pacific, water-column denitrification and to a lesser extent anaerobic ammonium oxidation result from the decomposition of organic matter produced by nutrient upwelling along the eastern Pacific margin. These microbial processes impart a nitrogen deficit, which is augmented by sediment denitrification as waters flow north across the Bering and Chukchi seas, and maintains relatively low biological productivity in connected coastal areas of Arctic and Atlantic Canada (Tremblay et al. 2015). The nitrogen sufficiency index depicted in Figure 84 shows how the Canadian Arctic is affected by this large-scale connectivity and indicates that available nitrogen allows for a small fraction of the available phosphorus to be consumed by phytoplankton. The ongoing or future response of denitrification and, more generally, nitrogen balance to warming and sea-ice loss, and the consequences of this response on marine ecosystems of the Canadian Arctic represent a major knowledge gap at present.

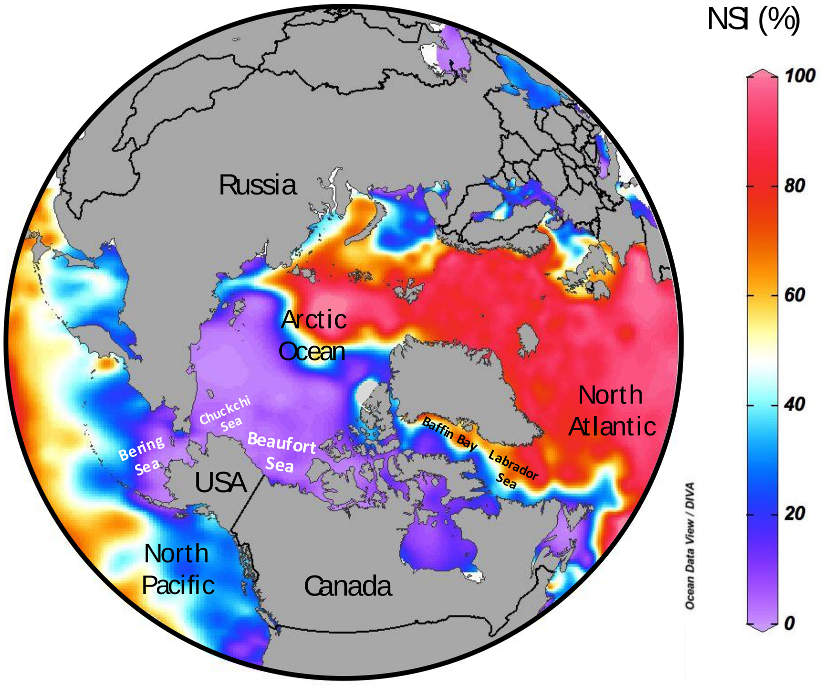

**Figure 84.** Large-scale view of the nitrogen sufficiency index (NSI) at the depth where the concentration of phosphate is 0.8 µM. Low values indicate where available nitrogen limits potential primary production. A value of 100% indicates that phytoplankton with a N:P requirement of 16 have enough nitrate to consume all the available phosphate. The path of low-NSI Pacific-derived waters across the Canadian Arctic is clearly visible (blue and purple shades). Data originate from the World Ocean Data Base (Boyer et al. 2013) and ArcticNet expeditions (Tremblay et al. 2015) and span the period 1928 – 2017, with most data obtained between 1985 and 2005. The distribution of NSI should therefore be considered as a climatology instead of a snapshot at any point in time. The NSI is calculated by multiplying observed nitrate concentrations by 100 and dividing by the observed phosphate concentrations times 16 (the globally-averaged Nitrate:Phosphate ratio of phytoplankton).

Despite denitrification and the relative deficit of nitrate with respect to other nutrients in Pacific-derived water, upwelling in the North Pacific results in the injection of considerable amounts of nutrients in the shallow Chukchi Sea. In the upper 50 m, nitrate inputs to the Arctic Ocean across the Bering Sea are nearly 20 times larger than those entering through the North Atlantic in the same depth layer (Tremblay et al. 2015). There are two major pathways that these nutrients take to reach the Canadian Arctic (Anderson et al. 2013). One occurs with the convection of winter water during cooling and ice formation on the Chukchi Sea. In the absence of significant primary production, dense water formation can entrain nutrient-rich water downward and off-shelf to maintain the upper halocline across the Beaufort Sea. The other occurs through the supply of remineralized nutrients following the decomposition of the organic matter produced by algae on the shelf during summer (Granger et al. 2018). These nutrients accumulate in the halocline, propagate toward the Canadian Arctic and maintain the mid-water nutrient maximum, where the concentration of phosphate is 0.8 µM, shown in Figure 84. This maximum is paramount for the productivity of subsurface phytoplankton layers and to inject large amounts of nutrients to the surface during episodic upwelling events (Tremblay et al. 2011). However, the climate sensitivity of the halocline and of the remote processes that generate the nutrient maximum it harbours is largely unknown.

The concentrations of all nutrients and those of phosphate and silicate in particular declined in the waters exiting the Arctic through the western Labrador Sea and Northern Baffin Bay (Hátún et al. 2018; P. Coupel, unpublished data), adversely impacting productivity (Bélanger et al. 2013; Bergeron and Tremblay 2014) and large-sized diatoms (Blais et al. 2017). These trends in nutrients cannot be fully explained but presumably result from greater vertical stratification (Peralta-Ferriz and Woodgate 2015), remote “upstream” changes in nutrient transports from the North Pacific and/or Atlantic oceans (Woodgate et al. 2012) and altered biogeochemistry (Tremblay et al. 2015).

In source waters of the North Pacific, regional climate oscillations impart significant periodicities in surface nutrient concentrations (Di Lorenzo et al. 2009; Yasunaka et al. 2016). When this effect is removed from the data, however, a time series for the period 1961-2012 indicates stable concentrations of nitrate and a decreasing trend for phosphate and silicate (Yasunaka et al. 2016). This pattern is explained by reduced vertical mixing and, for nitrate, a compensating nitrogen input via atmospheric deposition (Yasunaka et al. 2016). Increasing denitrification in the Pacific Arctic could explain the modest decline of nitrate in the Labrador Sea and in northern Baffin Bay but not the concurrent changes in other nutrients and in nitrogen sufficiency. This change is consistent with the negative trend in phosphate and silicate concentrations in the North Pacific, but may also result from a declining contribution of Pacific versus Atlantic water to the Arctic outflow. This decline is consistent with a larger presence of Atlantic-derived waters in northern Baffin Bay along the coast of Greenland. Probable implications for “downstream” areas include reductions in the biological productivity of eastern Canada’s major fishing grounds and nutrient inputs into the subpolar gyre (Hátún et al. 2017) and the central Labrador Sea where deep waters are formed (P. Coupel, unpublished data).

### 6.3 Marine Fish Movement Patterns and Connectivity

In contrast to the new ocean-scale knowledge for physical tracers of connectivity (Sections 6.1

and 6.2), most new knowledge of biological connectivity is more locally and/or regionally based. Acoustic and satellite telemetry have been used to study the movements of Arctic marine fishes. Deep water species, specifically Greenland Halibut (Barkely et al. 2018), Greenland Shark (*Somniosus microcephalus,* Hussey et al. 2018) and Arctic Skate (*Amblyraja hyperborean*, Peklova et al. 2014), have been tagged in various locations in the Eastern Canadian Arctic, including Cumberland Sound, Scott Inlet, off Broughton Island, Jones Sound, Tremblay Sound, Eclipse Sound, Pond Inlet and offshore locations in Baffin Bay and Davis Strait. Smaller-bodied fishes, including Arctic Cod, Polar Cod (*Arctogadus glacialis*) and sculpins, have been tagged in inshore locations. The movements of individuals carrying acoustic tags have been tracked for periods of months (smaller fishes) to ~5 years (Greenland Halibut and Greenland Shark). Greenland Halibut are also tagged with uniquely numbered external plastic tags (floy tags) during annual surveys in Cumberland Sound and Baffin Bay. Inert floy tags require that a fish be recapture to provide data on movement patterns or connectivity, but they are significantly cheaper than electronic tags, allowing more fish to be tagged each year, and are not limited by ice cover or battery life (although they can be broken or lost over time).

Greenland Halibut movement patterns are of particular interest given their role as marine predators and marine mammal prey in the ecosystem, and the value of the commercial Greenland Halibut fishery to Nunavut and Canada. Peklova et al. (2012) used archival pop-off satellite tags to study the movement patterns of Greenland Halibut in Cumberland Sound in relation to water temperature, diurnal cycle and date; no diurnal patterns in habitat use (i.e., depth) were observed, but preferred depth changed among seasons and ambient water temperature changed slightly between seasons (>2.3°C September to November; 1.8 to1.9°C February to April). Hussey et al. (2017) further examined the movement patterns of Greenland Halibut in Cumberland Sound using acoustic telemetry tags and found that biotic and abiotic factors were driving fish movements. Greenland Halibut moved seasonally between the southern and northern regions of Cumberland Sound in response to changes in water temperature, dissolved oxygen levels and sea-ice cover. Barkley et al. (2018) tagged Greenland Halibut in Scott Inlet with acoustic telemetry tags and tracked individual fish over the course of a year to assess local habitat use and connectivity between the fiord and the offshore Greenland Halibut stock in Baffin Bay. The data analysis classified most Greenland Halibut into two distinct movement patterns. Most of the tagged fish were detected within the study system after tagging, but moved into deeper offshore waters by the end of November when sea ice started forming (n = 47, 72%). A second smaller group of fish remained in the system after being tagged, moved offshore at the same time as the other fish and then returned to the fiord system in the winter after landfast ice had formed (n = 8, 12%). Greenland Halibut tagged with floy tags in Cumberland Sound and Baffin Bay have been recaptured on the Grand Banks and off the west coast of Iceland two or more years after their release, as well as within eastern Canadian Arctic (K. Hedges, unpublished data). Recaptures of floy tagged Greenland Halibut have shown much broader movements than have been document with satellite or acoustic telemetry tags, but is likely because of the larger number of floy tagged fish, the limited battery life of satellite tags (long deployments have spanned ~1 year) and the reliance of acoustic tags on infrastructure that can detect the tag transmissions (e.g., moored receivers).

The movement patterns of Greenland Shark are also of keen interest; the species is a top predator in Arctic marine ecosystems and is caught as bycatch in both offshore and inshore Greenland

Halibut fisheries. Hussey et al. (2018) used a novel application of satellite tags to track the movements of Greenland Sharks that provided multiple locations per individual (typically only two locations are determined for deep-sea fishes: the location of tagging and the location of tag release) and revealed a previously unknown directed migration from the Canadian High Arctic (Jones Sound) to Northwest Greenland. Recent tracking data are showing greater connectivity and oceanographic features such as sills are not complete barriers to fish movement as previously thought.

## 6.4 Connectivity and Competition

As warming trends continue both ringed and harp seals distribution will likely overlap and might result in new competition between the two species (Ogloff et al. 2019). This will occur as harp seals distribution expands northward from the Atlantic to Arctic regions. Harp seals require pack ice as a platform for resting, to give birth and nurse their young and a decline in the amount of seasonal pack ice in Atlantic Canada may force harp seals to adapt by moving northward, a response which may be exacerbated by shifts to their prey base (Hammill et al. 2005). Harp seals in Newfoundland waters appear to target Capelin and likely time their northward migration with the spawning season of Capelin to maximize Capelin consumption (Beck et al. 1993). In contrast, Arctic Cod appear to be a mainstay of ringed seal diet in the Canadian Arctic region and evidence is accumulating that Cod may be less common in traditional subpolar environments as environmental conditions change (Gaston et al. 2003). Recent diet studies (Figure 85) of seals co-occurring in Cumberland Sound indicate that while

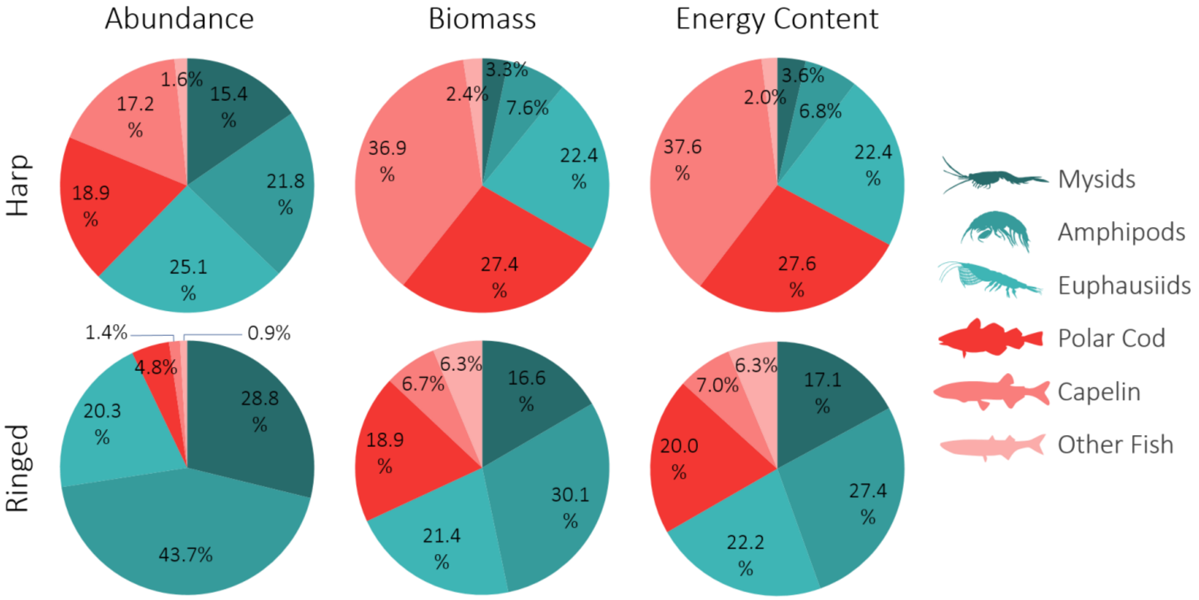

**Figure 85.** Mean percent composition of frequently-occurring prey from stomachs of ringed (n=65) and harp (n=18) seals captured in Cumberland Sound from 2008-2016 during the open-water period. Seals of all ages are grouped. Percentage of frequently-occurring diet components is shown based on mean abundance (by number), mean dry biomass, and mean energy content (source: adapted from Ogloff et al. 2019).

harp seals consume many of the same prey as ringed seals, harp seals tend to consume larger fish than ringed seals, likely owing to differences in body size and diving capabilities (Wathne et al. 2000; Ogloff et al. 2019). Currently, there is not enough evidence to suggest direct competition between ringed seals and harp seals in Cumberland Sound, though the similarities in their diets suggest that, with continued changes to the prey base, there is potential for competition to arise in the future.

## 6.5 Marine Bird Migrations – Multiple Oceans Matter

Studying the full annual cycle of an organism is critical for understanding how the effects of behaviour and environmental conditions carry over between the seasons, especially in a context of changing ice conditions and increasing human activities. To document annual movements in marine birds nesting near East Bay Island, in the Eastern Canadian Arctic, multiple tracking techniques are used for different species including satellite telemetry in common eiders and king eiders (*Somateria spectabilis*), and GPS devices on herring gulls. These species migrate to and from their breeding grounds, accessing a bounty of foraging resources in the Arctic that can support reproduction. In particular, eiders forage on benthic prey and gulls forage in intertidal areas, all of which increase in availability and area as Arctic ice begins to melt and break up in the early spring.

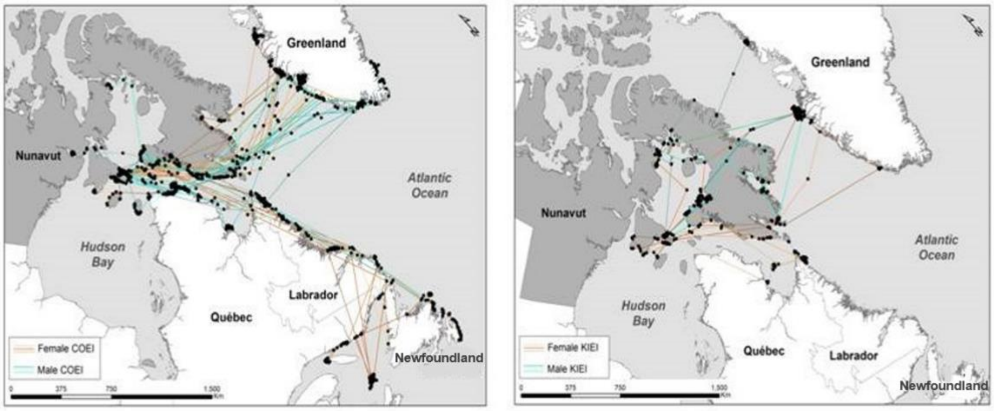

**Figure 86.** Annual migratory movements (autumn migration to wintering grounds, to Greenland or southern locations) of male and female common (COEI) and king (KIEI) eiders. Each colour represents a different individual. (source: F. Jean-Gagnon, unpublished data).

Despite both common and king eiders breeding at East Bay in the same colony, there are substantial differences between species and among individuals in terms of their migratory decisions, strategies and pathways (Figure 86). King eiders showed slower migration movements compared to common eiders, taking longer to get to their wintering grounds with most individuals migrating to Greenland for the winter months before migrating back to the Canadian Arctic to breed (F. Jean-Gagnon, unpublished data). Overall, common eiders nesting at the East Bay colony winter in two locations: Greenland or along the coast of Labrador and Newfoundland (Figure 86). The birds that winter in Greenland tend to stay in one location over the winter, finding open water in bays and polynyas, whereas the birds wintering in Newfoundland and

Labrador tend to move south along the coast of Labrador as the sea ice begins to form, pushing the birds farther south into unfrozen waters and foraging grounds before returning to the breeding grounds in Nunavut in the spring.

Herring gulls breeding in the Arctic migrate long distances to spend the winter in marine habitats of the Gulf of Mexico (Anderson 2017) (Figure 87). Many of the herring gulls breeding in Nunavut make prolonged autumn stopovers (19-101 days) in Hudson Strait and Foxe Channel at the beginning of their migration, which may help prepare them for their long-distance flights to their next stopover sites; these flights often covered 2000 km or more in 3 days. Gulls demonstrated preferences for coastal habitats, likely because they contain predictable sources of food, and coastal topography creates opportunities for energetically efficient soaring. This information provides an important baseline demonstrating long-range connectivity between oceans. Understanding this connectivity is necessary to examine potential effects of large scale environmental changes and human influences on both Arctic breeding and outside wintering grounds.

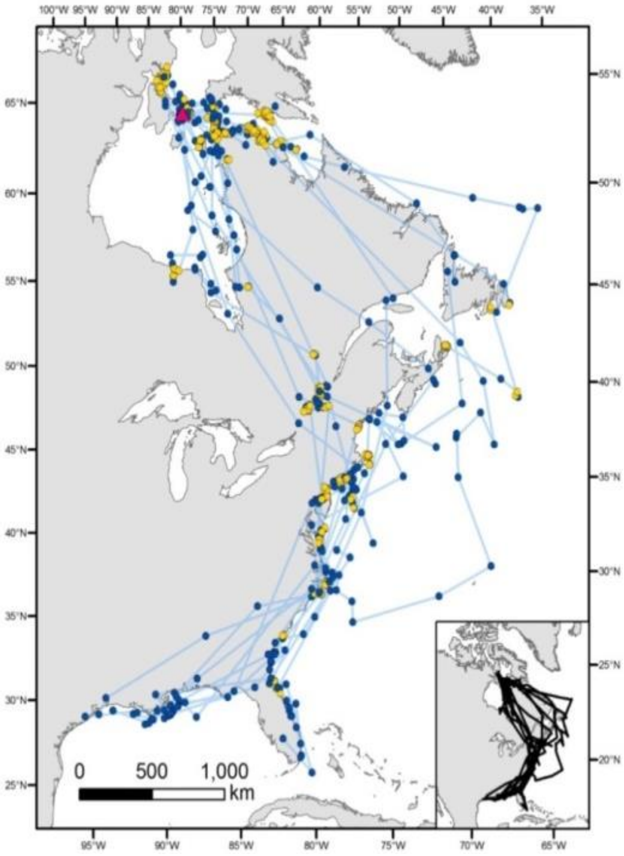

**Figure 87.** Southward migratory movements (blue dots) and stopover sites (yellow dots) of herring gulls nesting at East Bay (source: Anderson 2017).

## CASE STUDY 14: Range Expansions and New Species Occurrences

The Arctic is inherently dynamic, seemingly isolated, exceedingly vast, and some areas are experiencing rapid changes in biodiversity that have both local and global implications. Indeed, climate change is currently the most significant over-arching threat to current biodiversity in the Arctic (CAFF 2013), as the north is perceived both as a global conservation haven for species shifting distributions northward (Yoon et al. 2015), and a potential global conservation hazard for cold-adapted species in a warming environment (Reist et al. 2006a). The importance of assessing biodiversity is rooted in reconciling the emerging potential of the Arctic with protection of its environment, its species, and its Indigenous cultures.

Biologically, culturally and economically relevant indicator species provide information to assess ecosystem-level implications of on-going environmental changes in the Arctic. They also serve as a guide to the development of emerging opportunities. To be an effective indicator of a changing Arctic, however, species must be both sensitive to, and reflective of, environmental change within a defined period of time, detectable across a remote area and above ambient variability, scientifically based but not necessarily scientifically derived, and be relevant to the broader issues (DFO 2015).

**Figure 88.** Charlie Erigaktoak and Danny Gordon Jr. with a salmon they harvested in 2016 at Shingle Point, Yukon (photo credit: Michelle Gruben).

Pacific salmon (*Oncorhynchus* spp.) are ideal harbingers of change because they have been identified as indicators of ocean status (Irvine and Riddell 2007), are responding to changing environmental conditions (Grebmeier et al. 2006; Dunmall et al. 2013; Nielsen et al. 2013), and can be tracked at northern distributional extremes using an established community-based monitoring program (Dunmall et al. 2013) (Figure 88 and Figure 89). The distributions of salmon species can reflect shifting environmental conditions both directly because fish, as ectotherms, maintain thermal preferences through behavioural choices (Reist et al. 2006b), and indirectly through the link between increased productivity and prey availability for potentially colonizing species (Dunmall et al. 2013). While salmon are not new to the Arctic (reviewed in Nielsen et al. 2013), current increases in abundance and distribution of salmon in the Arctic likely reflect broader-level changes. Salmon are a unique indicator of connectivities among oceans, countries, cultures, economies, and ecosystems.

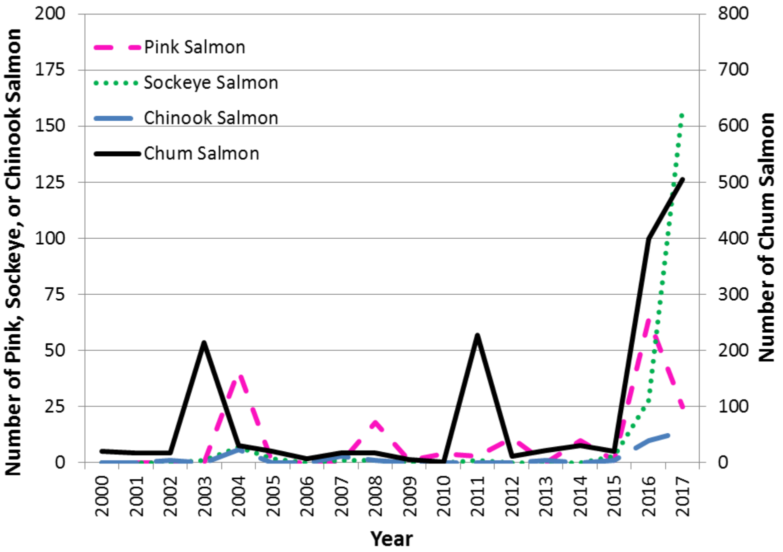

**Figure 89.** The number of each species of Pacific salmon received by the Arctic Salmon community-based monitoring program from harvesters across the Canadian Arctic from 2000–2017. Only one coho salmon was reported during this period (in 2011), thus it is not included (source: Dunmall et al. 2018).

Killer whales (*Orcinus orca*) also represent connectivity between and changes within Canada's oceans. In the eastern Canadian Arctic, killer whales (Figure 90) occur seasonally from about July to October, when the open water allows them to enter bays and inlets in search of marine mammal prey. Throughout their range from northern Baffin Island to southern Hudson Bay, killer whale sightings have increased over the past several decades (Higdon and Ferguson 2009; Higdon et al. 2013). Although killer whales are distributed worldwide and occur in relatively high densities at high latitudes, they are generally ice-avoidant in the Arctic (Matthews et al. 2011). The recent increases in sightings have been correlated with concurrent reductions in sea-ice extent and duration, with previously ice-covered areas that acted as barriers now opening up and allowing killer whale passage into areas where they have historically been rarely or never observed (Higdon and Ferguson 2009). Inuit in the eastern Canadian Arctic have reported that killer whale presence is increasing throughout the region (Higdon et al. 2013). Hudson Bay in particular has had an almost exponential increase in the number of killer whale sightings over the past several decades at the same time the region has experienced drastic sea-ice reductions (Higdon and Ferguson 2009). Although sightings data, separate from organized surveys, are subject to bias such as increased reporting awareness, it seems likely the greater numbers of sightings reflect a distribution shift, higher numbers, or a combination of both.

The consequences of an expanding Arctic killer whale presence with diminishing Arctic sea ice have been the focus of research at DFO over the past decade. Compilations of Inuit Ecological Knowledge and historical sighting reports that involve predation events indicate marine mammals are the primary, if not only, prey of Arctic killer whales (Higdon et al. 2013; Westdal et al. 2016a). Modelling exercises suggest mortality from killer whale predation could potentially be high enough to impact other Arctic marine mammal populations (Ferguson et al. 2012). Other recent studies led by DFO have shown the negative effects of killer whale predation extend beyond direct mortality of prey. Killer whales, for example, have a strong impact on the behaviour and distribution of narwhals (*Monodon monoceros*). In the absence of killer whales, narwhals preferred to be in open, deep waters, while in their presence, narwhals preferred shallow, nearshore areas (Breed et al. 2017). Although this behaviour has been long known to Inuit, this study was unique in that it showed the narwhal response was sustained for as long as they shared the relatively large inlet with killer whales, and persisted beyond discrete predation events. Bowhead whale (*Balaena mysticetus*) behaviour and selection of sea-ice habitat is also greatly impacted by killer whale presence. Bowhead whales in the Gulf of Boothia also preferred open-water habitat in the absence of killer whales, but rapidly retreated into ice cover and close to shorelines when killer whales were present (C. Matthews, unpublished data). Again, the behaviour was exhibited gulf-wide by all tagged bowheads for the duration of time killer whales were present, representing a response that had never been documented for marine vertebrates on such a large scale. The pronounced killer whale-mediated shifts in the behaviour and habitat use of Arctic marine mammal prey could translate into costly non-consumptive effects through lost foraging opportunities or increased stress, potentially having a negative impact on prey populations that stands to be exacerbated by climate change (Breed et al. 2017; C. Matthews, unpublished data).

Anticipated killer whale range expansions in the Arctic, however, may not be so clear-cut. At the same time killer whale sightings have increased in the eastern Canadian Arctic, so too have the number of ice entrapments involving killer whales. Hidgon and Ferguson (2014) and Westdal et al. (2016b) report on several fatal killer whale ice entrapments in the eastern Canadian Arctic since the early 1950s, which is more than the reported number of similar events over the previous century. During the most recent of these, in 2016, killer whales were observed overwintering in southeast Hudson Bay, but were found dead the following spring. Matthews et al. (2019) speculated that the whales entered Hudson Bay in pursuit of beluga the previous summer, but failed to exit prior to ice formation and died of starvation after being unable to meet energetic requirements throughout the winter. The four confirmed deaths from the most recent event combined with the deaths from the previous ice entrapments represent a significant portion of the estimated population of killer whales that occur in the eastern Canadian Arctic (Young et al. 2011). Killer whale ice entrapments are almost always fatal and can wipe out entire family groups, with long-lasting demographic impacts (Higdon et al. 2013). Ice entrapments could therefore slow Arctic killer whale range expansions, particularly in areas where killer whales that are unfamiliar with sea-ice patterns fail to exit prior to ice formation in winter (Matthews et al. 2019).

**Figure 90.** Killer whale in Eclipse Sound, Nunavut in summer 2018 (photo credit: Maha Ghazal).

## CASE STUDY 15: Marine Mammal Hotspots: Focal Points of Energy Flow Within the Canadian Arctic

Quantifying biogeographical attributes, such as Arctic marine predator movements and their distributions, has important implications for understanding how the Arctic ecosystem is structured and how it functions (Moore and Huntington 2008). Highly mobile marine predators (e.g., marine mammals, seabirds and large fishes) integrate resources across numerous spatial and temporal scales, therefore can act as sentinels for areas of high productivity and how this changes seasonally in highly dynamic environments such as the Arctic (Boyce et al. 2015). Observing animals within the dynamic nature of Arctic marine environment is difficult, but the application of animal telemetry devices has revolutionized our understanding of the movement ecology of marine species (Hussey et al. 2015). Traditionally, telemetry studies on Arctic marine predators have focused on single or a few species, but given the amount of telemetry data currently available for Arctic marine predators one can now quantify species diversity hotspots, and infer specific areas of higher biological importance (i.e., hotspots) during summer-autumn and winter-spring.

A compilation of existing animal tracking data was collected between 1989 and 2016 for 1,283 individuals of 21 iconic Arctic marine species across cetacean, pinniped, seabird, polar bear (*Ursus maritimus*) and fish species groups. Some iconic species include: belugas (*Delphinapterus leucas*), narwhals (*Monodon monoceros*), ringed seals (*Pusa hispida*), Atlantic walrus (*Odobenus rosmarus rosmarus*), common eiders (*Somateria mollissima*), northern fulmars (*Fulmarus glacialis*), thick-billed murres (*Uria lomvia*) and Greenland sharks (*Somniosus microcephalus*). Hotspots were generally along the continental shelf and slope throughout summer-autumn and were generally offshore in known areas of moving pack ice during winter-spring, therefore generally correspond to seasonal productivity patterns ( Figure 91 and Figure 92). These movements exhibit seasonal connectivity and connectivity between offshore and nearshore energy channels during winter-spring and summer-autumn, respectively. Specifically, in the west, nutrient-rich waters from the Pacific Ocean and Bering Sea flow northward through the Bering Strait and southern Chukchi Sea leading to enhanced pelagic and benthic faunal biomass in the area and along the continental shelf and shelf break to the Mackenzie Delta (Grebmeier et al. 2006). During winter-spring, hotspots occurred in productive areas westward of the Cape Bathurst Polynya. In the East, Baffin Island consists of many productive fjords due to increased organic carbon content in the water column (Syvitski et al. 1990). During winter, species diversity hotspots were concentrated in dense mobile pack ice areas of Baffin Bay and Davis Strait. In the South, species diversity hotspots coincided with productivity patterns of the Hudson Bay complex (Harvey et al. 2006). And overwintering hotspots were within the moving pack-ice and open-water areas of Hudson Strait. Overall, hotspots in the winter highlight the ecological importance of polynyas and pack ice areas to Arctic ecosystem structure and function (Stirling 1997). As such, identifying areas where predator densities are highest provides critical information for understanding the dynamics of energy flow throughout the Arctic and thereby demonstrates the importance of connectivity for conservation efforts.

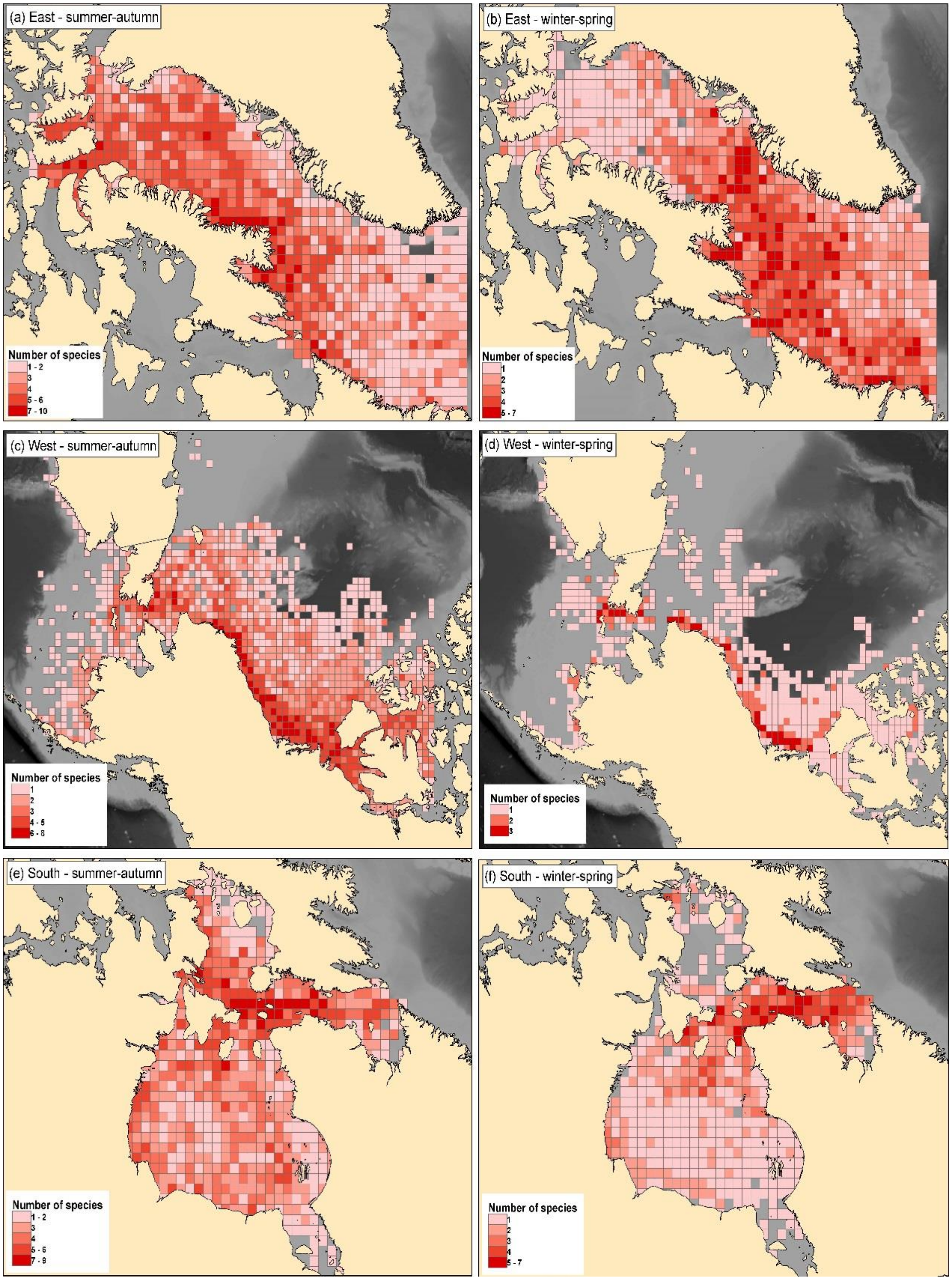

**Figure 91.** Spatial distributions of density of unique number of species across 21 species per 50 km x 50 km grid cell within each of the three geographic areas during summer-autumn (a, c, e) and winter-spring (b, d, f). The legend for winter-spring is different from summer-autumn, as is the legend between each geographic area (source: Yurkowski et al. 2019b).

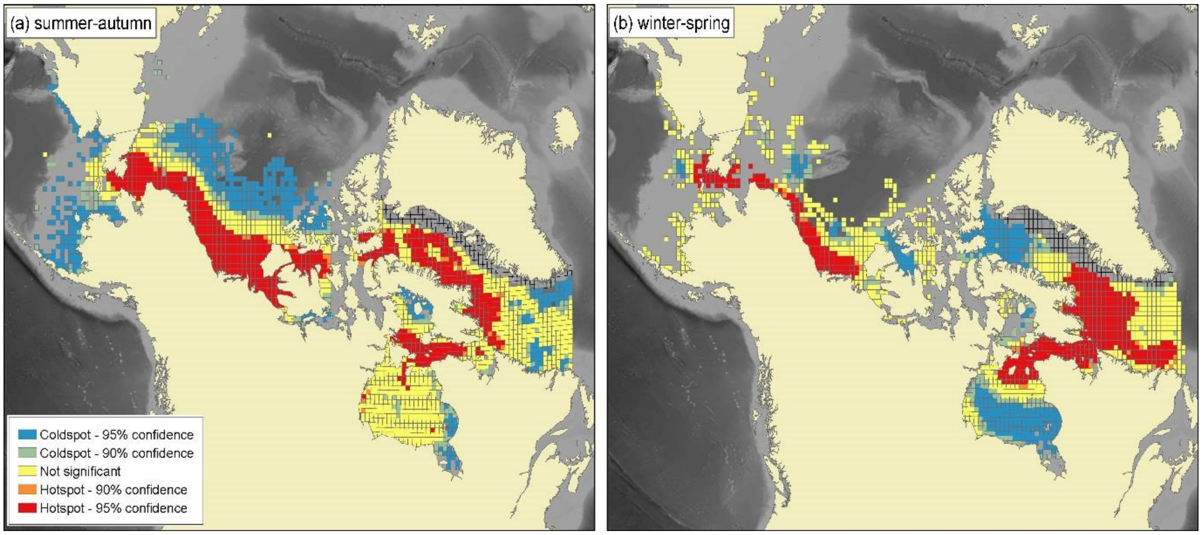

**Figure 92.** Species diversity hotspots (red) and coldspots (dark blue) by summer-autumn (a) and winter-spring (b) of all tracked species per 50 km x 50 km grid cell across the study area. Grid cells along the West Greenland continental shelf have been masked due to a lower number of tagging locations in these areas than in Canadian waters resulting in less confidence in identifying hotspots and coldspots along the West Greenland coast (source: Yurkowski et al. 2019b).

## CASE STUDY 16: Association Between Beluga Migration Dates and Changing Ice Regimes Revealed by Inuit Land-based Sightings

Of all marine mammals, beluga (*Delphinapterus leucas*) are the most frequently hunted by the Nunavimmiut (Inuit of Nunavik). This subsistence hunt represents an important traditional activity occurring mainly during spring and summer, when both western and eastern Hudson Bay beluga populations migrate through Hudson Strait. Sightings of the species are therefore of particular interest. Since 1993, land-based detections by Inuit observers have been recorded weekly in several communities, thus allowing us to estimate the dates of those migrations.

At the same time, important modifications of the ice regime in Hudson Bay and Hudson Strait have been associated with climate change, with a trend towards earlier ice breakup and later freeze-up, particularly since the 1990’s (Gagnon and Gough 2005; Galbraith and Larouche 2011; Kowal et al. 2017; Andrews et al. 2018).

Potential relationships between beluga migration dates and ice conditions in Hudson Strait were examined by comparing their relative trends over the last 25 years. Migration dates were defined as the peak in number of animals seen from the Indigenous communities of Quaqtaq and Kangiqsujuaq (Figure 93). Spring migration was better detected in Kangiqsujuaq, while there was a better data set on autumn migration in Quaqtaq. Ice break-up and freeze-up dates in the eastern and southern parts of the Hudson Strait were calculated from weekly ice cover data provided by the Canadian Ice Service.

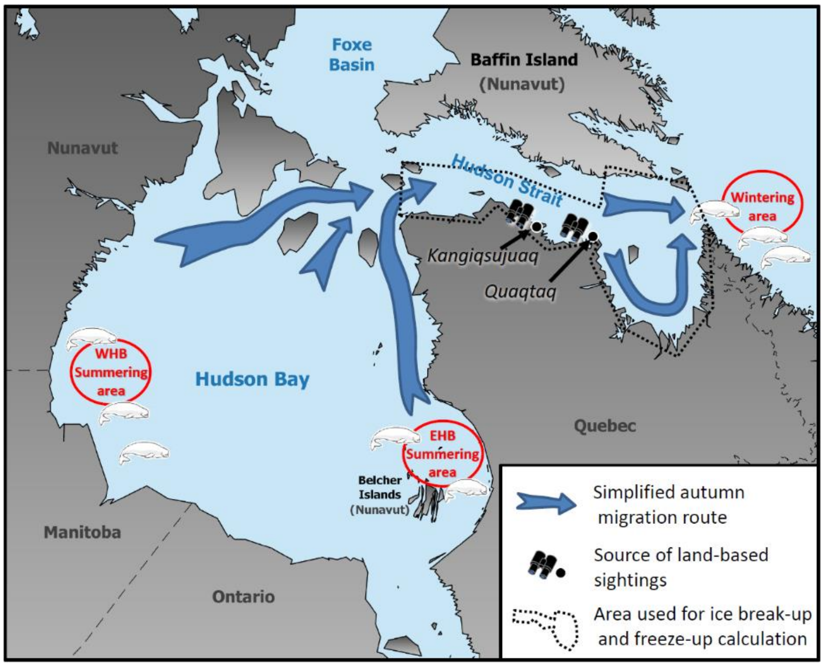

**Figure 93.** Location of land-based sightings sources (i.e., Inuit communities of Kangiqsujuaq and Quaqtaq) and area considered for the calculation of ice break-up and freeze-up dates. Beluga summering and wintering areas are also indicated along with a simplified representation of their autumn migration route (note: there is no information available about their spring migration route). EHB and WHB stand for Eastern Hudson Bay beluga and Western Hudson Bay beluga respectively.

Linear regressions applied to the migration data reveal a significant trend for a later date of migration in autumn (p = 0.021), showing an average shift of 10 days per decade. Spring migration, on the other hand, tends to start earlier with a shift of 6 days per decade (p = 0.016). Spring migration dates follow closely the ice break-up dates (Figure 94), which show a similar shift of 6 days per decade (p = 0.006). In contrast, ice freeze-up dates show only a slight, non-significant, tendency to occur later in the year (+2 days per decade) with a larger inter-annual variability in recent years. Before 2008, autumn migration generally took place more than five weeks before the freeze-up date. However, as their trends differ, autumn migration can now occur closer to the freeze-up. As a result of the shift in migration dates in spring and summer, beluga now tend to spend less time on their wintering grounds and more time on their summer grounds.

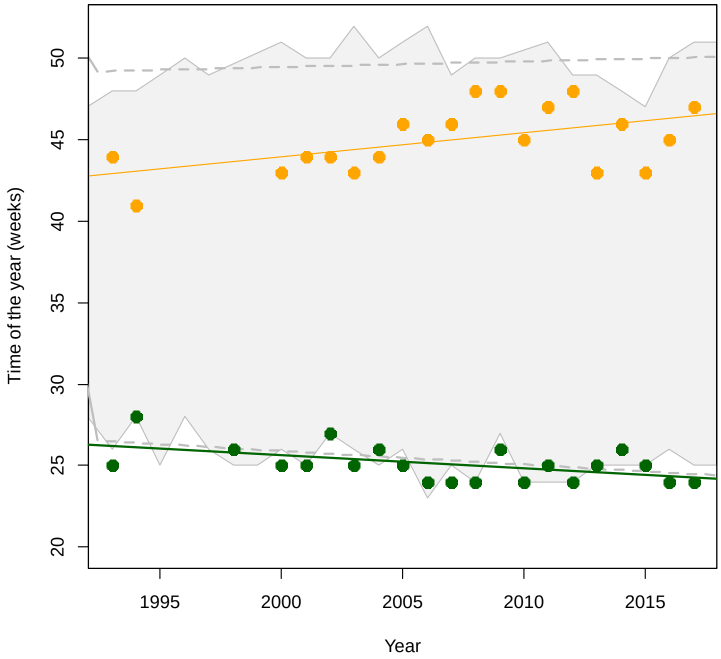

**Figure 94.** Temporal trends of spring (green dots) and autumn (orange dots) migration dates of beluga in the Hudson Strait along with ice break-up dates (lower grey line) and ice freeze-up dates (upper grey line). Results of linear regressions on those time-series are presented as solid lines (migration data) and dotted lines (ice data).

Other beluga stocks in the Arctic, like the Chukchi Sea population, also seem to take advantage of later freeze-up to stay on their summer grounds longer. However, the Beaufort Sea population with which they share this summering ground does not seem to modify its behaviour, keeping the same timing regardless of changes in ice conditions (Hauser et al. 2017a). This variability in migration strategies may have important effects on the population dynamic of those stocks, possibly determining their fate in a changing environment.

Monitoring these patterns is crucial to evaluate the impacts of climate change in the Arctic and this study shows that the contribution of Indigenous Knowledge can be a key element in providing the long time-series of data needed to detect these effects.

## 7.0 Coastal Ecosystems

In this section we consider coastal ecosystems found generally within 5 km of shore and/or inshore of the 20 m isobath. This area is highly energetic as ocean meets land and rivers meet the sea. Ice and winds behave differently nearshore than in the offshore (e.g., landfast versus pack ice) and the interface of nearshore and offshore waters, as well as their mixing, are key processes affecting the function of coastal ecosystems. This shallow region is the home for 46 Canadian communities located along the shoreline (6 in the Inuvialuit Settlement Region, 15 in Nunavik and 25 in Nunavut) and is thus the primary domain for Inuit culture, history and way of life (Figure 95). The follow sections discuss key coastal processes highlighting changes in this nearshore area.

**Figure 95**. Inuit Nunangat, the Inuit homeland, comprised of four Inuit regions, Nunavut, Nunavik, Nunatsiavut and the Inuvialuit Settlement Region. Approximately 65,000 Inuit live in communities spread across the region.

## 7.1 The Terrestrial Connection – Changes in the Beaufort-Mackenzie Ecosystem

In the western Canadian Arctic, terrestrial changes are affecting nearshore and marine environments. Increasing air temperature, changes in precipitation and winds, and the increasing frequency of extreme precipitation events, and coastal storms are impacting river discharge, erosion and thermokarst (i.e., thawing of ice rich terrain) processes (Ramage et al. 2018). Erosion and accelerated melting of ice-rich permafrost is changing the landscape within the Mackenzie Delta and along the shores of the Beaufort Sea. Erosion rates have more than doubled for many regions of the Beaufort Sea coast (Couture et al. 2018) and the size and number of retrogressive thaw slumps, slope failures due to permafrost thaw, continues to increase.

In 2012 and 2013 erosion on Herschel Island and along the Yukon coast was found to be mostly uniform in low-elevation areas, eroding at a rate up to 20 m $y^{-1}$. However, erosion was highly variable at coastlines with higher elevations where slumping could decrease erosion and even induce the growth of coastal areas (i.e., progradation) by up to 40 m $y^{-1}$ (Obu et al. 2017). For the Yukon coast specifically, the number of thaw slumps has increased by 73% between 1952 and 2011, displacing at minimum 16.6 x $10^6$ $m^3$ of material including ice and soils (Ramage et al. 2018). Erosion and slumping (Figure 96) modifies the physical environment within the nearshore coastal region and mobilizes terrestrial carbon and other nutrients. Recent estimates by Couteur et al. (2018) suggests that 0.17 Tg of particulate organic carbon (POC) is supplied by Canadian Beaufort Sea coastal processes (i.e., erosion, slumping, excluding riverine input) each year. This recent estimate is almost three times higher than previous values used for organic carbon budget calculations (Rachold et al. 2004).

Although the contribution of organic carbon from coastal processes is increasing in the western Canadian Arctic, the primary source of terrestrial organic carbon for the marine ecosystem remains Arctic rivers, in particular the Mackenzie River. The flux of POC, based on data up to 2012, from the Mackenzie River is estimated to be 0.758 ± 66 Tg $y^{-1}$ (McClelland et al. 2016). Riverine contributions of sediments and organic carbon are important for the Beaufort Sea ecosystem since effects extend beyond the nearshore, reaching the shelf and slope. Between 2003 and 2013 the freshwater discharge of the Mackenzie River had large seasonal (4000 $m^3$ $s^{-1}$ in winter versus 25 000 $m^3s^{-1}$ in summer) and inter-annual variabilities, and freshwater discharge significantly increased by 22% (Doxaran et al. 2015). In the same 11-year period the discharge of suspended particulate matter also significantly increased in the Mackenzie Delta (50%) and river plume (35%) areas. The increased export of particulate matter, which includes inorganic particles as well as terrestrial organic carbon, to the mouth of the river is likely due to enhanced erosion processes (Figure 96) linked to temperature and precipitation effects within the expansive drainage basin of the Mackenzie River (Doxaran et al. 2015). Therefore, terrestrial carbon input has significantly increased in the western Arctic from multiple sources, over a relatively short period of time (e.g., 10 years) for glaciated landscapes. It is suggested that climate change may accelerate the continuing processes of deglaciation of the western Arctic, previously covered by the Laurentide Ice Sheet, with potential significant alterations to landscapes and coastal-marine interactions (Kokelj et al. 2017).

**Figure 96**. Slumping in the Mackenzie Delta. This and many other slumps from the summer of 2017 transported large amounts of organic matter into the Mackenzie River (photo credit: Doug Esagok).

The supply of terrestrial organic carbon can alter marine food webs although terrestrial carbon has historically been considered unavailable for marine food webs. Current studies demonstrate that microbial food webs can re-mineralize terrestrial carbon (e.g., Bell et al. 2016; Le Fouest et al. 2018) allowing this energy source to enter the classical food web (Section 4.3). Terrestrial organic carbon has been found to be a subsidy for both estuarine and marine pelagic and benthic communities (Casper et al. 2015; Roy et al. 2015a), weakening pelagic-benthic coupling in terrestrially impacted areas (Stasko et al. 2018). One study (Harris et al. 2018) has detected terrestrial organic carbon signals in beluga tissues, and further studies are required to identify what proportion of Beaufort Sea beluga diet may be originally derived from terrestrial carbon sources. It is now evident that terrestrial (including associated freshwater sources) organic matter can be a subsidy for multiple trophic levels in coastal/marine food webs, creating key linkages between riverine transported/coastally mobilized organic matter and secondary production in the Mackenzie-Beaufort ecosystem. Further study is needed to determine how terrestrial energy sources will affect marine food webs as coastal change continues.

## 7.2 Western Arctic Coastal fishes and Habitats (Mackenzie Delta, Yukon North Slope, and Marine Coastal Zones)

The coastal Beaufort Sea supports important linkages among freshwater, anadromous (occupy fresh waters during the winter, coastal areas in the open-water season), and coastal marine species. Anadromous fishes are particularly important in subsistence fisheries, which occur throughout the Canadian Arctic. Significant knowledge gaps still exist, however, with respect to the interactions among co-occurring fishes, their life history characteristics, and habitat associations throughout the year. These gaps are especially relevant during the open-water season when large numbers of anadromous fishes rely upon the coastal habitats for feeding and where they interact with marine fishes and other biota in nearshore habitats. Much of the knowledge obtained on coastal fishes in the western Arctic has been in association with the Mackenzie River delta and along the Tuktoyaktuk Peninsula where both research and subsistence harvests of anadromous fishes have occurred over long periods. Life history and habitat associations of similar species in marine coastal zones of the Beaufort Sea are not well understood, but knowledge has been gained through the history of subsistence harvest by coastal communities in those regions.

Coastal habitats in the western Arctic are broadly divided into two types, the freshened coastal habitat of the Mackenzie River Estuary (freshened plume area), and coastal marine sites that are typically colder and more saline (e.g., Franklin Bay) (Figure 97). The Mackenzie River provides large volumes of fresh water, sediments and nutrients to the Beaufort Sea, which have considerable influence on the coastal characteristics and freshwater mixing of the Beaufort Shelf. During spring break-up, sea ice is pushed out by relatively warmer, less saline water, allowing anadromous fishes to access coastal areas. Alternatively, coastal marine sites are greatly influenced by oceanographic processes of the Beaufort Sea. Such processes include upwelling of cold, nutrient-rich water up along the continental shelf into coastal areas, scour and grounding of sea ice during the winter, and overall less terrestrial influence than habitats near to the outflow of a major river system.

### *Mackenzie River Estuary and Yukon North Slope*

The Mackenzie River Estuary is a coastal region that is freshened and generally warmer than other Arctic coasts, especially where sediment heavy waters from the Mackenzie River meet the Beaufort Sea. The plume formed by the Mackenzie River extends beyond the coastline of the estuary and the Tuktoyaktuk Peninsula and often offshore to near the shelf edge. Accordingly, stenohaline (narrowly salt tolerant) species of fish (e.g., anadromous whitefishes) are able to venture farther offshore here than is typically possible into coastal marine habitats. This transition zone between habitats serves as critical foraging habitat for anadromous fishes after spring break up, but it also supports marine-associated species that are able to tolerate a wide range of salinities (i.e., euryhaline species).

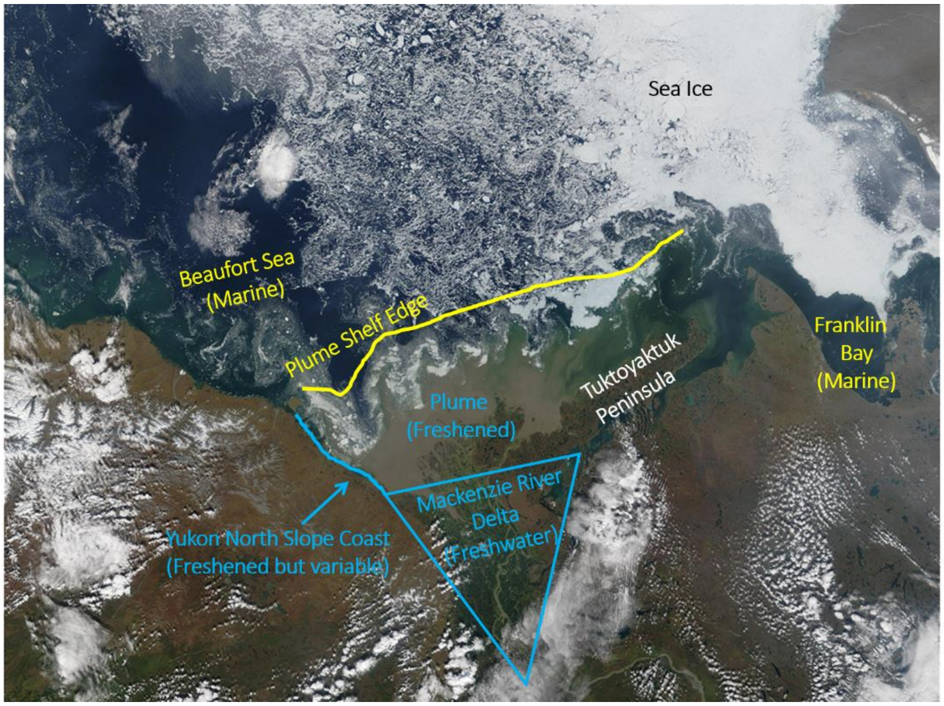

**Figure 97.** Mackenzie River Delta MODIS (Moderate Resolution Imaging Spectroradiometer) satellite image and associated habitat features available to coastal fishes. The designated habitat features such as the plume (seen as brownish water throughout the estuary) and Yukon North Slope coastal waters are used by narrowly salt tolerant (stenohaline) fishes including anadromous species, whereas the Beaufort Sea and coastal areas in marine locations (e.g., Franklin Bay) support marine (euryhaline) fishes.

Fishes that characterize the Mackenzie estuary include whitefishes or coregonines (Arctic Cisco (*Coregonus autumnalis*), Broad Whitefish (*C. nasus*), Least Cisco (*C. sardinella*), Lake Whitefish (*C. clupeaformis*), Round Whitefish (*Prosopium cylindraceum)*, and Inconnu), and anadromous northern Dolly Varden Char. Differing tolerances to salinity and temperature exist among these anadromous fish species, thus their life histories vary within this area (Reist and Bond 1988, Harris et al. 2012). Marine associated species are also often observed in the region including Pacific Herring (*Clupea pallasii)*, Saffron Cod (*Eleginus gracilis*), sculpins or cottids (e.g., Shorthorn Sculpin (*Myoxocephalus scorpius*) and Fourhorn Sculpin (*M. quadricornis*)), and flounders (Arctic Flounder (*Liopsetta glacialis*) and Starry Flounder (*Platichthys stellatus*)). Although less frequent, freshwater-associated species such as Northern Pike (*Esox lucius*), or

Burbot (*Lota lota*) may also be observed in the estuary, near the upper limits of their salinity tolerances (Żarski et al. 2010). Among these species, the fishes used for subsistence harvest by the Inuvialuit and Gwich'in communities have been the best studied in regards to their life history and relative abundance in the region. Recent studies on the Yukon North Slope have indicated that distinct foraging groups exist among freshwater, coastal and marine associated species (Brewster et al. 2016) reflective of differential habitat use.

While extensive studies in recent decades have examined fishes of this region, many research questions are directed towards the status of Dolly Varden char, a critical subsistence species (Byers et al. 2019) that is listed as a species at risk (special concern). Many Dolly Varden are harvested in freshwater areas, or on the western coastlines of the estuary. Recent studies, however, indicate that some individuals travel far offshore during the summer season and are not restricted to the nearshore region as was previously thought (Courtney et al. 2018). Although other anadromous fishes generally have not been directly observed far offshore, it is possible that they travel in the plume of the estuary in order to optimize their foraging during the open-water season. The stable isotope signatures obtained from muscle tissue of one such species, Arctic Cisco, suggests that their diet includes prey from offshore sources, which is parallel to that of Dolly Varden char (Brewster et al. 2016; D. McNicholl, unpublished data).

### *Coastal Marine Beaufort Sea*

The coastal marine areas of the Beaufort Sea are influenced to a greater degree by oceanographic processes. Fishes in these regions must tolerate higher salinities and colder temperatures, and likely also higher variations in these variables. In some embayments, that are sheltered relative to areas exposed to the Amundsen Gulf, both coastal anadromous and marine fishes occupy the same habitat. Water temperatures in these areas are generally warmer and subject to less variation than for habitats exposed to cold water upwelling along the continental shelf edge. Species with a greater sensitivity to cold, saline water (i.e., less tolerant), are more likely to be found nearshore and within the freshened Mackenzie plume.

Fishes that characterize the coastal marine habitats include coregonines (Arctic Cisco, Broad Whitefish), and anadromous Arctic Char, Pacific Herring, Saffron Cod, Greenland Cod (*Gadus ogac*), sculpins or cottids (Shorthorn Sculpin, Arctic Staghorn Sculpin (*Gymnocanthus tricuspis*) and Fourhorn Sculpin), Flounders (Arctic Flounder and Starry Flounder), and forage fishes such as Capelin or Pacific Sand lance (*Ammodytes hexapterus*) which are often observed in the stomachs of subsistence species (D. McNicholl, unpublished data).

Subsistence harvest of fishes during the summer is an important part of life for the Inuvialuit from the communities of Sachs Harbour, Paulatuk and Ulukhaktok, and on the Yukon North Slope by both Inuvialuit and Gwich'in peoples (Bell and Harwood 2012; Byers et al. 2019). Coastal fisheries target most of the same species of anadromous fishes as do fishers in the Mackenzie River Estuary and inland areas, with the exception of Dolly Varden that are generally captured west of the estuary and Arctic Char collected to the east. Arctic Cisco (locally known as herring, Table 5) and Broad Whitefish are commonly harvested as well, among coastal communities on the mainland, and like char, serve as a culturally important food source.

Much of the known information on these fishes, their life histories, habitat associations and trophic linkages was gathered during the summer months when both coastal anadromous fishes and marine fishes overlap in the nearshore (0-20 m) zones. Recent studies in the newly established Anguniaqvia niqiqyuam Marine Protected Area (ANMPA) in Darnley Bay (McNicholl et al. 2017) found that there are distinct groups of pelagically and benthically associated prey consumed by coastal fishes, but some species also receive significant contributions to their diets from terrestrial sources (i.e., suggesting the relevance of freshwater influences from the smaller rivers in the area). Species that occupy a similar dietary niche, such as juvenile Capelin and Arctic Cod, display a substantive amount of overlap and may compete with one another should prey availability change (McNicholl et al. 2016).

Studies of coastal and nearshore fishes and their habitat usage in the ice-on winter season are needed for many areas. During the winter months, marine and anadromous species are presumed to have minimal overlap, as anadromous species will have returned to their freshwater overwintering areas and marine species will remain in the ocean environment, likely farther offshore to avoid coastal sea-ice dynamics. Nearshore habitats in this area are also restrictive to marine fishes due to grounded sea ice in shallow areas, or stamukhi zones made up of an accumulation of grounded sea ice, which trap freshwater outflow throughout the winter. Rivers that continue to flow during winter may create large areas of freshened water under the sea ice, especially offshore of the Mackenzie River Estuary (Carmack and Macdonald 2002). These areas are restricted by sea ice and impede movement of marine fishes due to physical barriers and low salinity; however, it is unknown if such areas are also utilized during winter by anadromous species.

*Relevance of coastal fishes*

The habitats that support coastal fishes in the Beaufort Sea are of great relevance to Inuvialuit and Gwich’in harvesters, who rely on their catch for much of their summer and early winter food supply. There are no commercial fisheries in the region, and with the increasing cost of transportation to remote communities, access to fresh, quality foods is a significant issue. Harvest of whitefishes (coregonines) and chars is also a culturally significant practice in the western Arctic in which community members are closely linked to this important food source (Bell and Harwood 2012). Understanding habitat use and linkages of these fish to the variable coastal environment is essential to effective management of their stocks and continue sustainable harvest in the future. Research focused on basal energetic sources of the fish (terrestrial versus marine sources), the importance of winter habitats, the interactions between freshwater, anadromous and marine species, and limitations in sensitive coastal areas is becoming more important as climate change affects habitats and ecosystems. Additionally, understanding the movements of these species in marine areas and identifying critical habitats associated with life history is necessary in order to manage these species across both land claim and international borders.

In recent years the increase in ocean temperatures appears to have facilitated a northward distributional shift of sub-arctic species into the Canadian Arctic. Species that were generally uncommon at the northern edge of their geographic range are now becoming more prominent in Arctic ecosystems and potentially overlapping with Arctic endemic species for prey and habitat (e.g., Dunmall et al. 2013). Pacific salmon are one group of species that has increased substantially in abundance in the western Arctic, as observed in the nets of subsistence harvesters (Dunmall et al. 2018). Research is underway to better understand coexistence of salmon and local char species (e.g., Dolly Varden, Lake Trout (Salvelinus namaycush), Arctic Char) using a community-based approach to document their change in abundance (Dunmall and Reist 2018; Byers et al. 2019).

**Table 5.** Siglit names of fishes found in the Mackenzie River Estuary, with their corresponding common and scientific names.

| ***Siglit* Name** | **Common Name [local name]** | **Scientific Name** |
|---|---|---|
| Iqalukpik | Arctic Char | *Salvelinus alpinus* (Linnaeus 1758) |
| Qaaqtaq | Arctic Cisco [Herring] | *Coregonus autumnalis* (Pallas 1776) |
| Iqalugaq | Capelin | *Mallotus villosus* (Müller 1776) |
| Uugavik | Greenland Cod [Rock Cod] | *Gadus ogac* (Richardson 1836) |
| Pikuktuuq | Lake Whitefish [Crooked Back] | *Coregonus clupeaformis* (Mitchill 1818) |
| Piqquaqtitaq | Pacific Herring [Blue Herring] | *Clupea pallasii* (Valenciennes 1847) |
| Iqaluaqat | Pacific Sand lance | *Ammodytes hexapterus* (Pallas 1814) |
| Iqaluaqat | Rainbow Smelt [Stink Fish] | *Osmerus mordax* (Mitchill 1814) |
| Uugaq | Saffron Cod [Tom Cod] | *Eleginus gracilis* (Tilesius 1810) |
| Nataarnaq | Flounder | Pleuronectidae. |
| Kanayuq | Sculpin | *Cottidae* spp. |
| Anaaktiq | Whitefish | *Coregonus* spp. |

## 7.3. Estuarine and Brackish Water Habitat

Estuaries are known to play important roles for the biological production of many species of invertebrates in Arctic ecosystems. The estuarine environment shapes communities through the physiological capacity of organisms to osmoregulate and through the effects of terrestrial erosion and nutrient input (Brown TM et al. 2011; Carmack et al. 2016). This latter mechanism often results in turbid waters leading to low levels of primary production thus limited zooplankton diversity, but offering plenty of opportunities for benthic organisms to prosper due to the abundance of resources (Wassman 2015). Parsons et al. (1989) described gammarid amphipods, mysids and small copepods as being representative species of some near shore estuarine environments. This benthic assemblage has been found to support higher trophic consumers such as fish (e.g., Least Cisco and freshwater Arctic Grayling (*Thymallus arcticus*), and marine birds and mammals (e.g., Loseto et al. 2009).

Estuarine environments, such as the Mackenzie River delta, have been described as having long food-web structures due to the contribution of terrestrial organic matter (Bell et al. 2016), and have been shown to support large communities of epibenthic mysid and amphipod species, which are prevalent during the summer (Dunton et al. 2006). Many polychaete species have also been shown to favour estuarine conditions around the Mackenzie River (Conlan et al. 2008). One concern is the potential for increased freshwater input that could render estuarine habitats more susceptible to ocean acidification due to the lower buffer capacity and lower calcium ion concentrations at the surface (Carmack et al. 2016). Understanding the ecological function of these dynamic ecosystems, especially during the seldom-studied winter months (McClelland et al. 2012), is necessary to address cumulative effects of change in coastal habitats.

## 7.4 Estuarine Use by Beluga Whales

Beluga whales are circumpolar in distribution, found discontinuously in Arctic and sub-Arctic waters. They primarily inhabit waters off the coast of Alaska, northern Canada, western Greenland, and northern Russia, though isolated populations exist farther south in the St. Lawrence River in Atlantic Canada, and the Sea of Okhotsk in Eastern Russia (Rice 1998). Many beluga populations are migratory, travelling from deep-water over-wintering sites to shallow, coastal areas and estuaries in the summer (Heide-Jørgensen et al. 2001).

The reasons for summer estuarine use are poorly understood, though several hypotheses have been proposed, including: feeding, calving, moulting, refuge from predators, or socializing. The feeding hypothesis has been supported by observations of belugas feeding in coastal waters in East Bering Sea (Huntington 1999) and near the mouth of the Churchill estuary (Watts and Draper 1986), however, historically most belugas caught in both the Mackenzie and Churchill estuaries had empty stomachs, while those caught at sea had full stomachs (Sergeant 1973; Harwood et al. 1996). The number of mothers and newborn calves observed in the estuaries supports the hypothesis that the estuaries provide warmth and shelter for calving (Sergeant 1973), although births are rarely observed and calving is thought to occur prior to the arrival of whales in some locations (Cobb et al. 2008). There is evidence to suggest that the low salinity and high temperatures in estuaries help accelerate moult (St. Aubin et al. 1990). In support, whales at all stages of moult have been observed over the course of the summer in Hudson Bay estuaries (St. Aubin et al. 1990) and whales have been observed rolling against the substrate in the estuary of the Churchill River (Watts et al. 1991; Smith et al. 1992). It is also thought shallow coastal waters and estuaries provide relief from predators (primarily killer whales), however, belugas face hunting pressure from humans in several of the estuaries where they gather. Finally, the large size of summer aggregations and observations of social behaviours has led to the hypothesis that belugas gather to socialize. Unfortunately, observing social behaviour away from coastal waters and estuaries is challenging, making this hypothesis difficult to test. Ultimately, reasons for estuarine use may vary among populations and may not be mutually exclusive.

Recently patterns of estuarine habitat use have been closely examined within the Eastern Beaufort Sea beluga population, which form large aggregations in the Mackenzie Estuary from late-June – August. Individual whales appear to spend only 3-5 days in the estuary before moving offshore, so the aggregation is likely composed of different whales filtering in and out as the season progresses (Richard et al. 2001). Within the estuary, a clumped distribution pattern has been identified, where belugas are more likely to congregate in certain ‘hot spots’ year after year (Harwood et al. 2014). This is in contrast with offshore habitat use which is widespread, consisting of single belugas or small groups of two or three (Norton and Harwood 1985). Usage of these hot spots appears to be independent or loosely associated with sea-bottom substrate (D. Whalen, unpublished data), suggesting hotspots and by extension estuarine use may not be governed by rubbing activity for moulting. On the other hand, recent spatio-temporal analyses revealed beluga presence to depend on warm, fresh conditions, whereby belugas use locations farther into the estuary when oceanic influxes inundate hot spots with cold, saline water (K. Scharffenberg, unpublished data). These findings support hypotheses that beluga use the estuary for thermal benefits and/or to facilitate moulting.

High-speed winds also appear to influence patterns of beluga habitat use in estuaries. For example, in the Nastapoka Estuary (Nunavik), belugas favoured the upper estuary during high-speed winds (Caron and Smith 1990), and it has been suggested that beluga seek calmer waters close to shore in the Bering Sea when wind-speed increases (Mymrin and Huntington 1999). In the Mackenzie Estuary, the detection of beluga sounds at typical aggregation locations decreased significantly during strong winds (K. Scharffenberg, unpublished data). This was particularly evident during a 4 day storm in 2016, when no belugas were detected by hydrophones at high-use locations for 5 days (K. Scharffenberg, unpublished data). In this location, it is thought that the shallow waters (~2 m deep) are difficult to navigate when surface waters become rough (maximum wave height >1 m, i.e., half the depth of the water column), and present a danger of stranding, entrapment, and/or exhaustion, especially for young belugas who frequent the area. These findings highlight the need for continued monitoring in the Mackenzie Estuary as storminess in the Arctic is expected to increase (Manson and Solomon 2007; Sepp and Jaagus 2011; Vermaire et al. 2013).

## 8.0 Co-management for the Canadian Arctic Ocean

In the Canadian Arctic the management of fish and marine mammal stocks and the habitats upon which they depend is significantly different than in other parts of Canada. As well as cultural and traditional differences the process of management and protection has been defined by modern comprehensive land settlement agreements, or treaties, between the original peoples of the Arctic coast, the Inuit, and the governments of Canada, provinces and territories. The four Inuit regions of Canada, collectively called Inuit Nunangat (ITK 2019) include the Arctic coastline and adjacent islands and oceans from the Yukon/Alaska border across the Inuvialuit Settlement Region in Yukon and the Northwest Territories, Nunavut, Nunavik in northern Quebec and Nunatsiavut in northern Newfoundland and Labrador. The agreements, while differing in detail, all established co-management boards for fisheries and wildlife management, and environmental protection and planning. As a result the Inuit people of Arctic Canada are now directly involved in resource management decision making in the Arctic Ocean, in cooperation with the federal government. It should also be noted that these agreements are protected under the Canadian Constitution and if there is a conflict between federal, provincial or territorial legislation and a settlement agreements, the settlement agreement prevails.

This requirement for partnership has been recently highlighted with DFO’s announcement (October 2018) of an Arctic Region with the Regional Director General (RDG) located in Rankin Inlet and the Regional Director of Coast Guard located in Yellowknife. The reorganization is being pursued to enhance program and service delivery in the Arctic and to better meet the needs of northern communities. The new organizational structure is expected to ensure that northerners have a greater say in DFO’s decisions and operations.

To end this report we present Case Studies that describe co-management activities and the integration of scientific and Inuit knowledge as we continue to strive to better understand the state of the Canadian Arctic Ocean.

## CASE STUDY 17: Linking Traditional Ecological Knowledge, Western Science, and Environmental and Fisheries Management in the Western Canadian Arctic

The comprehensive land claims in the Canadian Arctic recognize the rights of the Inuit to the renewable resources of the region and the right to participate in the management of those resources. They also recognize the traditional cultures of the Inuit, and that Inuit knowledge and practices need to be reflected in management of the wildlife. Governments have responded to these agreements, and to numerous court cases by modifying laws, policies and practices to ensure that Indigenous knowledge, as well as Western-based science helps to support resource management decision making. But the way forward to translate the numerous words into the realities of everyday actions in the management and protection of fisheries and wildlife and their associated habitats is far from clear (e.g., Laidlaw 2015).

In recent years there have been continued efforts to document and catalogue ecosystem Traditional Ecological Knowledge[1] (TEK) (e.g., ISR Traditional and Local Knowledge Catalogue, Hudson Bay SIKU, Nunavut Coastal Inventory, Byers et al. 2019). Here we describe an environmental and fisheries management model (Dorcey and Hall 1981) that is expanded to include TEK. It is presented from the perspective of the Inuvialuit Settlement Region (ISR) (Canada 1984) but could be applied elsewhere.

The model (Figure 98) is a visualization of the link between knowledge generation (TEK and Western Science) and environmental and fisheries management decision-making within the co-management framework established by the land claims. The intention is to provide an approach to incorporating TEK as a useful tool of fisheries and environmental management by recognizing the importance of the full spectrum of Inuit understanding of the environment.

Environmental and fisheries management decisions can be viewed as a spectrum or continuum from single purpose, to complex multi-purpose, or integrated decisions. The bottom horizontal arrow in Figure 98 shows this continuum and examples of the decision processes from the ISR that are regularly invoked in the Canadian Arctic. Community Conservation Plans (CCPs) (EISC 2018), developed by the Hunters and Trappers Committees (HTCs), are key processes for environmental decision making. CCPs reflect community values and goals and categorize land and resource uses for the area. Scientific information is included to complement the TEK but the CCP origins are within the communities and then are linked directly to the planning of proposed industrial development. The diverse management processes on the decision continuum are supported by research activities that span the spectrum from descriptive (e.g., what species and where) to functional knowledge (e.g., system relationships such as how seal pup survival varies with ice formation or how char populations will respond to fishing).

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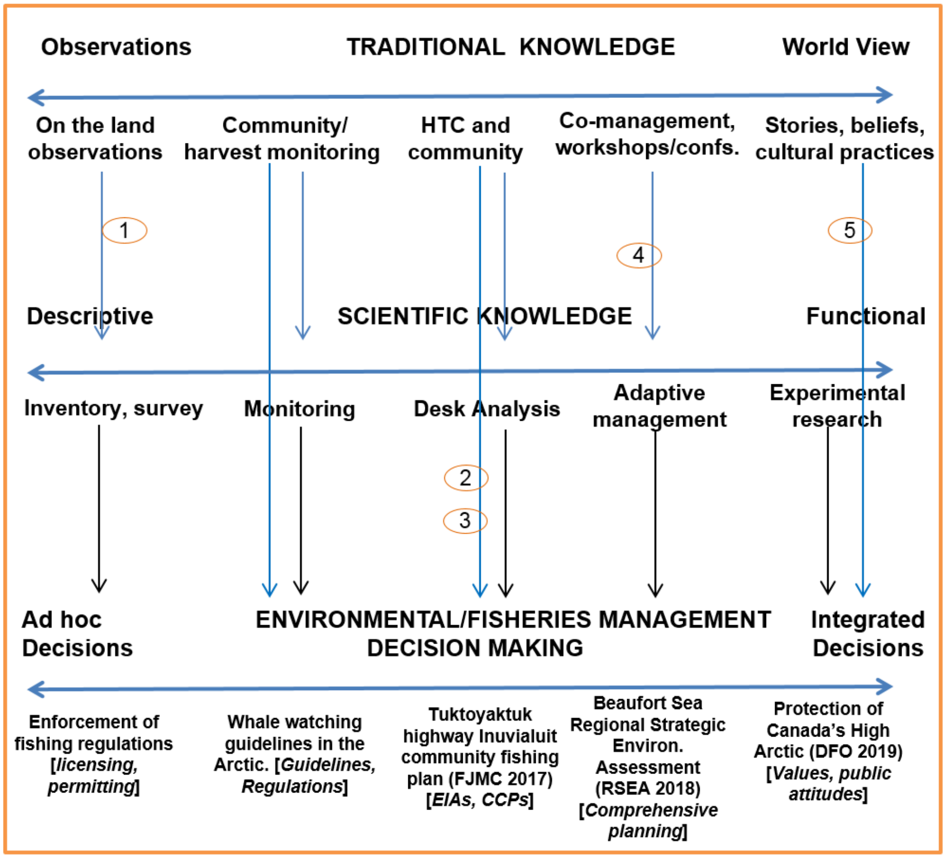
[1] Traditional Ecological Knowledge (TEK) is not a concept that is easily defined or categorized. Here we use the definition from Berkes et al. (2000): “A cumulative body of knowledge, practice and belief - evolving from adaptive processes and handed down through generations by cultural transmission - about the relationship of plants and animals (including humans) with one another and with their environment.” Other definitions and nomenclature such as Local or Fishers Knowledge or Inuit Qaujimajautuqangit as used in Nunavut, would be just as appropriate for this case study.

In the model, the black vertical arrows demonstrate the link between the scientific knowledge spectrum and the management decision spectrum. The relative position of the five research activities and the management decisions is important. Descriptive knowledge contributes primarily to the single objective, single purpose end of the management decision-making spectrum while new functional knowledge is essential for integrated decisions but also contributes to the other end of the spectrum. Dorcey and Hall (1981) argue that if management is to be improved, decision making should move to the right with greater emphasis on support for enhancing functional knowledge and thus specific hypothesis testing.

TEK also can also be viewed as a spectrum of complexity from simple individual observations, to community governance and knowledge, to world views and values. Along the top horizontal arrow some activities supported by co-management with respect to TEK are presented as a continuum of complexity. The vertical blue arrows show linkages and parallels between the TEK and science spectrums and then indirectly to the management spectrum. There are also direct linkages (vertical blue arrows) from the TEK spectrum to the management spectrum. Five examples are provided to illustrate TEK flow through the management model. The blue arrow on the far right identifies that Inuit stories, beliefs and cultural practices can directly affect management decisions. In the western Arctic influential elders including Alex Aviugana and Billy Day helped negotiate the Inuvialuit Final Agreement (IFA) (Canada 1984) and served with effectiveness and distinction on many Inuvialuit and co-management organizations bringing their traditional knowledge to the negotiations framed primarily by a western bureaucratic public administration (Beck 1994; Bell 2009). More recently Inuit are speaking via Facebook, Twitter and videos documentaries directly to a broader public to explain their lives and culture. In “Angry Inuk” Inuit director Alethea Arnaquq-Baril (Arnaquq-Baril 2016) challenges the EEC (European Economic Community) ban on commercial seal harvests. In so doing she has helped to raise awareness of Europeans and other North Americans to Inuit desire for a sustainable economy and food source based on traditional resources of fish and marine mammals rather than welfare and imported southern produce. While the campaign was ultimately unsuccessful, it is approaches like this that can lever the world view of some 132,000 Inuit to help influence public attitudes of over one billion people in Europe and North America to enhance environmental sustainability and protection for the entire Arctic.

The model is open to the criticism that it is a typical Western bureaucratic approach to the integration of TEK into management and does not adequately reflect the real differences between aboriginal cultures and the main stream view of the world. As Stevenson (2004) has argued, this approach may just be seen as further appropriation of TEK into Western scientific thought and practice. This may be so but the reality is that the co-management system in the Arctic is primarily a Western state system that requires the full spectrum of both TEK as well as Western science. The proposed model highlights potential relationships between the spectrums of knowledge and how, together, they can contribute to the range of practices required for environmental and fisheries management in the Arctic. Functioning under such model should facilitate communication between participants (e.g., harvesters, scientist, politicians) and help focus TEK and western science efforts on specific activities required to improve decision making.

The model presented here, implemented within a co-management framework, offers promise to enhance the interface between TEK and Western science and environmental and fisheries management. Paraphrasing White (2006), co-management boards in the Arctic are substantively important in terms of gauging the influence of TEK and represent the best opportunity for imbuing public, non-Aboriginal governmental institutions with TEK. In other words if co-management boards cannot successfully integrate TEK into their processes and decisions it is unlikely that another public institution would fare any better.



1) Inuvialuit, Gwich'in and Sahtu fishers provide primary data to assess the migrations of salmon

2) Management plan for sustainable subsistence and recreational fishery along Tuktoyaktuk highway is based primarily on community TEK.

3) In the 1990s and 2000s the planning for oil and gas exploration and development was guided by the land use plans spelled out in the CCPs.

4) The 2016 Beluga Summit, hosted by DFO, the FJMC and the IGC, generated a state-of-knowledge about beluga that gave equal weighting to TEK and western science (Loseto et al. 2018b).

5) Elder representation (e.g. IFA negotiations) and recent multi-media activities have shared Inuit lives and culture with the broader public.

**Figure 98.** A visual model of the relationship between TEK, Western Scientific Knowledge and Environmental/Fisheries Management Decision-Making. EIA: Ecosystem Impact Assessment; FJMC: Fisheries Joint Management Committee; IGC: Inuvialuit Game Council.

## CASE STUDY 18: Citizen Science, Arctic Style

**Figure 99**. Brandon Green and Steve Illasiak processing fish for samples and recording biological data in Anguniaqvia niqiqyuam marine protected area, Northwest Territories, 2018 (photo credit: Darcy McNicholl).

The rapidly changing Arctic presents challenges to both scientists assessing impacts and opportunities, and to Indigenous Peoples who are intimately connected to the environment and its resources. Arctic biodiversity is irrevocably linked to the culture of Indigenous Peoples in the north and their perceptions of change are rooted in their dependence on the environment and social values to protect subsistence opportunities (CAFF 2013). Indeed, the dearth of scientific information about species and their habitats in the Arctic (Reist et al. 2006a) is contrasted with the breadth of Inuit knowledge about the environment. Therefore, innovatively creating the opportunity to assess change by those directly observing immediate effects provides a powerful approach to facilitate human influence on the pace of science as well as our role in the pace of change. Citizen science in the Canadian Arctic can be an important community-based monitoring tool that bridges Indigenous knowledge and scientific research, and ultimately results in knowledge co-production (Dunmall and Reist 2018).

The commonality of using specific and easily documented indicators to assess environmental change in both Indigenous and scientific knowledge systems provides the foundation for citizen science in the Canadian Arctic (Dunmall and Reist 2018). The contemporary knowledge obtained by monitoring the environment through indicators can be translated to developing baseline data and quantitatively monitoring ecological changes at both fine- and broad-spatial scales. Although the broad suite of indicators usually gathered by Indigenous knowledge is often different than the specific indicators used in scientific research, both of these monitoring methods are linked and thus can highlight similar ecosystem-level changes (Riedlinger and Berkes 2001; Berkes et al. 2007; Tremblay et al. 2008). Communication and outreach is vital to the success of citizen science in the Arctic, and is facilitated in part through the use of social media (e.g., Facebook) to distribute information and interact with participants and observers (Dunmall and Reist 2018).

The prevalence of community-based monitoring is increasing in the Canadian Arctic. The Arctic Salmon program (www.facebook.com/arcticsalmon) is using a community-based monitoring approach to track increasing abundances and broadening distributions of Pacific salmon (*Oncorhynchus* spp.) and distributional shifts of fishes in the Canadian Arctic (Dunmall et al. 2013, 2017, 2018). Harvest-based monitoring of beluga whales provides important data about beluga (*Delphinapterus leucas*) health and condition based on the provision of samples and measurements of specific indicators (Loseto et al. 2018c). Community-based monitoring of the physical environment, including the collection of Inuit knowledge is also occurring in Hudson Bay (e.g., https://arcticeider.com/siku). Community-based monitoring of the coastal ecosystem, including data collections on environmental parameters, primary production, benthic habitats, and fish biodiversity has been on-going in Darnley Bay, Northwest Territories, since 2012 (McNicholl et al. 2017) and was recently developed into a community-based monitoring framework tested for its transferability in the coastal environments near Kugluktuk, Nunavut in 2017 and Sachs Harbour, Northwest Territories in 2018 (McNicholl and Dunmall 2018a). In communities with relatively high shipping activity, and thus at higher risk for invasive species, techniques for community-based port surveys and environmental DNA (eDNA) sampling has been introduced (2015-18: Churchill, MB, Salluit (Nunavik), Iqaluit and Pond Inlet (Nunavut)) (Polar Knowledge Canada 2017). These efforts have been combined with youth focused educational workshops to raise awareness and provide identification guides/hands on training in how to report new sightings and distinguish high risk invasive species from similar native species.

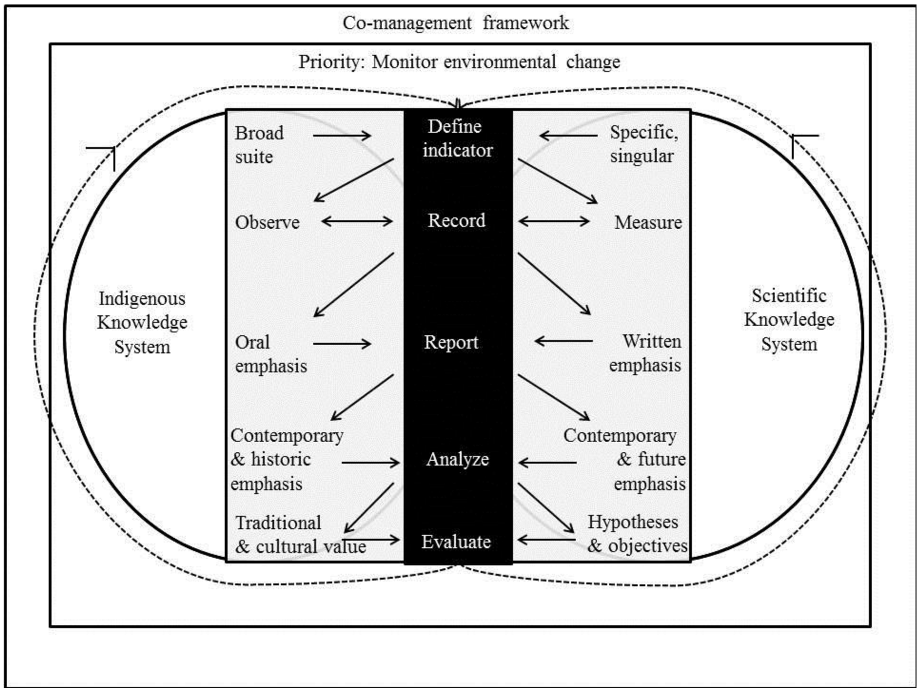


**Figure 100.** A model for citizen science to monitor a changing Canadian Arctic. Under a common priority of monitoring environmental change, citizen science (grey square) can bridge Indigenous and scientific knowledge systems (white circles). The arrows depict the contributory flow of information from the general citizen science framework (black box) out to each knowledge system and back to the framework at each step in the process, which equalizes the value of information derived from indigenous knowing and scientific knowledge and contributes to knowledge co-production. Each step in the framework is described from the perspective of each knowledge system. A key element is the interactive reporting process and ongoing communications among participants (source: Dunmall and Reist 2018).

Community-led monitoring is now also emerging in the Canadian Arctic. This represents a subtle but very important shift to leadership roles by Indigenous Peoples in all aspects of field-based monitoring efforts within a collaborative framework rooted in science. Transitioning to this community-led effort is a process that requires time and effective communication, motivation, and mutual agreement on indicators and goals, as well as capacity building through the provision of protocols, gear, and training. Community-led monitoring efforts in Anguniaqvia niqiqyuam Marine Protected Area, near Paulatuk, Northwest Territories, successfully collected data in 2018 on indicators spanning multiple trophic levels, as well as environmental data regarding the coastal ecosystem (McNicholl and Dunmall 2018b) (Figure 99). Leadership in beluga whale monitoring has been consistent among Inuvialuit and the recent collection of TEK (Ostertag et al. 2018; Waugh et al. 2018) complements these efforts by providing ecosystem-level context to specific indicators (Loseto et al. 2018c).

Citizen science is broadly appealing as a tool to assess environmental change in the Arctic. When carefully applied in a model that emphasizes continuous effective communication and ensures the collaborative production of knowledge (Figure 100), citizen science can provide critical information necessary to predict impacts and opportunities associated with biodiversity shifts and rapidly changing ecosystems in the Arctic. Moreover, if eventually applied consistently using a common framework, citizen science delivered by Indigenous Peoples provides wide geographic coverage and monitoring over the longer term, which will lead to better understanding of the nature, rates and consequences of Arctic change. This, in turn, will result in more effective resource co-management and environmental stewardship.

## CASE STUDY 19: Beluga Monitoring, Management, and Human Relations

Each summer thousands of Eastern Beaufort Sea (EBS) beluga, qilalukkaq (*Delphinapterus leucas*) whales aggregate in the Mackenzie Estuary of the Canadian Beaufort Sea. This population is recognized as one of Canada's largest, last estimated at approximately 40,000 individuals (Hill and Demaster 1999, Harwood et al. 1996). The subsistence harvest of these beluga, by Inuvialuit, the Inuit of Canada's Western Arctic, has, and continues to be of important economic, dietary, and cultural importance. EBS belugas are co-managed by the Fisheries and Oceans Canada (DFO) and the Fisheries Joint Management Committee (FJMC) under the guidance of the Inuvialuit Game Council (IGC) as per the Inuvialuit Final Agreement land claim (Canada 1984). The IFA, the Beaufort Sea Beluga Management Plan and earlier conservation management efforts supported the collection of beluga harvest data through partnerships among co-management bodies and in cooperation with the local Hunters and Trappers Committees (HTCs).

As a result, more than 40 years of data have been collected about the EBS beluga via the harvest monitoring program, a community-based monitoring (CBM) program (Harwood et al. 2002). The program has evolved to provide a centre-point to bring together scientists, community members and co-management boards to work as a team to address community concerns and identify research directions. In 2010, the beluga management zones identified as 1a became the first Arctic Marine Protected Area, the Tarium Niruitait MPA (Loseto et al. 2010). Part of the MPA monitoring and management framework involves the use of indicators that are used to measure and communicate the health of MPA. Over the last 10 years the existing beluga CBM grew in depth and breadth to include indicators on beluga condition, diet, health that included contaminant and disease monitoring and other physiological indicators that can also be used to extrapolate to ecosystem health (Loseto et al. 2018b). While the monitoring expanded to include multiple health and ecological indicators it was noted that the CBM program was lacking a mechanism to include the extensive Inuit knowledge, referenced as Local and Traditional Ecological Knowledge (LEK, TEK) held by Inuvialuit in the ISR.

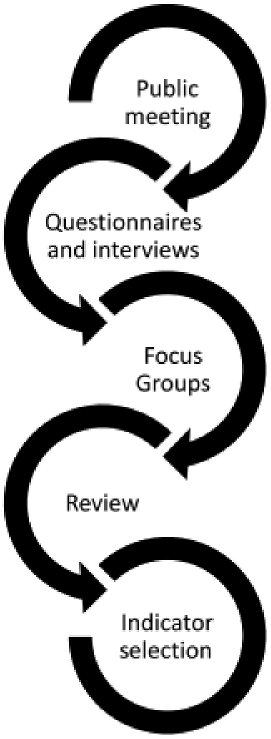
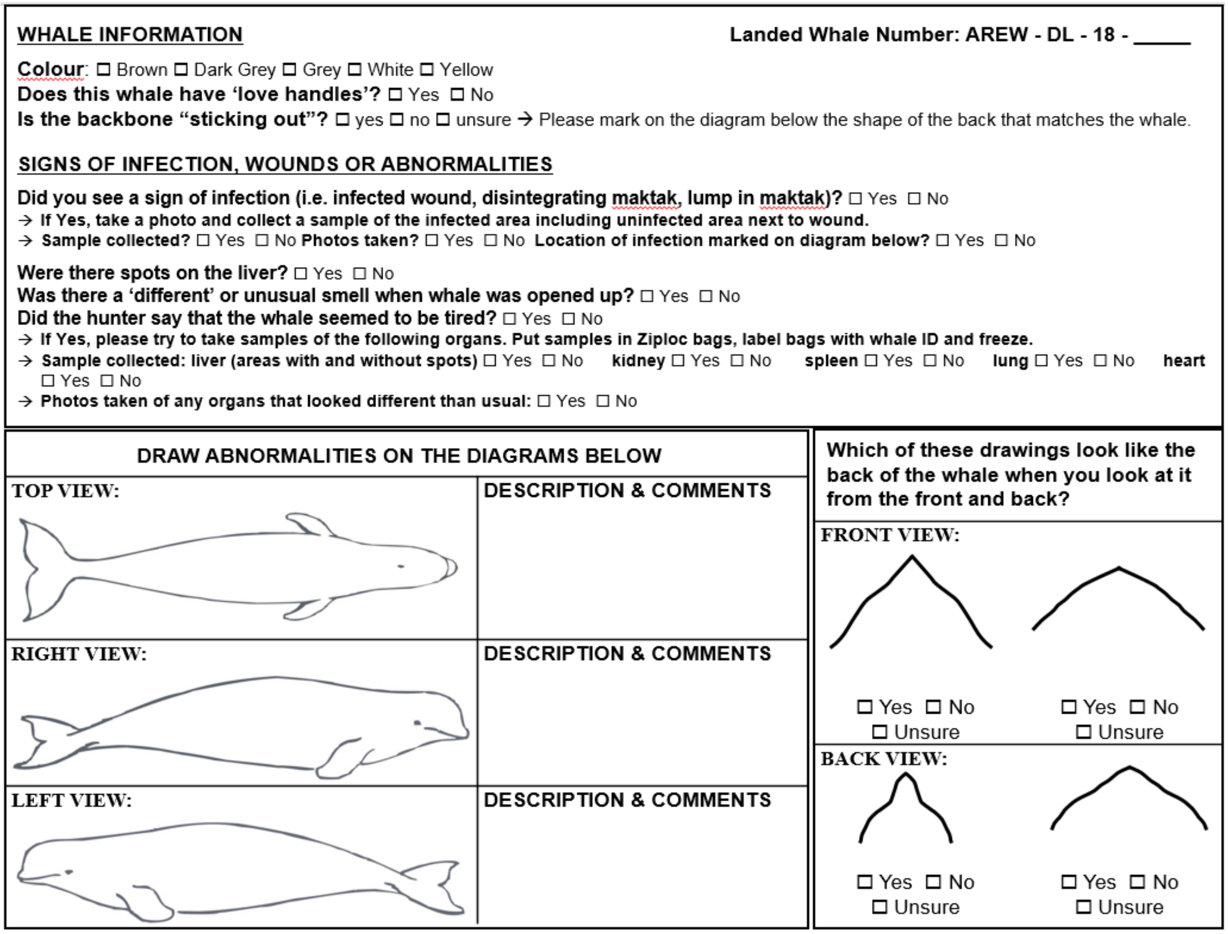


**Figure 101.** The process followed to select beluga health indicators with Inuvik, Tuktoyaktuk and Paulatuk.

Inuvialuit and their ancestors have sustainably managed the population for hundreds of years (McGhee 1988; FJMC 2013). Subsequently, the Inuvialuit have extensive knowledge about the behaviour and health characteristics of beluga whales in the ISR. Through long-term working relationships established through collaboration on various beluga-related projects, a project was initiated to address gaps in the integration of LEK and TEK in the beluga CBM program (S. Ostertag, unpublished data). Through an extensive consultation process (2012-2017), indicators of beluga condition and disease were identified by beluga knowledge-holders in the three most active beluga harvesting communities in the ISR; Inuvik, Tuktoyaktuk and Paulatuk (S. Ostertag, unpublished data). This process focused on Inuvialuit knowledge-sharing, frequent communication, and collaborative feedback through various stages of research (S. Ostertag, unpublished data) (Figure 101). Examples of indicators identified by the three communities include: the colour and texture of the fat/uqsuq, the shape of the body (broad or round back, fat rolls described as 'love handles') and signs of infection. These indicators have now been incorporated into the FJMC Fish and Marine Mammal Community Monitoring Program to ensure that Inuit observations about beluga health and condition are recorded for harvested beluga whales (Figure 102).



**WHALE INFORMATION** **Landed Whale Number: AREW - DL - 18 - _____**

**Colour**: ☐ Brown ☐ Dark Grey ☐ Grey ☐ White ☐ Yellow
**Does this whale have 'love handles'?** ☐ Yes ☐ No
**Is the backbone "sticking out"?** ☐ yes ☐ no ☐ unsure → Please mark on the diagram below the shape of the back that matches the whale.

**SIGNS OF INFECTION, WOUNDS OR ABNORMALITIES**

**Did you see a sign of infection (i.e. infected wound, disintegrating maktak, lump in maktak)?** ☐ Yes ☐ No
→ **If Yes, take a photo and collect a sample of the infected area including uninfected area next to wound.**
→ **Sample collected?** ☐ Yes ☐ No **Photos taken?** ☐ Yes ☐ No **Location of infection marked on diagram below?** ☐ Yes ☐ No

**Were there spots on the liver?** ☐ Yes ☐ No
**Was there a 'different' or unusual smell when whale was opened up?** ☐ Yes ☐ No
**Did the hunter say that the whale seemed to be tired?** ☐ Yes ☐ No
→ **If Yes, please try to take samples of the following organs. Put samples in Ziploc bags, label bags with whale ID and freeze.**
→ **Sample collected: liver (areas with and without spots)** ☐ Yes ☐ No **kidney** ☐ Yes ☐ No **spleen** ☐ Yes ☐ No **lung** ☐ Yes ☐ No **heart** ☐ Yes ☐ No
→ **Photos taken of any organs that looked different than usual:** ☐ Yes ☐ No

**DRAW ABNORMALITIES ON THE DIAGRAMS BELOW**

| | |
|---|---|
| **TOP VIEW:** | **DESCRIPTION & COMMENTS** |
| **RIGHT VIEW:** | **DESCRIPTION & COMMENTS** |
| **LEFT VIEW:** | **DESCRIPTION & COMMENTS** |

**Which of these drawings look like the back of the whale when you look at it from the front and back?**

**FRONT VIEW:**

| | |
|---|---|
| ☐ Yes ☐ No<br>☐ Unsure | ☐ Yes ☐ No<br>☐ Unsure |

**BACK VIEW:**

| | |
|---|---|
| ☐ Yes ☐ No<br>☐ Unsure | ☐ Yes ☐ No<br>☐ Unsure |

**Figure 102.** FJMC/DFO beluga monitoring sheet (1 of 2 sheets) that includes TEK based indicators.

The success of the community-identified beluga health indicators is largely due to the repeated annual observations of active harvesters on the land and their interacts with beluga whales. Inuvialuit knowledge of the beluga whale hunt is dynamic with deep roots containing both traditional components, passed down through oral history, as well as current and ever-changing local observations. However, despite this intergenerational beluga whale harvest, recent changes – both environmental and social – have impacted human-beluga relations in the region. For example, Aklavik a community with a long history of active beluga harvesting, has experienced a sharp decline in the annual whale harvest (Worden 2018) (Figure 103).

**Figure 103.** Aklavik's annual beluga whale harvest from 1975-2019 (source: FJMC).

Another TEK study was led to try to understand the drivers of the decline in beluga harvest. TEK collections demonstrated that the knowledge of how to successfully hunt still remains among Elders and experienced adults in Aklavik. However, environmental and social changes are working together to create a new reality where the beluga whale harvest is not possible for many people in the community. The changing environment (i.e., increased storms and delta erosion/slumping) affects access to the coast, safety on the ocean, and the erosion of preferred coastal whaling camps. Other key factors include hunting and fuel costs, and few stable jobs in Aklavik to meet the cost of the beluga hunt. Lastly, values are changing in Aklavik with the passing of Elders and the influence of Southern culture. Because the beluga hunt is based on sharing, teamwork and patience, these changing values are changing how and if people harvest whales. Shingle Point is now the main camp used in the summer for coastal harvesting, but it is not ideal as a whaling location. Camp life is too noisy and whales stay far out in deep water, which makes hunting dangerous, difficult and expensive (Worden 2018). With climate change and modernization prevalent across the Arctic, the observed shifts in Aklavik's use of marine resources may be observed or manifested in different ways across Arctic communities.

**APPENDIX A:** Sea-ice dependencies for marine mammals in the Canadian Arctic.

| **Species and ice dependency** | **Preferred sea-ice conditions** |
|---|---|
| **Ice-obligate** | |
| Polar bear | Strong association with shore-fast ice, dense annual pack ice. Dependent on sea ice to reach denning locations and as a hunting platform. |
| Walrus | Sex-specific site use for haul-outs; often overwinter in polynyas; highly associated with dense annual pack ice and shallow water. |
| Bearded seals | Typically associated with shallow water on continental shelf, moving dense or loose annual pack ice, shore leads, polynyas |
| Ringed seals | Wide range, highly diverse. Heavily associated with shore-fast ice, moderately associated with loose or dense annual pack ice. Drifting and landfast ice used for breeding. |
| **Ice-associated** | |
| Bowhead whales | Inhabit polynyas in winter/spring, open water or light sea-ice cover in summer, associated with continental shelf and upwelling for feeding. |
| Beluga | Diverse: associated with loose annual and multiyear pack ice, polynyas, shallow continental shelf waters and deep, open-water conditions. |
| Narwhal | Strong association with dense annual pack ice, leads/shear zones, and the shelf break/deep overwintering grounds. |
| **Seasonally migrant** | |
| Harp seal | Uses sea ice for breeding and capable of navigating sea ice and hauling out onto glaciers and ice floes to rest. |
| Gray whale | North Pacific population at or near carrying capacity; positively correlated calving rates with ice-free conditions in Arctic waters |
| Northern bottlenose whale | Relatively low densities occur in the deep (>500 m) cold subarctic waters of Davis Strait, the Labrador Sea, and the Greenland Sea. Able to tolerate light ice areas. |
| Minke whale | Can negotiate light sea-ice conditions. |
| Sperm whale | Males use high latitude regions for feeding during summer sea-ice minimum. |
| Humpback whale | Typically found close to coastlines and able to make long seasonal migrations that include use of Arctic waters in summer but typically leaves the region prior to ice formation. |
| Harbour seal | Long association with sub-Arctic regions. Typically temperate species but able to adapt to seasonal sea-ice conditions. |

**APPENDIX B.** Residency status, seasonal distribution, availability of abundance estimates, and trends in abundance of marine mammals in the Canadian Arctic.

| Common Name | Residency Status | Populations/Stocks | Summer/Winter Distribution | Abundance Estimates | Abundance Trend | Reference |
|---|---|---|---|---|---|---|
| **Residents** | | | | | | |
| **Pinnipeds** | | | | | | |
| Walrus | Year-round resident | Foxe Basin | North and Central Foxe Basin | Yes | Uncertain | Stewart and Hamilton 2013; DFO 2016c |
| | | Hudson Strait-Davis Strait | Hudson Strait-Davis Strait | Yes | Uncertain | DFO 2016d |
| | | South and East Hudson Bay | South and East Hudson Bay | Yes | Unknown | DFO 2016d |
| | | Baffin Bay | Baffin Bay | Yes | Unknown | DFO 2013d |
| | | Penny Strait-Lancaster Sound | Penny Strait-Lancaster Sound | Yes | Unknown | DFO 2013d |
| | | West Jones Sound | West Jones Sound | Yes | Unknown | DFO 2013d |
| Ringed seal | Year-round resident | | Circumpolar year round | Yes | Unknown | Reeves 1998 |
| Bearded seal | Year-round resident | | Circumpolar year round | Yes | Unknown | Cleator 1996; Cameron et al. 2010 |
| **Cetaceans** | | | | | | |
| Narwhal | Year-round resident | Somerset Island | Somerset Island in summer/Baffin Bay in winter | Yes | Unknown | Heide-Jørgensen et al. 2003; Doniol-Valcroze et al. 2015a |
| | | Eclipse Sound | Eclipse Sound in summer/Baffin Bay in winter | Yes | Unknown | Watt et al. 2012; Doniol-Valcroze et al. 2015a |
| | | Admiralty Inlet | Admiralty Inlet in summer/Baffin Bay in winter | Yes | Unknown | Watt et al. 2012; Doniol-Valcroze et al. 2015a |
| | | Jones Sound | Jones Sound in summer/Baffin Bay & north | Yes | Unknown | Doniol-Valcroze et al. 2015a |

| **Common Name** | **Residency Status** | **Populations/Stocks** | **Summer/Winter Distribution** | **Abundance Estimates** | **Abundance Trend** | **Reference** |
|---|---|---|---|---|---|---|
| | | | water polynya in winter | | | |
| Narwhal | Year-round resident | East Baffin Island | East Baffin Island in summer/Baffin Bay in winter | Yes | Unknown | Doniol-Valcroze et al. 2015a |
| | | Smith Sound | Smith Sound in summer/Baffin Bay & North Water in winter | Yes | Unknown | Doniol-Valcroze et al. 2015a |
| | | Northern Hudson Bay | Northern Hudson Bay in summer/Labrador Sea in winter | Yes | Unknown | Asselin et al. 2012; Watt et al. 2017 |
| Beluga | Year-round resident | Eastern Beaufort Sea | Eastern Beaufort Sea in summer/ western Chukchi and Bering Strait in winter | Yes | Unknown | Harwood et al. 1996; Stafford et al. 2018 |
| | | Cumberland Sound | Cumberland Sound year round | Yes | Unknown | Marcoux et al. 2016; Watt et al. 2016 |
| | | Eastern High Arctic-Baffin Bay | Somerset Island area in summer/North Water polynya in winter | Yes | Unknown | Koski et al. 2002 |
| | | Western Hudson Bay | Western Hudson Bay in summer/Hudson Strait in winter | Yes | Unknown | DFO 2018b |
| | | James Bay | James Bay in summer/Hudson Strait in winter | Yes | Unknown | DFO 2018b |
| | | Eastern Hudson Bay | Eastern Hudson Bay in summer/Labrador Sea in winter | Yes | Unknown | Lewis 2009; DFO 2018b |
| Bowhead whale | Year-round resident | Eastern Canada-West Greenland | Around Baffin Island summer/winter in unconsolidated pack ice in the same regions | Yes | Recovering | Doniol-Valcroze et al. 2015b |

| Common Name | Residency Status | Populations/Stocks | Summer/Winter Distribution | Abundance Estimates | Abundance Trend | Reference |
|---|---|---|---|---|---|---|
| Bowhead whale | Year-round resident | Bering–Chukchi–Beaufort | Beaufort Sea in summer/winter in Bering Sea and migrate through the Chukchi Sea | Yes | Recovering | COSEWIC 2009; Schweder et al. 2010 |
| **Polar bears** | | | | | | |
| | Year-round resident | Baffin Bay | Sea-ice covered areas | Yes | Unknown | Durner et al. 2018 |
| | Year-round resident | Davis Strait | Sea-ice covered areas | Yes | Stable | Durner et al. 2018 |
| | Year-round resident | Foxe Basin | Sea-ice covered areas | Yes | Stable | Durner et al. 2018 |
| | Year-round resident | Gulf of Boothia | Sea-ice covered areas | Yes | Unknown | Durner et al. 2018 |
| | Year-round resident | Kane Basin | Sea-ice covered areas | Yes | Increasing | Durner et al. 2018 |
| | Year-round resident | Lancaster Sound | Sea-ice covered areas | Yes | Unknown | Durner et al. 2018 |
| | Year-round resident | M'Clintock Channel | Sea-ice covered areas | Yes | Unknown | Durner et al. 2018 |
| | Year-round resident | Northern Beaufort Sea | Sea-ice covered areas | Yes | Stable | Durner et al. 2018 |
| | Year-round resident | Norwegian Bay | Sea-ice covered areas | Yes | Unknown | Durner et al. 2018 |
| | Year-round resident | Southern Beaufort Sea | Sea-ice covered areas | Yes | Likely decline | Durner et al. 2018 |
| | Year-round resident | Southern Hudson Bay | Sea-ice covered areas | Yes | Likely decline | Durner et al. 2018 |
| | Year-round resident | Viscount Melville Sound | Sea-ice covered areas | Yes | Unknown | Durner et al. 2018 |
| | Year-round resident | Western Hudson Bay | Sea-ice covered areas | Yes | Likely decline | Durner et al. 2018 |
| **Migrants** | | | | | | |

| **Common Name** | **Residency Status** | **Populations/Stocks** | **Summer/Winter Distribution** | **Abundance Estimates** | **Abundance Trend** | **Reference** |
|---|---|---|---|---|---|---|
| **Pinnipeds** | | | | | | |
| Harp seal | Seasonal migrant | | Newfoundland | Unknown | Increasing | |
| Hooded seal | Seasonal migrant | | Newfoundland | Unknown | Unknown | |
| Ribbon seal | Seasonal migrant | | Bering Sea | Unknown | Unknown | |
| Spotted seal | Seasonal migrant | | Bering Sea | Unknown | Unknown | |
| Harbour seal | Seasonal migrant | | Coastal sub-Arctic | Unknown | Unknown | |
| **Cetaceans** | | | | | | |
| Killer whale | Seasonal migrant | | | Minimum estimate | Unknown | Young et al. 2011 |
| common dolphins | Seasonal migrant | | | Unknown | Unknown | |
| Blue whale | Seasonal migrant | | | Unknown | Unknown | |
| Sei whale | Seasonal migrant | | | Unknown | Unknown | |
| Minke whale | Seasonal migrant | | | Unknown | Unknown | |
| Sperm whale | Seasonal migrant | | | Unknown | Unknown | |
| Northern bottlenose whale | Seasonal migrant | | | Unknown | Unknown | |
| White-beaked dolphin | Seasonal migrant | | | Unknown | Unknown | Reinhart et al. 2014 |
| Atlantic white-sided dolphin | Seasonal migrant | | | Unknown | Unknown | |
| Fin whale | Seasonal migrant | | | Yes | Unknown | Heide-Jørgensen et al. 2010 |
| Humpback whale | Seasonal migrant | | | Unknown | Unknown | |

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