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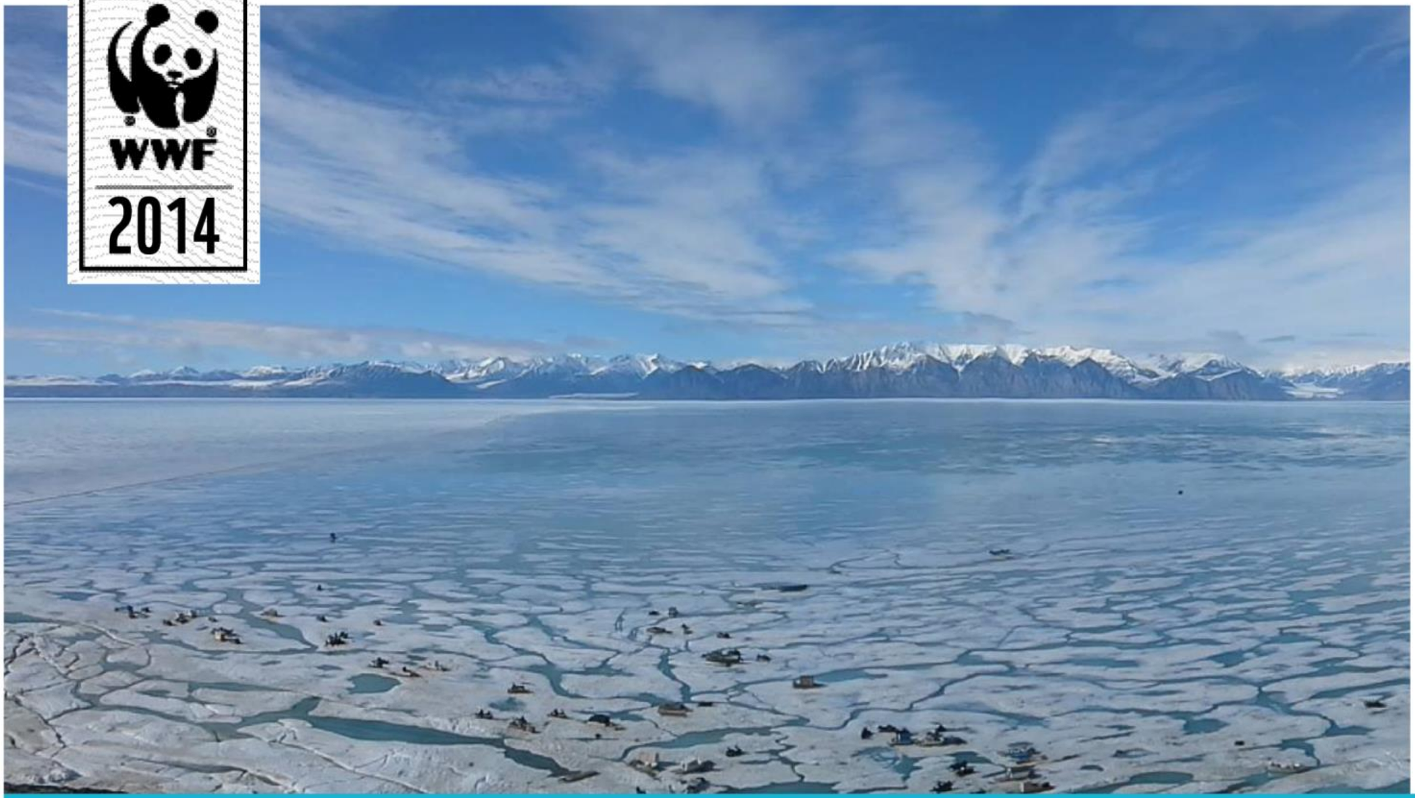

Last Ice Area Biophysical Reader

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1. Introduction

This is one of a series of research resources commissioned by WWF to help inform future management of the Area we call the Last Ice Area. We call it that because the title refers to the area of summer sea ice in the Arctic that is projected to last. As climate change eats away at the rest of the Arctic's summer sea ice, climate and ice modellers believe that the ice will remain above Canada's High Arctic Islands, and above Northern Greenland for many more decades.

Much life has evolved together with the ice. Creatures from tiny single celled animals to seals and walrus, polar bears and whales, depend to some extent on the presence of ice. This means the areas where sea ice remains may become very important to this ice-adapted life in future.

One of my colleagues suggested we should have called the project the *Lasting* Ice Area. I agree, although it's a bit late to change the name now, that name better conveys what we want to talk about. While much is changing, and is likely to change around the Arctic, this is the place that is likely to change the least. That is also meaningful for the people who live around the fringes of this area – while people in other parts of the Arctic may be forced to change and adapt as summer sea ice shrinks, the people around the LIA may not have to change as much.

As a conservation organization, WWF does not oppose all change. Our goal is to help maintain important parts of the natural world, parts that are important just because they exist, and important for people. WWF does not have the power and authority to impose its vision on people. Instead, we try to present evidence through research, and options for action. It is then up to the relevant authorities as to whether they will take action or not; the communities, the Inuit organizations, and the governments of the Last Ice Area will decide its future fate. We hope you will find the information in these reports useful, and that it will help you in making wise decisions about the future of the Last Ice Area.

Clive Tesar, Last Ice Area lead.

2. Executive Summary

This reader is a summary compilation of the main biophysical characteristics of the Canadian and Greenlandic regions of the LIA. It provides an up-to-date overview of the most important marine and terrestrial components of the LIA. “Biophysics” is the science that deals with the application of physics to biological processes. Hence, this document describes the main physical aspects of the marine and terrestrial LIA environment that are influencing the ecosystems and their biodiversity. Most of the species described have some level of ice dependence, underlying the importance of the LIA to their long-term survival. Predictions about the future state of the ecosystems and Arctic species within LIA are discussed, leading to potential scenarios about the future of the LIA. This is relevant, as it will inform the management decisions which need to be taken in the near future in order to safeguard biodiversity conservation and human use needs. The sources of this document are recent journal publications, scientific reports, websites and other relevant publications. It is intended to be a handbook for the WWF staff and it will be available publicly on the WWF website.

This reader recognizes the Arctic definition of the Conservation of Arctic Flora and Fauna working group, which comprises the Arctic Ocean and the adjacent terrestrial regions of the United States (Alaska), Canada, Denmark (Greenland), Iceland, Russia, Finland, Norway and Sweden. The LIA core area includes the Canadian High Arctic Islands north of the Parry Channel, and the northern part of Greenland (an imaginary line between the western settlement of Savissivik and the peninsula Kronprins Christian Land). The LIA exhibits many landscapes. The eastern part of the Canadian Arctic Archipelago is mountainous and ice caps, fiords and glaciers are present, while the central and western parts of the Canadian Arctic Archipelago are mainly flat. A very thick ice sheet covers Greenland, and its northern coastline harbours fiords and islands. Four marine ecoregions and ten terrestrial ecoregions characterize the LIA region. Marine ecoregions are identified based on species groups of plants and animals, while terrestrial ecoregions are identified based on plant species groups. Within these, 14 Ecologically or Biologically Significant Areas have been identified, which indicate areas specifically identified for conservation due to their uniqueness or vulnerability.

Climate change due to human activities is now clear. The rate of climate warming in the Arctic has been twice as fast than the global average in the last decades and this trend is projected to continue in the future. Major implications of a warmer climate for the Arctic environment are the melt of glaciers, a reduced sea ice cover, and a northward recession of the permafrost boundary. The Arctic climate is characterized by extremes in air temperature, light availability, and snow and ice covers. The climate of different locations in the Arctic varies greatly because of the topography and distance to the coast. Snow is a prominent feature of Arctic terrestrial landscapes and marine icescapes. It provides important habitats for several Arctic species, but rising temperatures decrease the extent and duration of Arctic snow, which affect soils, plants, animals and marine productivity.

The Arctic Ocean occupies a huge portion of the Arctic marine environment. Broad continental shelves, large riverine inputs, and its predominant ice cover characterize this ocean. The LIA marine environment includes the continental shelves north of Greenland and of the Canadian Arctic Archipelago, water between islands of the Canadian Arctic Archipelago, Lancaster Sound and fiords located on the northern coast of Ellesmere Island and Greenland. Arctic marine productivity and biodiversity are influenced by connections to the Pacific and Atlantic oceans, and a strong stratification of the water layers with different densities. The wind-driven surface circulation of the Arctic Ocean controls the movement of sea ice. The Beaufort Gyre pushes ice along the northwestern coast of the Canadian Arctic Archipelago, and the Transpolar Drift moves ice from the Siberian coast across the Arctic Ocean towards Greenland. This results in the location of the thickest sea ice along the northern coast of Greenland and the northwestern coast of the Canadian Arctic Archipelago, and corresponds to the area covered by the LIA project. Major effects of climate warming on the Arctic Ocean water masses are the warming of the surface water and ocean acidification. Sea ice is found throughout the Arctic and its extent has dramatically declined in the last decades. The record low ice coverage reached in September 2012 was the lowest in the last 112 years. Also, the sea ice cover is now younger, thinner and the ice volume is reduced. Due to the surface circulation of the Arctic Ocean, the ice that remains at the minimum sea ice extent is mostly located within and north of the LIA. The loss of Arctic sea ice is projected to continue and the Arctic Ocean is projected to become completely ice free during summer by mid-century. Sea ice plays several roles such as influencing local and global climates, affecting the albedo and ocean circulation and, determining atmospheric-ocean exchanges. Some features of the sea ice environment (marginal ice zones, flaw leads and polynyas) are especially productive. Ice shelves, very thick ice attached to the coastline, were extensive along the northern coastline of Ellesmere Island a century ago but they have undergone a drastic decline in the last declines.

The Arctic Ocean and nearby marine environments provide diverse habitats for a multitude of unique life forms highly adapted in their life history, ecology and physiology to the extreme and seasonal conditions of this environment. Arctic marine food webs involve numerous pathways, are relatively simple and vulnerable to perturbations. Primary production in the Arctic Ocean depends on light and nutrients, and comprises ice algae and phytoplankton photosynthesis. Primary production is low in the Arctic Ocean compared to other oceanic environments of lower latitudes because of low light availability. The reduced sea ice cover may increase primary productivity in the next decades and modify the interplay between the water column and seafloor systems. The biodiversity in the sea ice is astonishing and consists of a complete food web. The water column biodiversity is composed of phytoplankton, zooplankton, bacteria, archaea and other tiny organisms. Phytoplankton and zooplankton communities reveal a high diversity. Arctic seafloor biodiversity ranges from unicellular life to large invertebrates and the Arctic seafloor presents varied habitats. A study on large organisms dwelling on the seafloor (larger that 0.5 mm) suggested an intermediate biodiversity. The Arctic Ocean hosts few fish species compared to more temperate environments. Most fish live close to the seafloor but two species – Arctic cod and Ice cod – are closely associated with the sea ice. Subsistence fisheries are important for to local communities in Canada and commercial fisheries are essential to the economy of Greenland. Eleven marine mammals (including cetaceans, pinnipeds and polar bears) live in the Arctic all year long and many other species occupy Arctic waters seasonally. Changes in the Arctic climate along with the loss in sea ice cover may challenge the survivorship of marine mammals reliant on sea ice in their life cycle. The Arctic is an important region for seabird diversity and large breeding colonies are found on cliffs and islands.

The Arctic terrestrial environment is characterized by numerous lakes that dot the landscape and by the predominance of snow and ice in the form of glaciers, ice caps, ice sheets and permafrost (permanently frozen ground). The Arctic contains numerous freshwater ecosystems of different types (lakes, rivers, ponds, streams, wetlands). They are important for hunting and fishing by local communities, as supplies of drinking water and are a key resource for industries such as transport and mining. Lake and river ice cover duration is declining because of a warmer climate. Arctic glacier ice comprises mountain glaciers, ice caps and ice sheets. Within LIA, glaciers and ice caps are present on Devon and Ellesmere islands, and at the periphery of Greenland. The Greenland Ice Sheet spreads up to the northern part of Greenland. Similar to the different ice type trends, glacier ice is rapidly declining. Permafrost (permanently frozen ground) underlies the vast majority of the surface of the terrestrial Arctic, and is linked with biodiversity and ecosystem processes. The permafrost is degrading rapidly in most Arctic regions.

Terrestrial biodiversity comprises soil microbes, vegetation, animal, and lakes and rivers biodiversity. The biodiversity of these groups of organism declines with latitude. Arctic soils hold large reserves of microorganisms, but the Arctic climate strongly limits their metabolic activity. Warmer temperatures will increase the metabolic activity of these organisms and will lead to higher decomposition rates. Arctic vegetation is strongly controlled by summer temperature. Higher summer temperature cause the size, horizontal cover, abundance, productivity and variety of plants to increase. Most plants of the Arctic are dwarf shrubs, herbs, lichens and mosses. Arctic vegetation is relatively poor. The main impacts of climate change on Arctic vegetation are greening, shrub expansion and floristic changes. The biodiversity Arctic terrestrial animals is low and Arctic terrestrial food chains are short and simple. Terrestrial Arctic animals possess adaptations that enable them to cope with low winter temperatures and conserve energy. Climate change is having observed impacts on terrestrial Arctic animals by altering freeze-thaw cycles and by changing animal behaviours. Arctic aquatic food webs are simple compared to temperate latitudes. The level of nutrients available in the system would strongly influence the food web structure and diversity. Shifts in lake and river ice cover regimes will have cascading effects on the biological communities.

There are several protected areas in LIA and its vicinity, which cover terrestrial and marine environments. As of 2017, two regions within the LIA have been nominated for UNESCO World Heritage Status: Northern Baffin Bay Ecoregion and the Remnant Arctic Multi-Year Sea Ice and northeast Water Polynya Ecoregion. The Arctic is experiencing pressure from numerous sources. Apart from climate change that is having drastic impacts on the Arctic environment and biodiversity, enhanced mining and oil and gas activities, increased shipping, and contaminants by local pollution or long-range transport are additional factors that threaten the integrity of Arctic ecosystems.

This document identifies significant data gaps regarding the LIA and nearby regions. The logistical challenges imposed by the harsh Arctic environment limit field expeditions, especially during winter and in the most remote environments such as the seafloor. It would be important to gain more knowledge on long-term climatic data for the Greenlandic part of the LIA. The existing records are incomplete and make statistical analyses difficult. Also, the circumpolar flaw lead is not well characterized in the LIA region. This flaw lead is projected to enlarge and to last longer in the next decades and may become a highly productive area within the LIA. The studies of marine and terrestrial biodiversity of the High Arctic regions generally suffer from lack of data and low sampling effort. This area is changing at one of the most rapid pace on the planet and there is a pressing need to learn more about its biodiversity before it vanishes.

There are many other resources both existing and in production that cover all or part of the LIA area and that will provide more detail on various aspects of the biological and physical environment of the area, for instance the Life linked to Ice report of the Arctic Council's Conservation of Arctic Flora and Fauna working group (published), The Canadian ArcticNet – IRIS 2 report (published), and the Adaptation Actions for a Changing Arctic project of the Arctic council's Arctic Monitoring and Assessment Programme (published).

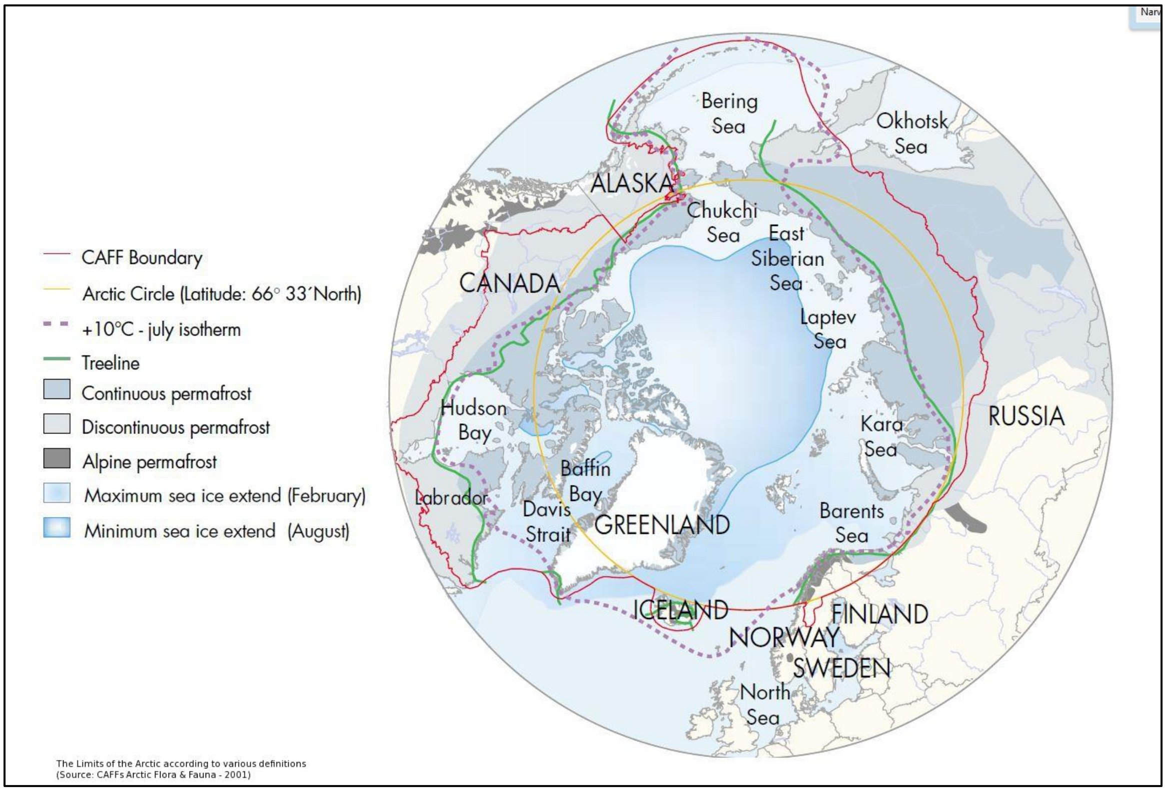
While this resource focuses on the Last Ice Area, it is important to view it also in the context of the future prospects of Arctic conservation as a whole. The ecology and the lives of Arctic peoples linked to that ecology are changing everywhere. In some places, resilient features (such as the continuing existence of summer sea ice) will likely allow for less change – in other places, those features will mean there is change in the ecology of the area, but it will likely remain biologically productive and important. WWF is working with local peoples and with governments to try to identify the sources of resilience for Arctic life, and to reduce the pressures on that resilience. The Last Ice Area is one pilot project in what must become a linked network of conservation if we are to preserve unique Arctic ecosystems and lifestyles.

3. Geography

WWF, like the Arctic Council, defines the Arctic as more than just the area within the Arctic Circle. It makes much more sense to include areas bound together by similar ecosystemic features, and also, for policy purposes there are political boundaries that help in defining what is Arctic. The result is a combination of factors that provide coherent and similar descriptions of the Arctic across the Arctic Council's working groups. As a conservation organization, WWF recognizes the boundary of the Conservation of Arctic Flora and Fauna working group of the Arctic Council as the most relevant to our work (Figure 1). Working with Arctic Council definitions, the Arctic is a vast region that covers more than 40 million square kilometres, and contains just over four million people (Larsen & Fondhal, 2015). It consists of the Arctic Ocean and the adjacent terrestrial regions of the United States (Alaska), Canada, Denmark (Greenland), Iceland, Russia, Finland, Norway and Sweden.

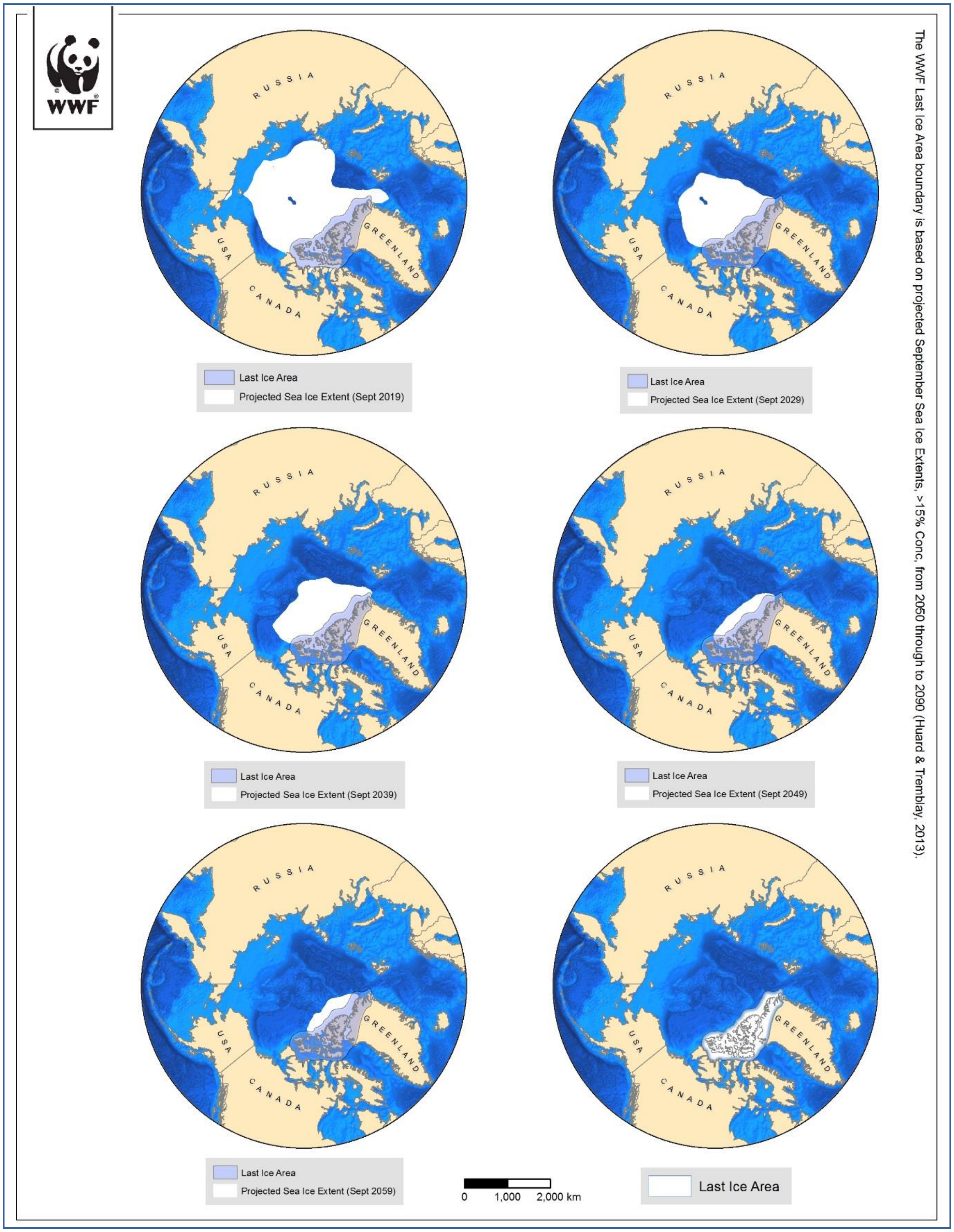
The LIA boundaries are loosely defined as they are based on projections of sea ice persistence that are not accurate predictions of the exact location of that ice in the future. The projection used to establish this area is based on an Intergovernmental Panel on Climate Change scenario called RCP 8.5, or “high emissions/business as usual” (Huard and Tremblay, 2013; Figure 2). The core of the area of interest includes the Canadian High Arctic Islands (also called the Queen Elizabeth Islands) that are located north of the Parry Channel, and the northern part of Greenland (an imaginary line between the western settlement of Savissivik and the peninsula Kronprins Christian Land). Figure 3 highlights communities across Greenland and Canada that are situated within the LIA, and is projected under the IPCC “medium emissions” scenario, RCP 4.5 (Forster, 2007). The Canadian communities included in the LIA area are: Arctic Bay (pop. 868), Pond Inlet (pop.1617) Grise Fiord (pop. 129) and Resolute (pop. 198) (Petrasek MacDonald Consulting 2016; Statistics Canada 2017). Appendix I further breaks down important geographic locations identified by Inuit in these communities. The Greenland communities of the LIA include: Qaanaaq (pop. 678), Savissivik (pop. 58), Qeqertat (pop. 28), Siorapaluk (pop. 56) and the US air force base at Thule/Pitufik (Frost, 2014).

The LIA is composed of many landscapes. Towering mountains with peaks over 2,000 m are found in the eastern islands of the Canadian Arctic Archipelago (Ellesmere, Axel Heiberg and Devon Islands) (Maxwell & Adams, 2006). The higher land on these islands is commonly covered by ice caps. Spectacular fiords and glaciers are also part of the landscape. The central and western islands of the Canadian Arctic Archipelago are generally flat with low relief (less than 200 m) (Maxwell and Adams, 2006). Greenland is the largest island and 85% is covered by an ice sheet nearly 3,000 m thick (Haven, 2007). Fiords and islands characterize the Greenlandic coastline.



The Limits of the Arctic according to various definitions
(Source: CAFFs Arctic Flora & Fauna - 2001)

Figure 1. The limits of the Arctic according to different definitions (Arctic Council - CAFF Working Group, 2001b).



The WWF Last Ice Area boundary is based on projected September Sea Ice Extents, >15% Conc, from 2050 through to 2090 (Huard & Tremblay, 2013).

Figure 2. Map of the LIA core area and projected future ice extent. Based on GFDL-CM3 projected ice extent model (Huard & Tremblay 2013).

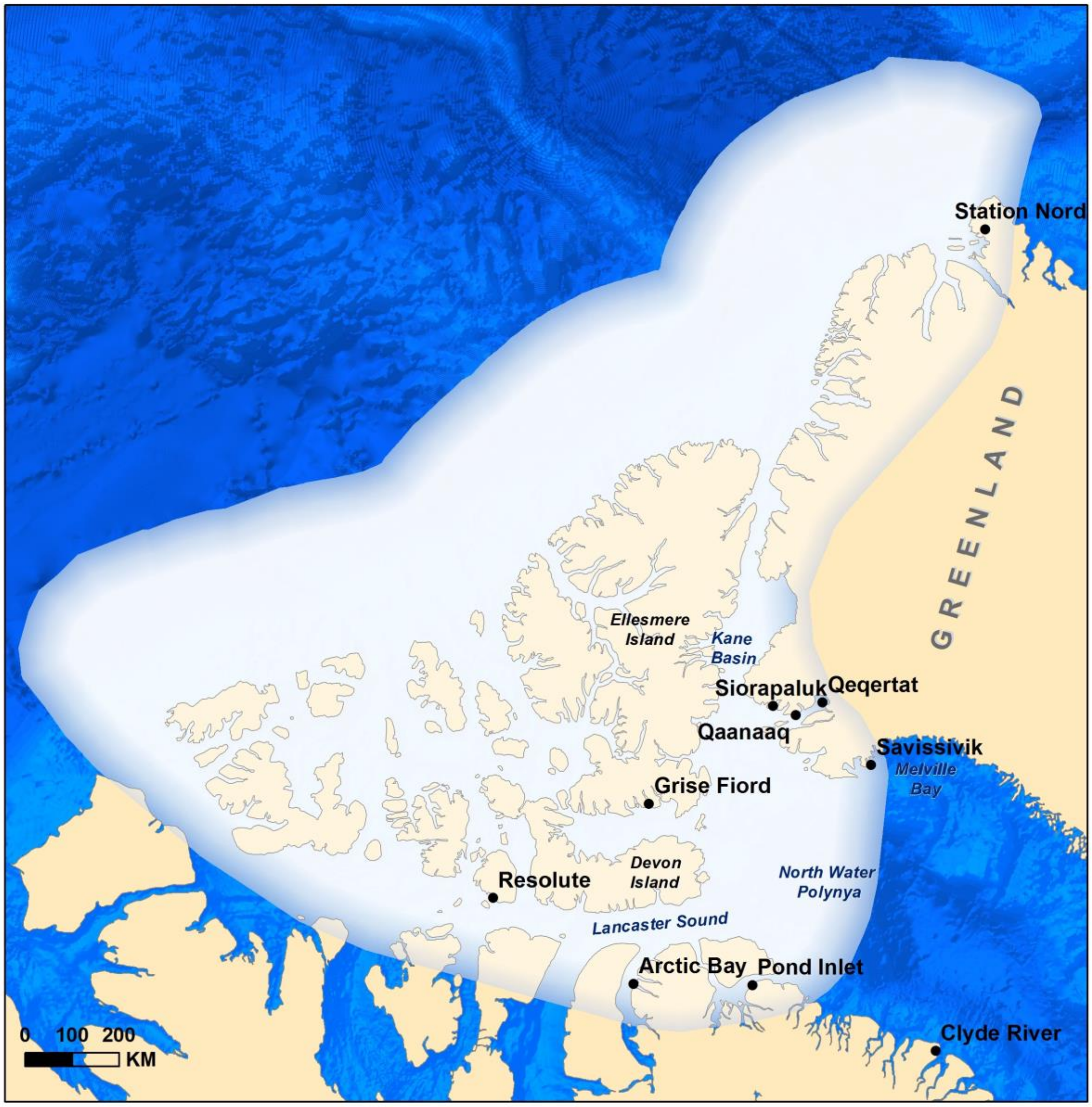


Figure 3. Communities within the Last Ice Area (taken from WWF, 2016).

4. Ecoregions

Since the mid-1980's, a number of government and non-government bodies including Fisheries and Oceans Canada (DFO), Convention on Biological Diversity (CBD) and WWF among others, have worked to identify Marine and Terrestrial areas of biological and ecological importance in Canada. Biogeographic units such as an ecozone or an ecoregion identify a region of land and/or water characterized by distinct regional ecological factors, including: climatic, vegetation, soil, water, fauna and land use (Ecological Stratification Working Group, 1995). The objective of designing ecoregions is to plan for conservation and set priorities (Skjoldal et al., 2012). At the coarsest scale, Natural

Resources Canada defines 15 terrestrial ecozones in Canada, two of which extend into Canadian LIA region: Northern Arctic and Arctic Cordillera (Wilken et al., 1996). These ecozones can be further divided into 10 terrestrial ecoregions (Figure 4). Tundra, permafrost, snow ice caps and glaciers characterize the terrestrial portion of the LIA (Wilken et al., 1996). The LIA also spans three marine ecozones including: the Arctic Basin, Northwest Atlantic and Arctic Archipelago Ecozone, which can be further refined into four ecoregions: Arctic Basin, Arctic Archipelago, Eastern Arctic and Western Arctic (Figure 4).

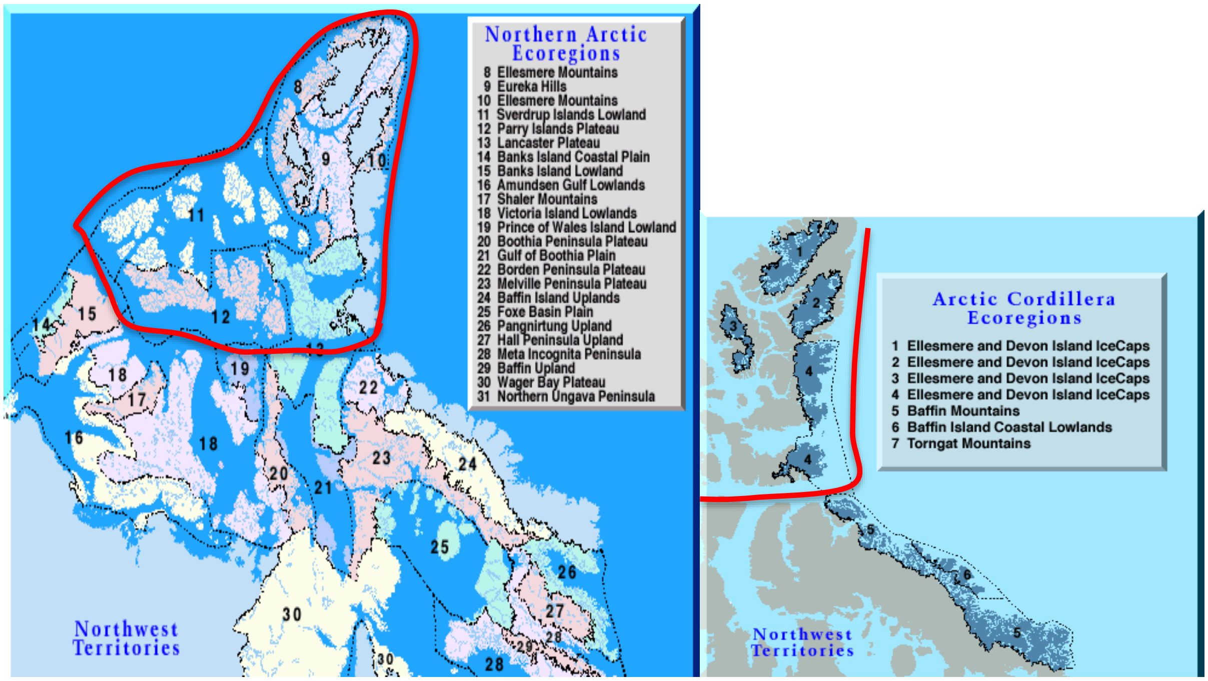


Figure 4. Left. Ecoregions of the Northern Arctic Ecozone. Right. Ecoregions contained within the Arctic Cordillera Ecozone. Red line highlights rough boundaries of Canadian LIA region. Taken from Wilken et al. (1996) and http://ecozones.ca/english/zone/index.html

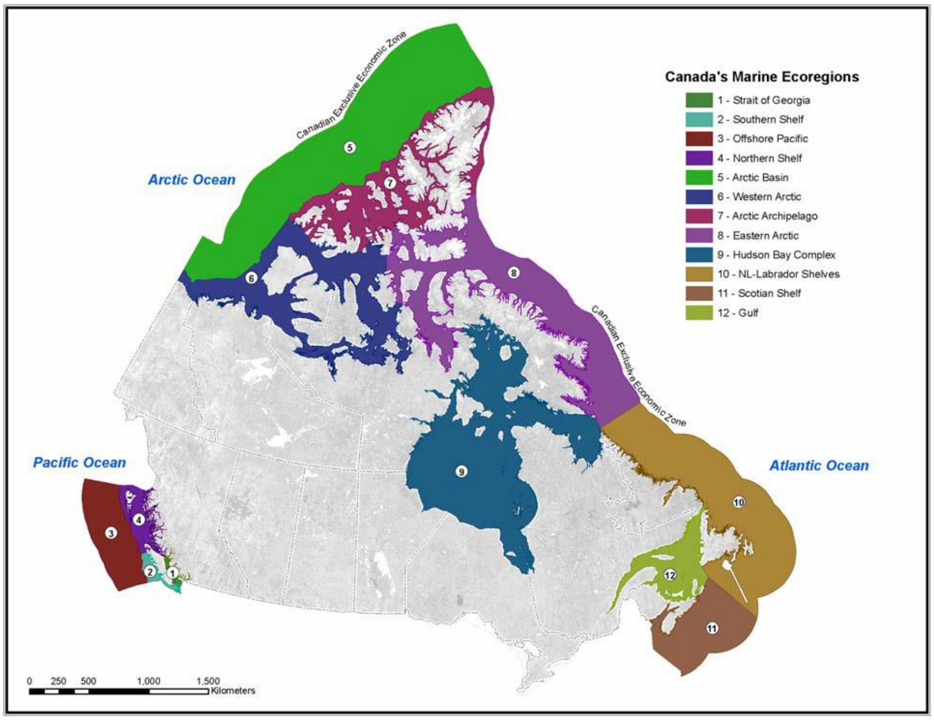


Figure 5. Marine Ecoregions of Canada (DFO, 2009).

In 2011, Canada, led by the DFO, made progress in identifying Ecologically and Biologically Significant Areas (EBSAs) in the Arctic. These are areas that are especially important for conservation due to their uniqueness or vulnerability, and were identified by the DFO science sector as well as through Northern community consultations. (Smith, 2009; DFO, 2011). The DFO criteria for selection are similar to past EBSA identification processes (Figure 3), and are meant to call attention to areas with particularly high ecological or biological significance to facilitate appropriate management. 14 of these EBSAs overlap with/fall within the boundaries of the LIA, and will be briefly discussed in the following paragraphs.

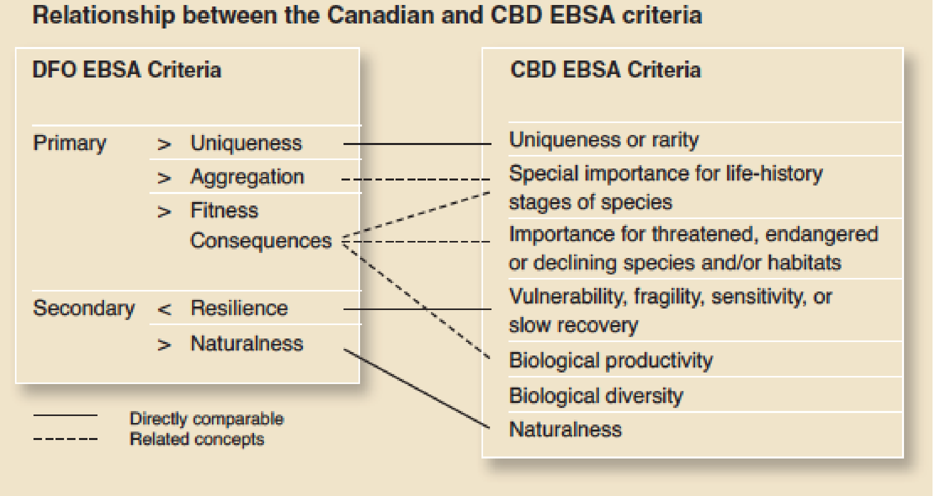


Figure 6. Relationship between the Department of Fisheries and Oceans EBSA criteria and Convention on Biological Diversity EBSA criteria (taken from Smith et al., 2009).

The Beaufort Sea Large Ocean Management Area (LOMA) (which spans parts of the Arctic Archipelago, Western Arctic and Arctic Basin Ecoregions) contains three EBSAs within LIA Boundaries: Viscount Melville Sound, Arctic Basin Multi-Year Pack Ice and Archipelago Multi-Year Pack Ice (Figure 4). Viscount Melville Sound is a key region for prey species such as Arctic cod and is thus an important area for beluga and polar bear foraging (DFO, 2015). Additionally, local knowledge holders have observed beluga seeking refuge from killer whales in the shallow inlets and bays in this area (Brown & Fast, 2011). The Arctic Basin (seen fully in Figure 5) contains an EBSA called Multi-year Pack Ice, and is likely a core habitat for under-ice communities of heterotrophic microbes (DFO, 2014). The edge of this EBSA is also an important summer refuge for polar bears (DFO, 2011).

The Archipelago Multi-year Pack Ice EBSA is technically contained within the Arctic Archipelago ecoregion along with two other EBSAs: Norwegian Bay and Princess Maria Bay (Figure 4 and 5). According to local knowledge, Norwegian Bay and Princess Maria Bay host a diverse array of land mammals such as Arctic hare, muskox and caribou within the fiords. Additionally, narwhal, seals and walrus use these bays along their migration route (Brown & Fast 2011). The Archipelago Multi-year Pack Ice EBSA is one of the most expansive Arctic archipelagos in the world and is an important feeding and rearing area for the Norwegian Bay and Viscount Melville polar bear populations (DFO, 2011).

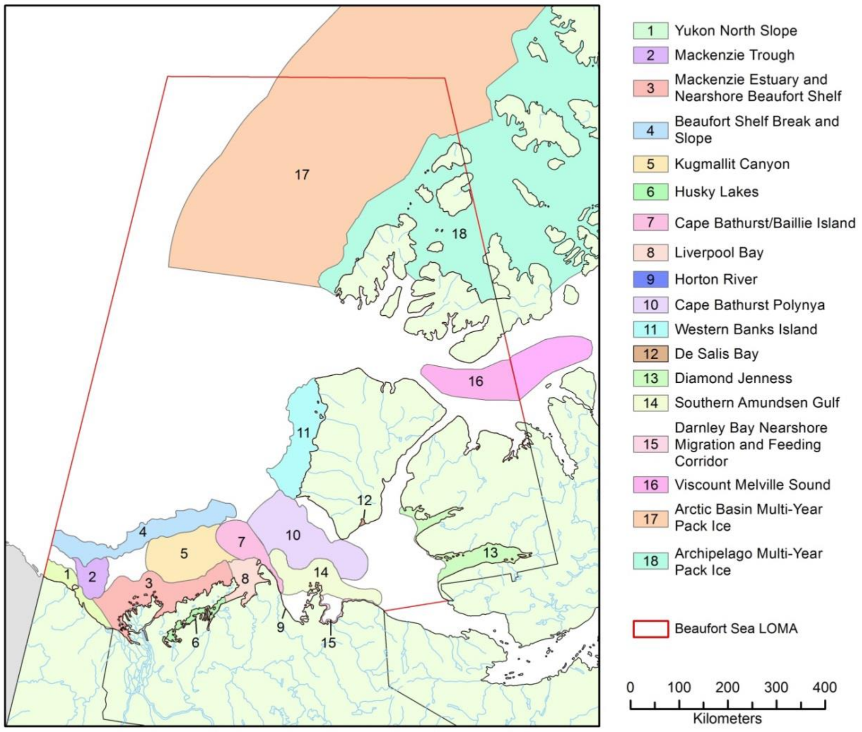


Figure 7. EBSA's of the Beaufort Sea. Viscount Melville Sound (16), Arctic Basin Multi-Year Pack Ice (17), and Archipelago Multi-Year Pack Ice (18) are within LIA boundaries. Image from DFO (2014).

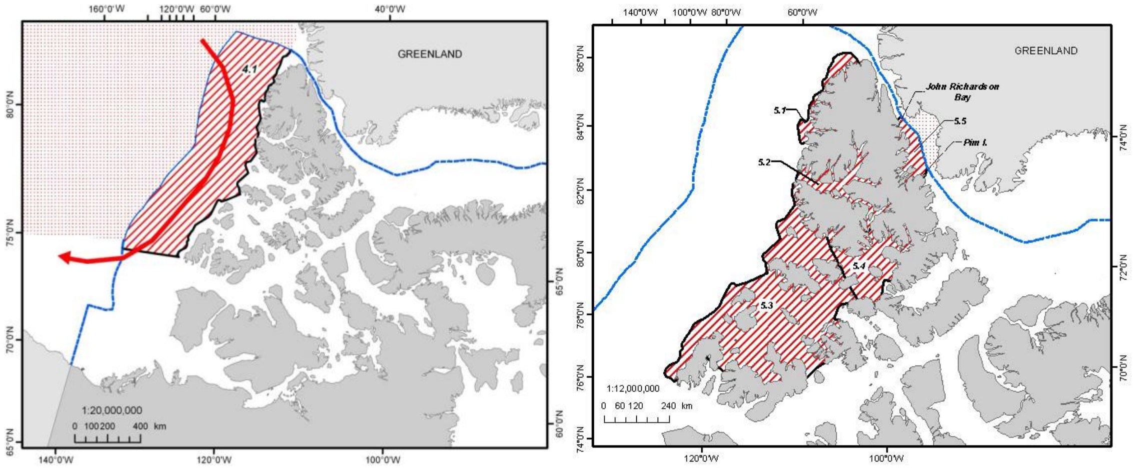


Figure 8. Left. Multi-year Pack ice EBSA identified for the Arctic Basin ecoregion. Right. EBSAs identified for the Arctic Archipelago ecoregion. These include: Archipelago Multi-year Pack Ice, Norwegian Bay and Princess Maria Bay. Blue lines define the political boundary between Canada and Greenland. Images take from DFO (2011).

The Eastern Arctic ecoregion contains the following EBSAs relevant to the Canadian LIA region: Penny Strait, Cardigan Strait/Hell Gate, Resolute Passage, North Water (NOW) polynya, Eastern Jones Sound, Gulf of Boothia, Lancaster Sound and Northern Baffin Bay (Figure 6). These eight EBSAs are very productive and biologically diverse. The NOW polynya EBSA contains a diverse array of marine and land mammals including: narwhal, seal and walrus that use the polynya and surrounding bays as nesting, breeding and feeding areas (DFO, 2015). Local knowledge holders report that the Penny Strait is important habitat for polar bear and their prey (Brown and Fast, 2011). Additionally, Lancaster Sound is a critical migratory corridor for several marine mammals, including beluga, narwhal and polar bear, as well as an important spring staging area for seabirds (Brown and Fast 2011; DFO, 2015) Other EBSAs such as the Resolute Passage are included for their uniquely high ice algal biomass (DFO, 2015).

The boundaries of a few EBSAs in the Canadian Arctic cross over with similarly identified regions in Northwest Greenland (Figure 7; AMAP/CAFF/SDWG, 2013). These include: the NOW Polynya, Princess Maria Bay and Northern Baffin Bay EBSAs. Additionally, Mellville Bay is a unique EBSA (called area of heightened ecological significance in AMAP, 2013) to Greenland. It is a critical habitat for narwhal in the summer, for polar bear in the winter and spring, and is an important migration corridor for whales and seabirds (AMAP, 2013). Notably, on the Greenland side, the NOW Polynya is recognized for supporting more than 80% of the world population of little auk from May to September (Egevang et al., 2003). It is also host to other seabirds such as the endangered ivory gull, king eider and thick-billed murre (AMAP, 2013).

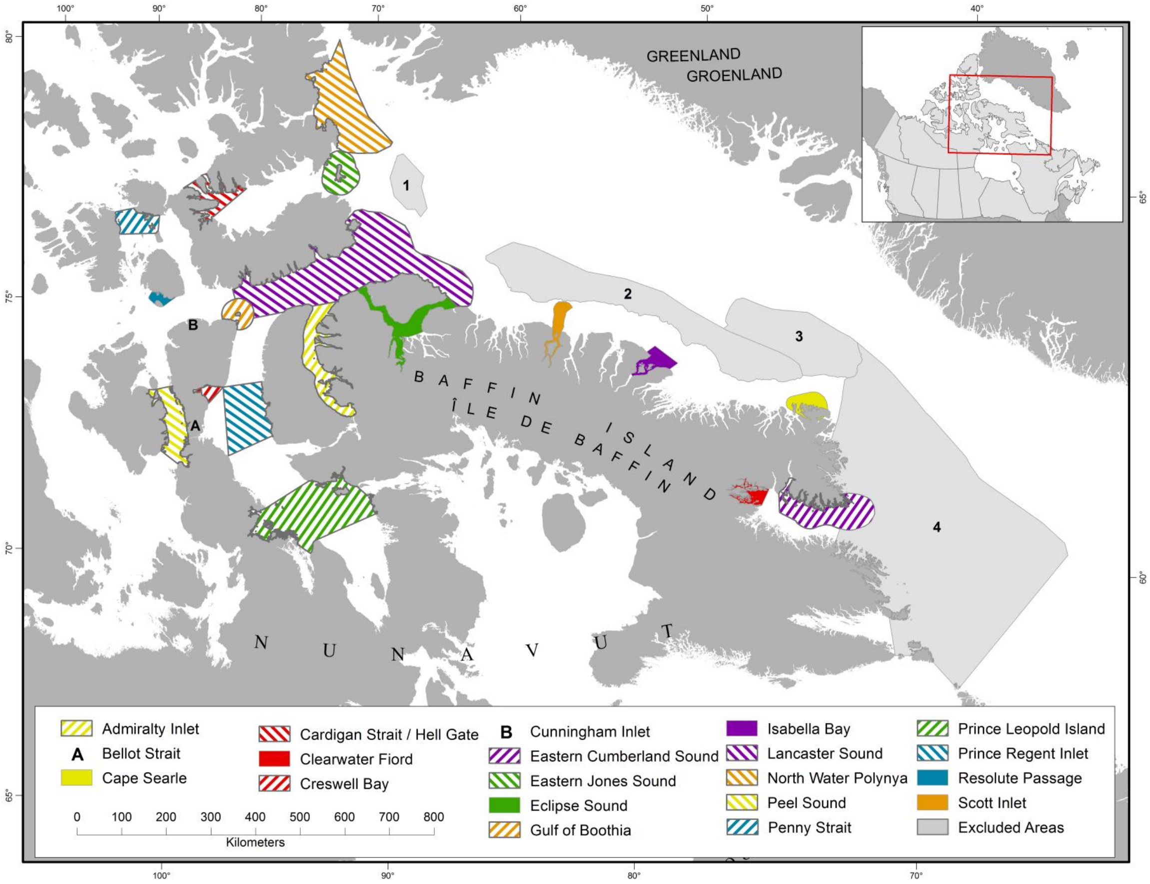


Figure 9. EBSAs in the Canadian Eastern Arctic. Image taken from DFO (2015).

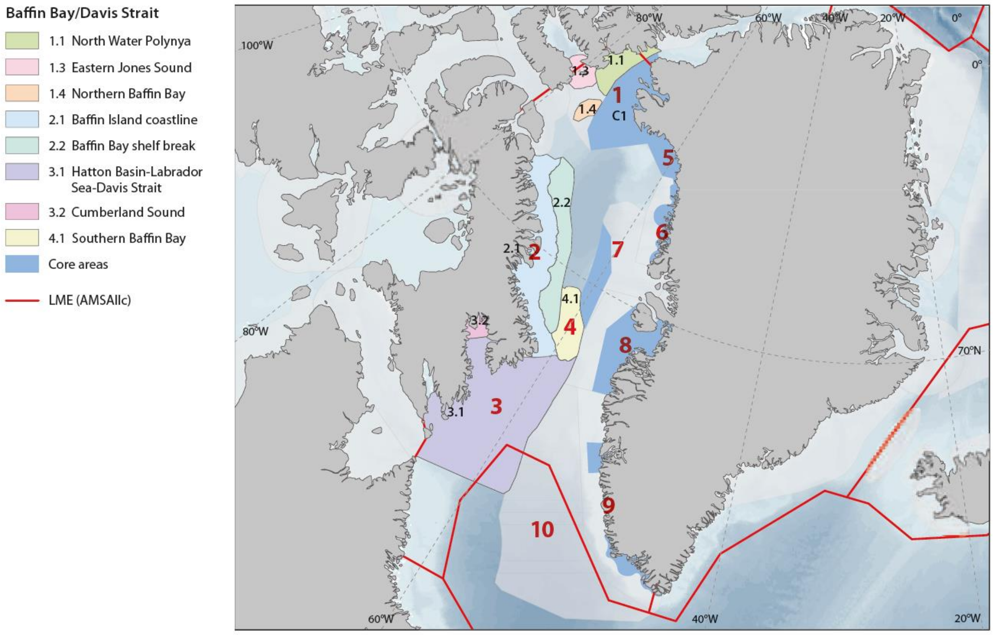
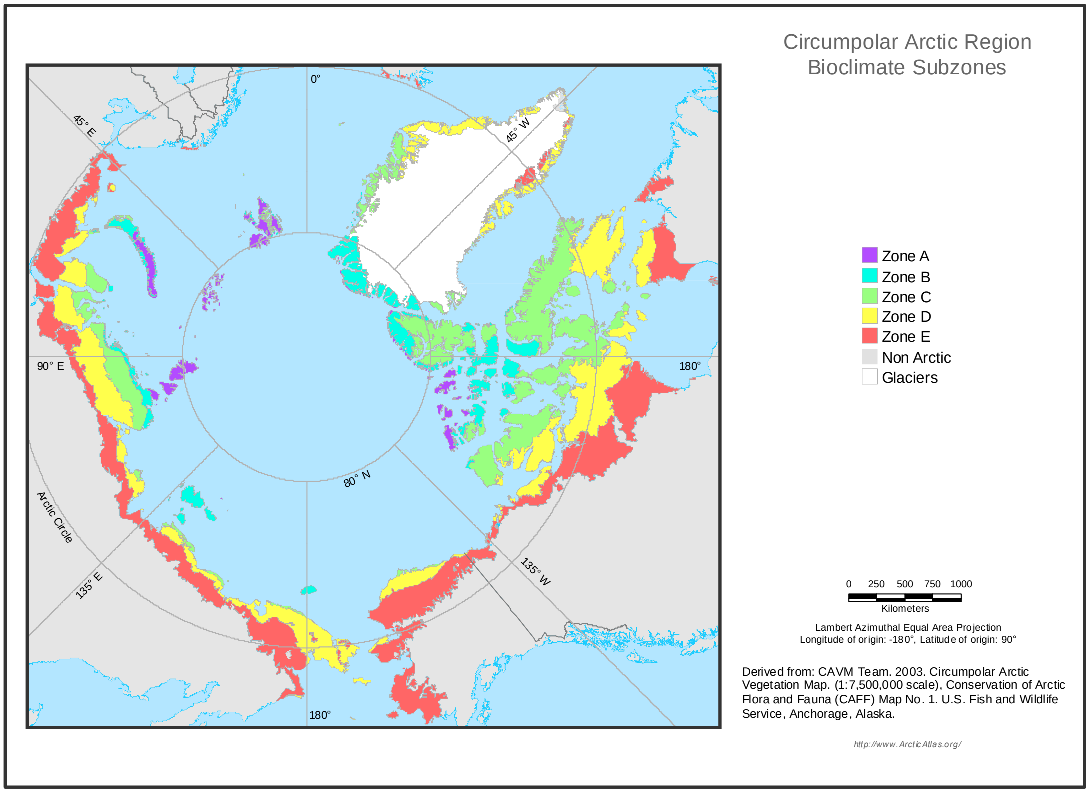


Figure 10. From AMAP (2013) exercise to identified areas of heightened or cultural significance. C1 represents the Greenland portion of the NOW Polyna; Area 1.4 represents Northern Baffin Bay; Area 5 represents Mellville Bay.

5. Climate

The Arctic climate is challenging for life and characterized by extreme seasonality. Air temperatures vary from glacial to temperate, the winter polar night is followed by the summer midnight sun, and snow and ice covers fluctuate significantly between seasons. Precipitation is generally low and some particularly arid regions are classified as “polar deserts” (Maxwell, 1981). Local conditions such as topography or distance to the coast have an impact the type of climate a region experiences (Figure 1). For instance, Alert (located on the northern coastline of Ellesmere Island) is influenced by cold air advection from the Arctic Ocean and the blocking of solar radiation by frequent low clouds and fog, while Eureka (located on the coastline of a fiord on Ellesmere Island but not exposed to the Arctic Ocean) is subject to the rain shadow effect of surrounding mountains (Maxwell, 1981).



Derived from: CAVM Team. 2003. Circumpolar Arctic Vegetation Map. (1:7,500,000 scale), Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

Figure 11. Bioclimate subzones of the circumpolar Arctic based on the Circumpolar Arctic Vegetation Map. Mean July temperature of zone A is 0-3°C, for zone B, 3-5°C, for zone C, 5-7°C, for zone D, 7-9°C, and for zone E, 9-12°C (CAVM Team, 2003).

In recent decades, climate conditions across the Arctic have been changing rapidly, and climate change is now at the forefront of the agenda of politicians, scientists, and the public. Human influence on the climate system is now evident by the observed increase in greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbon (CFC) (IPCC, 2013). Since 1750, the beginning of the industrial revolution, atmospheric concentrations of CO_2, CH_4, and N_2O

have increased dramatically and have reached values exceeding the interval of natural variation of the last 800,000 years (IPCC, 2013).

Global annual temperatures have increased at an average rate of 0.07˚C per decade since 1880, and at an average rate of 0.17 ˚C per decade since 1970 (NOAA, 2016). NOAA reported that 2016 was the warmest year in its 137-year record, and 16 out of the past 17 years have been the hottest on record since 2001. Air temperatures have increased in most regions although the most rapid changes are happening at high latitudes (NSIDC). The Arctic is warming at twice the global average and has seen an increase of 3.5˚C since the beginning of the 20th century. This warming trend is projected to continue in the future (Barnes and Polvani, 2015). As temperatures in the Arctic increase, sea-ice melts leaving more open water to absorb the sun's rays leading warmer ocean temperatures which accelerate sea-ice melt and contribute to the release of methane from deep-sea permafrost, also further accelerating warming. These positive feedback processes contribute to the accelerated warming trend in the Arctic called "Arctic amplification" (Sommerkorn & Hassol, 2009; AMAP, 2012). There is evidence that the Arctic Amplification is starting to accelerate significantly beyond the projections currently considered by policy-makers. For example, a report by AMAP (2011) notes that the largest and most permanent bodies of ice in the Arctic – multi-year ice, mountain glaicers, ice camps and the Greenland Ice sheet – have all been declining faster since 2000 than they did in the 1990s (AMAP, 2012). Additionally, increased Arctic temperatures will have major implications on the rate of glacier melt (Sharp et al., 2011), and the northward recession of the terrestrial permafrost boundary among other impacts (AMAP, 2012; Grosse et al., 2016). Temperature anomalies will likely continue to occur in the future as sea ice thins and allows more heat from the ocean to penetrate the ice layer, changing ocean-atmosphere interactions (Wang, 2016).

Impacts from changing climate conditions are far-reaching, affecting wildlife, their habitat, ecosystems and local communities (see AMAP, 2012; Christie & Sommerkorn, 2012; Gray, 2011; Arctic Council, 2016; Grosse et al., 2016). Recent observations suggest that some systems are approaching critical thresholds, upon which further change will result in an abrupt and discontinuous shift in ecosystem properties. Surpassing these ecological tipping points will have global implications. For example, between 1980-2000, the Arctic Ocean experienced a net freshening of about 100 ± 900 $km^3 yr^{-1}$ (Haine et al. 2015). However, within the last decade (between 2000-2010), melt of the Greenland Ice sheet, Arctic ice caps and glaciers has accelerated, and was estimated to have contributed an extra 1200 ± 730 $km^3 yr^{-1}$ of freshwater into the Arctic Ocean (Haine et al., 2015). This work may indicate the beginning of a freshening trend in the Arctic Ocean (Cottier et al., 2017). Not only will further melt contribute to global sea level rise, it could also alter large-scale ocean currents that affect climate on a continental scale (Koç et al., 2009; Castro et al., 2015; Vihma et al., 2014). Finally, although the effects have been ignored until recently, the economic impacts of a warming Arctic are now attracting media interest (Whiteman et al., 2013). For example, the economic consequences of the release of methane from thawing permafrost due to global climate change would cost trillions of dollars in the absence of mitigating action, since this extra methane in the atmosphere would accelerate the rate of warming, resulting in more climate uncertainty and frequency of extreme events such as flooding of low-lying areas, heat stress, droughts and storms.

State of Climate in the LIA

The availability of Canadian and Greenlandic Arctic climate data is skewed towards coastal stations. In addition, the records are often interrupted and long-term trends are difficult to calculate. In the Canadian portion of the LIA region, 6 weather stations owned by the Government of Canada exist (Alert, Eureka, Resolute, Grise Fiord, Pond Inlet, Clyde River). Normals for the period 1981-2010 are available for five of these stations (Table 1). Also, the Centre for Northern Studies (www.cen.ulaval.ca) has created a network of climate observatories along a south-north transect, from the boreal forest to the High Arctic, which is named the SILA Network. This network has stations within or close to the LIA on Bylot Island and on the northern coastline of Ellesmere Island, in the vicinity of Ward Hunt Island, and the data gathered are publicly available.

Table 1. Location and climate data for Canadian weather stations located in the LIA region or in its vicinity from 1981 to 2010. Data were obtained from the Government of Canada (Government of Canada, 2013a).

	Lat. (°N)	Long. (°W)	Temp. (°C)	Days > 0°C	Precipitation (mm)	Rainfall (mm)	Snowfall (cm)
Alert	82.52	62.28	-17.69	80.62	158.29	17.43	184.64
Eureka	79.98	85.93	-18.75	98.95	79.07	32.53	60.30
Resolute	74.72	94.97	-15.67	92.90	161.20	59.47	111.21
Pond Inlet	72.69	77.97	-14.56	119.62	189.01	91.02	131.90
Clyde River	70.49	68.52	-12.58	122.67	NA	63.29	194.74

The Danish Meteorological Institute owns several meteorological stations located in the LIA region: Pituffik, Kitsissut, Qaanaaq, Hall Land, Kas Morris Jesup, Kap Harald Moltke and Station Nord (Cappelen, 2012). However, in general data records for these stations are discontinuous (raw data is publically available at www.dmi.dk) and highly variable. A long-term station south of the LIA region, Upernavik (72.78°N, 56.13°W), has a mean daily temperature of -7.1 °C for 1981-2010 (Cappelen, 2011). Also, the north drainage basin of Greenland, which include the LIA region, has a mean daily temperature of -21.3°C and a total of precipitation of 182.5 mm (Lucas-Picher et al., 2012). Mernild et al., (2015) note that between 1890-2000, Greenland experienced a major shift in precipitation patterns towards wetter precipitation conditions on the coast. Additionally, there are sharp differences in temperatures from the coasts to the fiords in Greenland (Cappelen, 2013). In summer, drift ice and cold water along the coast make the fiords warmer places. In winter, the situation is reversed and coastal areas are warmer. Ellesmere Island and the north of Greenland are therefore very cold. Nevertheless, unusual, very warm temperatures have been recently recorded, such as a maximum of 20.5°C at Ward Hunt Island (83°N, 74°W) in summer 2008 (Vincent et al., 2009). Additionally, in 2016 an Arctic-wide temperature anomaly was reported for January and February surface air temperatures, which were an estimated 2˚C above previous records. These positive temperature anomalies were caused in part due to changes in mid latitude atmospheric circulation over the Atlantic (Overland & Wang, 2016).

6. Snow

Snow is an important and dominant feature of Arctic terrestrial landscapes and marine icescapes, with cover present for eight to ten months of the year. Its extent, dynamics, and properties (e.g. depth, density, water equivalent, grain size, and vertical profile structure) affect climate (e.g. ground thermal regime), human activities (e.g. transportation, resource extraction, infrastructure, water supply, use of land, and ecosystem services), as well as hydrological processes, permafrost, extreme events (including hazards such as avalanches and floods), biodiversity, and ecosystem processes (Callaghan et al., 2011b; AMAP, 2012). Air temperature and precipitation are the main drivers of regional-scale snow cover variability over the Arctic region, with local-scale variability in snow cover related to interactions with vegetation cover and topography through processes such as blowing snow and sublimation (when water changes directly from solid to vapor form without thawing) (Callaghan et al., 2011b; Hernández-Henríquez et al., 2015). Impurities in the snow (e.g. leaf litter and organic and black carbon) contribute to local (landscape) and regional (circum-Arctic) differences in how much of the sun's energy is absorbed, which influences spring season melt rates (Callaghan et al., 2011b). In contrast to temperate regions, most of the Arctic snowmelt during spring occurs over a very short period of time.

Snow provides important denning habitat for several Arctic species such as polar bears and ringed seals (Callaghan et al., 2011b; Liston et al., 2014). For instance, female ringed seals give birth to their young in snow dens on the sea ice. The snow cover provides protection from cold temperatures and predators. These snow dens are especially critical when pups are nursed from late March to June. For example, to successfully rear young, ringed seals in the central Arctic need on-ice snow depths in April of at least 20 cm (Iacozza & Ferguson, 2014). Such snow depths are usually found as snow drifts next to sea ice ridges but can also be present on flat landfast ice (Hezel et al., 2012). The period over which snow accumulates on ice is the primary factor influencing the quality of ringed seal breeding habitat (Smith and Lydersen, 1991). Therefore, inadequate snow depths can result in increased pup mortality due to exposure and predation (Ferguson et al., 2005; Iacozza & Ferguson, 2014).

During the sunlit times of the year, snow cover on sea ice limits the underwater light availability by strongly attenuating light penetration (Sturm & Masson, 2017). Snow cover can influence the timing of the early spring under ice productivity in the Arctic Ocean, since primary production is initiated by the growth of ice algae as soon as a critical amount of light reaches the ice-water interface in spring (Bokhorst et al., 2016). Recently it was discovered that primary production can occur under ice and/or snow if melt ponds are formed, which have a lower albedo than bare ice and snow, and thus can transmit sufficient light to initiate algal growth (Horvat et al. 2017). However, if the snow cover persists during the summer, it will ultimately reduce the light available for photosynthesis by the phytoplankton (Sturm & Masson, 2017).

Since 1978, the duration of winter snow cover has decreased between 4 and 9 days per decade in all Arctic coastal areas except the Kara Sea and the Chukchi Sea coasts (AMAP, 2012). The Arctic land area covered by snow in early summer has reduced by 18% since 1966, and the average snow cover duration is expected to decline by up to 20% by 2050, due to earlier melting in spring (Callaghan et al., 2011b). The rate of loss of June snow cover extent between 1979 and 2014 (-19.8% per decade) is even greater than the loss of September sea ice extent over the same period (-13.3% per decade), and demonstrates that both the terrestrial and marine cryosphere are responding to increases in surface temperatures (Derksen et al., 2014).

Despite these observed trends, it is difficult to predict how properties of snow will change in the future (Sturm & Masson, 2017). Callaghan et al. (2011b) suggest that snowfall will increase in all seasons, but mostly during winter. Others note that it is unclear whether this precipitation will fall as rain or snow (Leonard & Maksym, 2011; Sturm & Masson, 2017). The reduction in sea ice cover during late fall increases the atmospheric water vapor content in the Arctic region and supports increased snowfall (Liu et al., 2012). However, if sea ice freeze up timing occurs later, this could translate into increased snowfall into the unfrozen ocean; thus, increased snowfall may not mean deeper snow cover on ice (Hezel et al., 2012). Changes in snow depth will have negative implications for habitats of polar bear and their prey and could alter the timing of biological activity within and under the sea ice (Sturm & Masson, 2017)

Snow also plays a large role in ice-atmosphere exchange of biogases. Due to the snows proximity to pollutant sources and atmospheric circulation patterns, snow can accumulate soot, nitrogen compounds, ammonium and other contaminants (Bokhorst et al., 2016; AMAP, 2015; Sturm & Masson, 2017). Melting snow could allow contaminants to re-enter the environment and become exposed to the food chain (AMAP, 2012). One emerging contaminant of concern is mercury, which can be retained by snow via dry gaseous or particle deposition. It may be then re-volatized back to the atmosphere, or transported as melt water runoff to aquatic environments such as oceans (Mann et al., 2015; Wang et al., 2017). This could be taken up by sea ice-associated biota such as algae and biomagnify in the food web.

Changes in the amount of snow and the structure of the snowpack affect soils, plants, animals and marine productivity. Some species, such as pink-footed goose, benefit from less snow cover in spring, laying eggs earlier and raising more young in years with less snow cover between 2003 and 2006 (AMAP, 2012). Conversely animals such as caribou or reindeer suffer if winter rainfall creates an ice-crust over the snow, and prevents foraging access. This has been reported in the Canadian Arctic Archipelago, Greenland and Scandinavia (Langlois et al., 2017; AMAP, 2012). In addition, the Arctic snowpack is a habitat for microbial communities, so reduction in snow quality and extent will represent habitat loss for these organisms (Harding et al., 2011). Less snow and faster melting are also causing summer drought in forests, wetlands, and lakes supplied by snow melt, which are related to increased frequency and extent of fires (Mack et al., 2011; AMAP, 2012). Evidently certain properties of snow are critical to marine habitats and changes to the snowpack can have significant negative effects on many Arctic ecosystems.

7. The marine environment

The Arctic Ocean is unique. It has the most extensive continental shelves of all oceans: they cover 50% of its total area. It is the most extreme ocean in regard to the seasonality of light, large riverine inputs and its predominant ice cover. In addition, Arctic marine productivity and biodiversity are shaped by connections to the Pacific and Atlantic oceans, and a strong stratification (layering of water with different temperatures and salt levels).

7.1 Physical oceanography

Bathymetry

The Arctic Ocean is a nearly landlocked ocean and receives large amounts of freshwater from rivers such as the Ob, Lena, Yenisey and MacKenzie. It consists of a deep central basin (maximum depth of 4,400 m) divided by ridges (i.e. a chain of mountains that form a continuous elevated crest) and surrounded by broad and narrow continental shelves (Figure 6; Cottier et al., 2017); an interactive map can be seen at www.arkgis.org). It is the smallest of the world's oceans, but has the highest proportion of continental shelves, with shelf regions covering around 50% of the Arctic sea floor (Jakobsson et al., 2004). The continental shelves north of Greenland and of the Canadian Arctic Archipelago, part of the LIA, extend for a maximum of 300 km off the coast, up to a depth of around 400 m, until they reach the shelf break (i.e. where the slope is very steep). Water depths in the central Canadian Arctic Archipelago are generally shallow (< 100 m) although Lancaster Sound reaches depths of up to 800 m (Niemi et al., 2010). Fiords on the northern coast of Greenland can be very deep (Petermann Fiord is 1,100 m deep (Johnson et al., 2011)) while fiords located on the northern coast of Ellesmere Island are not well known, except that Disraeli Fiord is about 450 m deep (D. Antonaides, pers. comm).

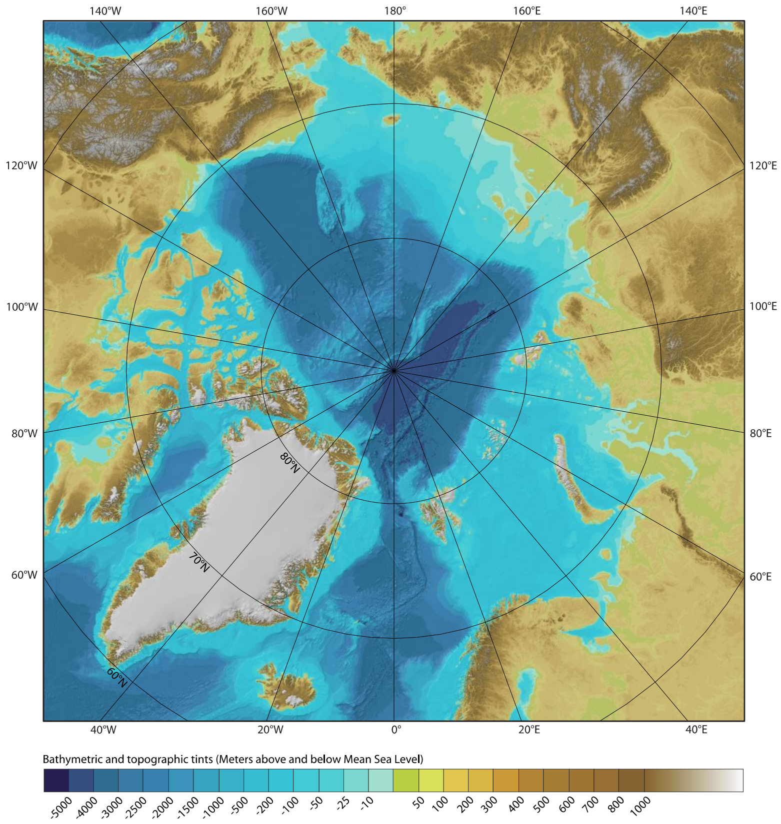


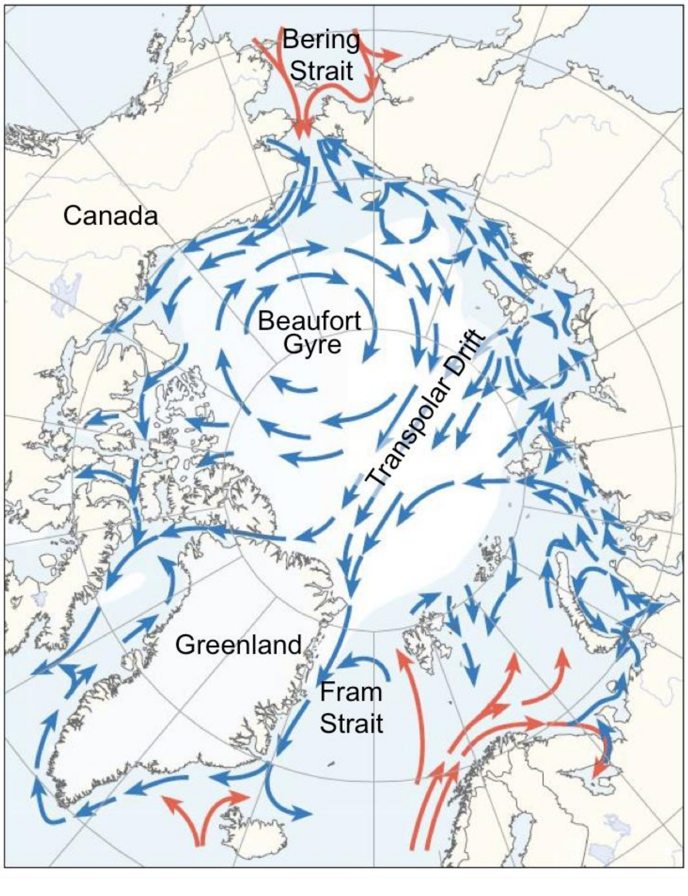
Figure 12. Bathymetry of the Arctic Ocean (Jakobsson et al., 2012).

Currents and water masses

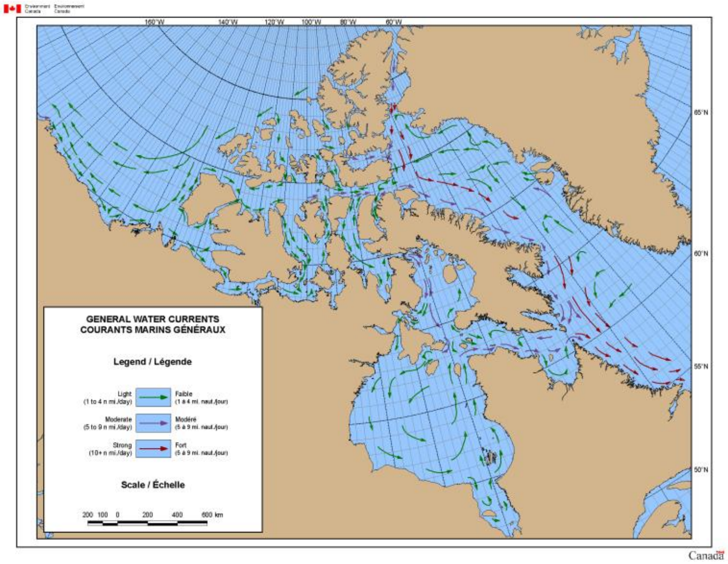
The circulation of surface waters in the Arctic Ocean are dominated by two wind-driven surface currents: the anti-cyclonic Beaufort Gyre over the Canada Basin and the Transpolar Drift that flows from the Siberian coast, across the north pole and exits through the western Fram Strait. (Figure 13). Atlantic Ocean Water enters through the Barents Sea opening and eastern Fram strait, providing the principle source of heat and salt to the Arctic Ocean (Cottier et al., 2017). Relatively cold and fresh waters of the Pacific Ocean flow to the Atlantic through several routes in the Canadian Arctic Archipelago, mainly in Lancaster Sound/Barrow Strait and in Nares Strait, and through Fram Strait, down the east coast of Greenland. The Pacific Ocean water is characterized by a low salinity (less than 33 ‰) and is nutrient-rich compared to the Atlantic Ocean water (Cottier et al., 2017). The Pacific waters are therefore less dense and form a layer on top of the Atlantic water mass. Freshwater from sea ice melt and river discharges add to this surface layer and contribute to the stability of the water column (Peterson et al., 2006). A consequence of these high freshwater inputs is the permanent stratification of the central Arctic Ocean with a surface salinity of 32 ‰ and a deep-water salinity of 34 ‰ (Gradinger et al., 2010). Surface waters become rapidly depleted in nutrients due to the blooms in primary productivity but the underneath layers remain nutrient-rich (Arrigo, 2017). The interplay between the winds and the stability of the stratification determine the vertical supply in nutrients by mixing deep waters into the surface layers (upwelling).

Water masses of the Arctic Ocean are found to vary in temperature, salinity and position from year to year. These changes, apart from modifying water stratification and mixing regimes, may affect nutrient concentrations, and the distribution of plankton, fish larvae and larger invertebrates. Arctic marine biodiversity is therefore linked to the dynamic pattern of oceanic conditions (CAFF, 2013b).

The wind-driven surface circulation in the Arctic Ocean also determines the movement of sea ice (Ito et al., 2015). The clockwise Beaufort Gyre controls the movement of the Arctic pack ice off the northern coast of Greenland and along the northwestern margin of the Canadian Arctic Archipelago (Figure 13a). By recirculating ice, the Beaufort Gyre produces the thickest and oldest ice in the Arctic Ocean (Lee et al., 2012). Moreover, the Transpolar Drift moves ice from the Siberian coast region across the Arctic Ocean towards and eventually through Fram Strait and Canadian Arctic Archipelago (National Snow and Ice Data Centre, 2013a; Meier, 2017). As a result, on a basin-scale, the oldest and thickest sea ice (mean thicknesses of 4 to 6 m) is located off the northern coast of Greenland and along the northwestern margin of the Canadian Arctic Archipelago (Lange et al., 2015), and is the region covered by the LIA project.



A)



B)

Figure 13. Surface ocean currents in A) the Arctic Ocean and B), the Canadian Arctic Archipelago. In A), blue arrows indicate cold currents and red arrows, warm currents (modified from (Arctic Council - CAFF Working Group, 2001a)). In B), green arrows indicate li light currents, purple arrows, moderate currents and red arrows, strong currents (Environment Canada - Canadian Ice Service, 2013).

Climate warming impacts on water masses

Climate warming has implications for the water masses of the global ocean, and changes have been observed for the Arctic Ocean. In recent years, reduced ice cover along with changes in wind-ice-ocean interactions has resulted in a greater contribution of warmer Atlantic Water to the Canada Basin, which can lead to further melting (Xue et al., 2013; Cottier et al., 2017). Figure 14b provides evidence that sea surface temperatures in August 2016 were up to 5˚C warmer than the 1982-2010 August mean in the Barents Sea, Chukchi Sea, and in the east and west coasts of Greenland. Additionally, eastern Baffin Bay has shown significant ocean surface warming trends, increasing at a rate of approximately 0.5˚C/decade since 1982 (Timmermans, 2016). The global ocean will continue to warm during the 21st century. Heat will penetrate from the surface to the deep ocean and affect ocean circulation (IPCC, 2013). Additionally, the thermal expansion of water and glacier mass loss is causing the sea level to rise. Over the period 1901-2010, global mean sea level rose by 19 cm, and is projected to continue to rise at a rate of approximately 3.2 mm per year (IPCC, 2013).

Due to its relative proximity to pollutant sources and atmospheric circulation patterns, the Arctic has been dealing greenhouse gas exchanges between sea ice and atmosphere (Tison et al., 2017). Rising Carbon dioxide gas (CO_2) concentration in the atmosphere since the industrial revolution is causing ocean acidification (AMAP, 2014). The primary driver of ocean acidification is the water absorbing CO_2 emitted to the atmosphere by human activities (Mathis & Cross, 2016). Around one third of the CO_2 produced by human activities has been taken up by the oceans (Sabine et al., 2004). Although this has slowed the rate of climate warming, it has made the ocean more acidic and has had significant consequences for marine life (Fabry et al., 2008). Factors that intensify ocean acidification include melting glaciers and ice caps, which add fresh water to the sea. Additionally, thawing permafrost releases long-stored carbon to the ocean (AMAP, 2014). Increase in CO_2 concentration in the ocean surface waters decrease the pH and lead to undersaturation in calcium carbonate ($CACO_3$). Under these conditions, marine organisms such as plankton, invertebrates and fish that use calcium to form shells and external skeletons are negatively affected (Fabry et al., 2008). Ocean acidification is therefore likely to affect the abundance, productivity, and distribution of marine species. The Arctic marine environment is especially prone to ocean acidification. This is due to the better dissolution of CO_2 into colder water than warmer water and to specific characteristics of Arctic Ocean water. In particular, increasing amounts of sea ice meltwater may deplete surface waters of the calcium carbonate ions necessary to build shells and skeletons (Yamamoto et al., 2012). The CO_2 can be absorbed during open water conditions and rejected along with brine from growing sea ice (Rysgaard et al., 2009). Barber et al. (2015) note that the Canadian Arctic Archipelago is positioned to see the largest relative increase in CO_2 uptake when compared to other Arctic regions. This is due to decreasing ice extent (and consequent increase in open water events) in the summer and autumn months. Typically primary productivity is higher under these circumstances and thus facilitates greater uptake of atmospheric CO_2. It is still unclear exactly what changes increased acidification will bring, but it is very likely that the water column food web of the Arctic Ocean will be affected (Riebesell et al., 2013). Many organisms grow more slowly under the acidification levels projected, and many shell building organisms such as Arctic mollusk may have difficulty developing and maintaining their shells (AMAP, 2014). Cross et al. (2016) note that this could negatively affect many upper trophic level organism such as salmon rely on marine calcifiers as a food source. Other marine mammals, seabirds and fish could also be affected by the loss in food source (AMAP, 2014).

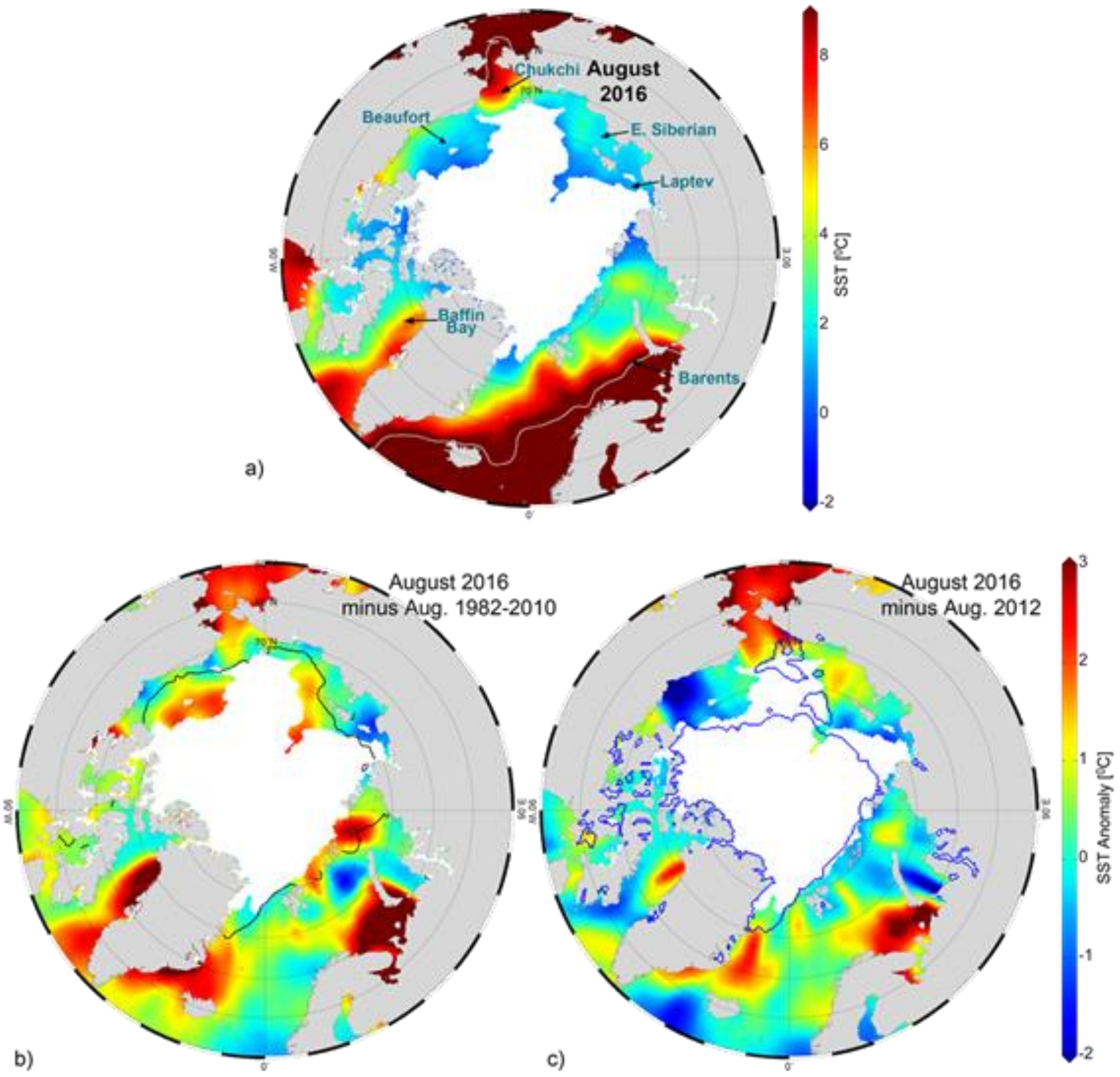


Figure 14.(a) Mean sea surface temperature (SST, °C) in August 2016. White shading is the August 2016 mean sea ice extent, and grey contours indicate the 10° C SST isotherm. (b) SST anomalies (°C) in August 2016 relative to the August mean for the period 1982-2010. White shading is the August 2016 mean ice extent and the black line indicates the median ice edge in August for the period 1982-2010. (c) SST anomalies (°C) in August 2016 relative to August 2012 (the year of lowest minimum sea-ice extent in the satellite record: 1979-present); white shading is the August 2016 mean ice extent and the blue line indicates the median ice edge for August 2012. Taken from Timmermans (2016)

7.2 Sea ice

What is sea ice?

Sea ice is frozen ocean water and it is found throughout the Arctic and Antarctic. Different types of sea ice are found and have distinct properties (Figure 15). First-year ice is floating ice of no more than one year's growth. Its thickness ranges from 0.3 to 2 m. This ice type is generally level but ridges that occur are rough and sharply angular (National Snow and Ice Data Centre, 2013a). As sea ice forms, it expels salt into the ocean water by the formation of brine (droplets of highly saline water) that is trapped in pockets between the ice crystals. Another way that salts are expulsed on new seasonal ice is by the formation of frost flowers on top of it (Barber et al., 2012a). When sea ice becomes multiyear ice (ice that has survived at least two summer melt seasons (Parkinson and Comiso, 2013), it becomes fresh as the salts have been expelled and all that remains is frozen water (Wang et al., 2017). Multiyear ice is therefore stiffer and is harder for icebreakers to navigate through it (National Snow and Ice Data Centre, 2013a). Extensive multiyear ice forms in the Arctic Ocean as it is land-locked (National Snow and Ice Data Centre, 2013a). Perennial ice is defined as ice that has survived at least one summer melt season (Parkinson and Comiso, 2013). The Arctic is covered by approximately 4.5-9.0 million km^2 of persistent multi-year ice, compared with only 3.5 million km^2 of multi year ice in the Antarctic (Arrigo, 2017). Finally, Landfast ice is defined as ice that grows out from the shore (Vincent et al., 2011).

Figure 15. Photos showing examples of the different sea ice types: on the left, first-year is shown (http://ice-glaces.ec.gc.ca/App/WsvPageDsp.cfm?ID=10975&Lang=eng) and, on the right, multiyear sea ice is illustrated (worldcomplex.blogspot.ca/2010/08/blowing-up-arctic_12.html).

Recent decline in sea ice

Several variables describe the Arctic sea ice cover: extent, concentration, volume, thickness, and age. Sea ice extent (ocean area with ice concentration of at least 15%) is the main variable used to describe the state of the Arctic ice cover and has been monitored by satellites since 1979 (Perovich et al., 2012). Sea ice extent has dramatically declined in the last decades. The year 2016 tied with 2007 for second lowest sea ice minimum. Additionally, for the last ten years (2007-2016), Arctic sea ice extent has been among the lowest in the satellite record (record began 1979) (National Snow and Ice Data Centre, 2016). The record low of 3.4 million km^2 was reached on 13 September 2012 (Parkinson and Comiso, 2013), and the 2016 low was recorded as 4.14 million km^2 on 13 September 2016 (Figures 16 and 17). The September 2012 minimum marked the lowest ice coverage in at least the last 112 years (Parkinson and Comiso, 2013). It is also interesting to note that although the summer minimum sea ice extent is declining rapidly, the winter maximum is relatively stable, although it is increasingly composed of first year ice (Figure 18). An animation of the change in ice extent is available online at:
http://nsidc.org/data/virtual_globes/images/seaice_2008_climatology_lr.mov.

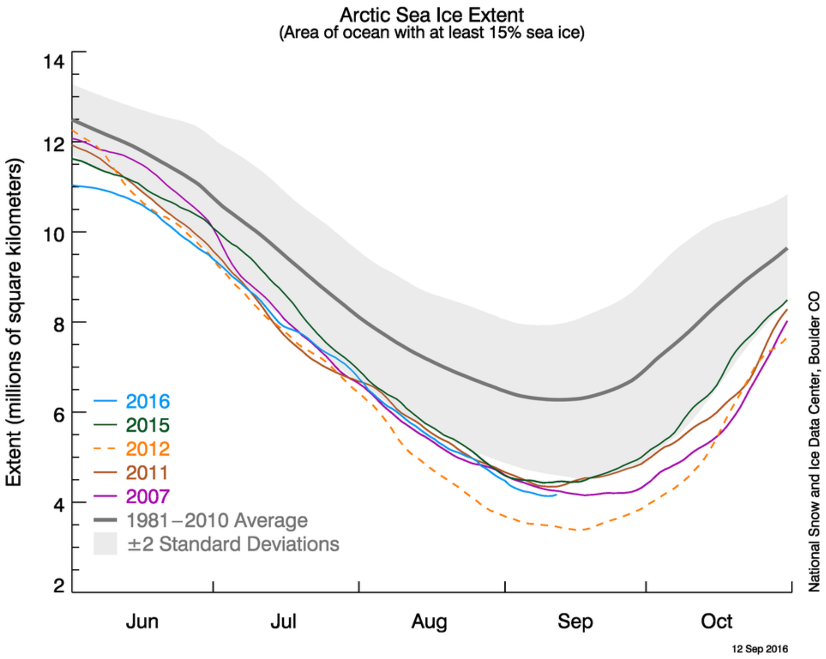


Figure 16. Comparison of the Arctic sea ice extent from 2007 to 2016 with the 1981-2010 mean (image provided by National Snow and Ice Data Center, University of Colorado, Boulder).

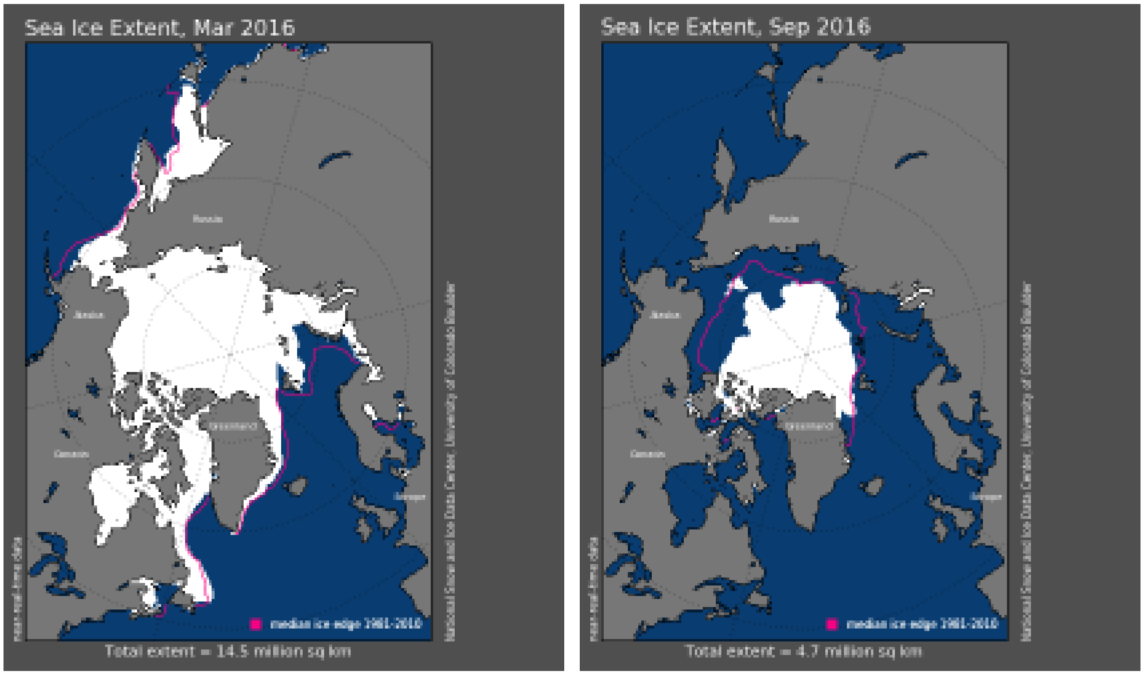


Figure 17. Arctic sea ice extent in September 2012 (left) and March 2013 (right) showing the summer minimum and the winter maximum in sea ice extent, respectively. The magenta line indicates the median ice extent for 1981-2010. Maps are from the National Snow and Ice Data Center Sea Ice Index, http://nsidc.org/data/seaice_index.

In addition to a decline in Arctic sea ice extent, the ice cover is now younger, thinner and the ice volume is reduced (Figure 18). Between 1979-2010, multiyear ice extent has decreased at -15.5% per decade (Comiso, 2012), and the extent of particularly old age sea ice that has survived at least four summers, declined from 50% to 10 % (Maslanik et al., 2011). The loss of older ice types is due in part to in situ melting, but is also due to advection out of the Arctic through Fram Strait and the Canadian Archipelago, which is not replaced because less first year ice is surviving the summer (Meier, 2017). This implies a reduction in the average ice thickness. A study found that the mean Arctic sea ice thickness declined from 3.59 m in 1975 to 1.25 m in 2012, a 65% decline (Lindsay and Schweiger, 2015). Younger and thinner sea ice cover leads to a significant reduction in the sea ice volume (Schweiger et al., 2011). First year ice is also the most likely to melt during the summer (Parkinson and Comiso, 2013), is more vulnerable to wind forcing and is more mobile (Rampal et al., 2009). Where sea ice melts during summer, annual sea ice is formed in the next winter.

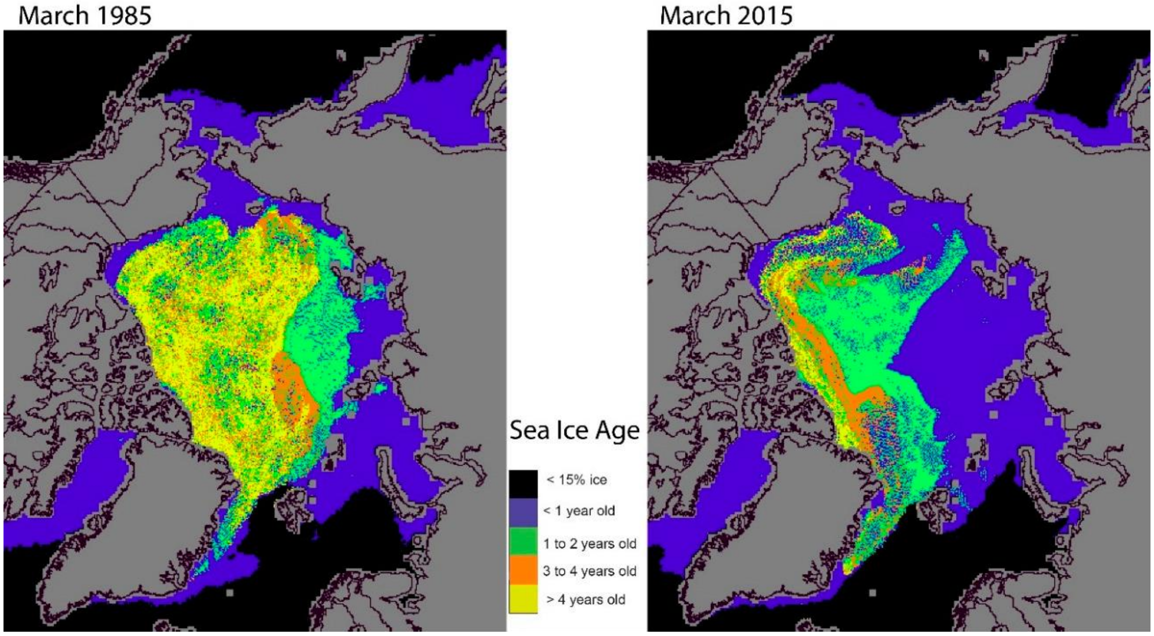
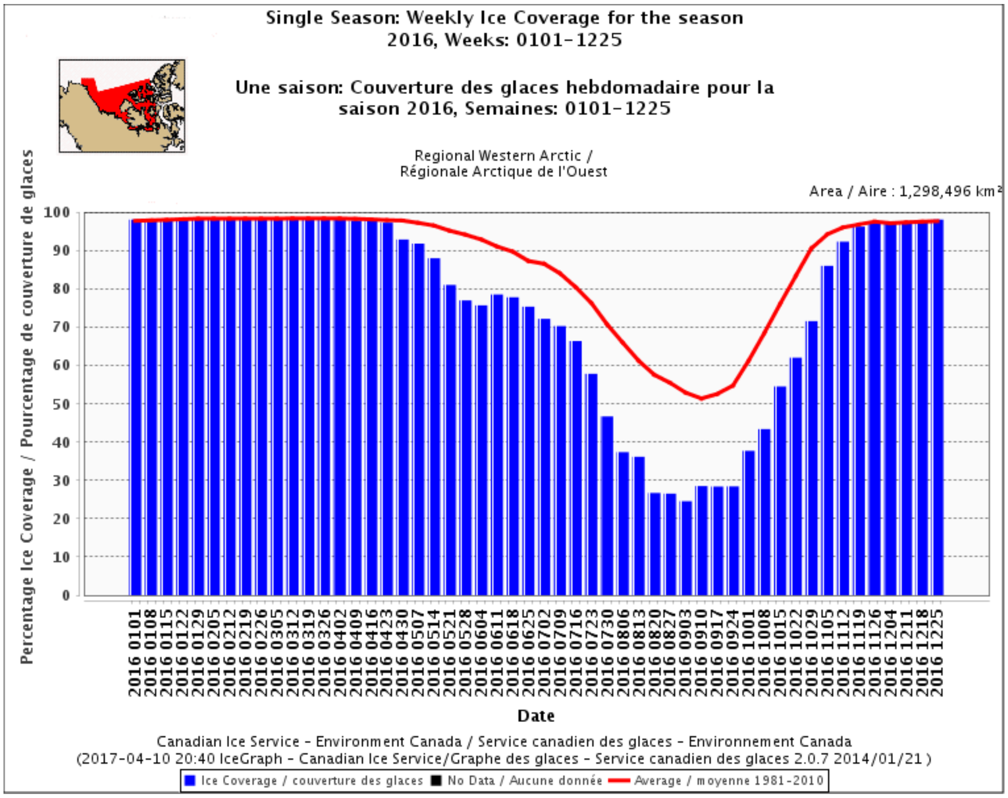


Figure 18. Comparing Sea ice age fraction for March 1985 and 2015 (from Perovich et al., 2015)

Figure 18 also illustrates that the ice that remains at the minimum summer sea ice extent is mostly located within and north of the LIA (see also Barber et al., 2015). Regional western and eastern Arctic weekly ice cover (Figure 19) similarly illustrate that the Canadian Arctic Archipelago and the western coast of Greenland are never completely ice-free. Nonetheless, the graphing tool is not indicating data on specific areas and does not include the northern coast of Ellesmere Island and Greenland. The coast of Ellesmere Island was reported to be fringed with multiyear land fast sea ice that is typically several decades of age (Jeffries, 1992). However, loss of this type of ice has also been reported in recent years and open water of several km off the coast along the shores and in bays and fiords is now occurring (Copland et al., 2007; Vincent et al., 2009; Light and Perovich 2015). Similarly, models also project that the summer sea ice cover of the LIA region will remain the longest and will be the thickest of the entire Arctic (Huard and Tremblay, 2013). This is because areas like the

Canadian Arctic Archipelago generate a considerable amount of ice and act as a sink for this ice from the Arctic Ocean (Mahmud et al., 2016). Shifts in ecosystems in LIA can be expected to be less rapid and of smaller amplitude compared to elsewhere in the Arctic. However, specific changes are already documented and changes observed elsewhere in the Arctic may be relevant for the LIA. Finally, models project that the loss in Arctic sea ice will continue over the next decades under an ongoing air temperature warming trend. It is projected that the September sea ice will disappear completely over the period 2045-2055 (Huard and Tremblay, 2013).



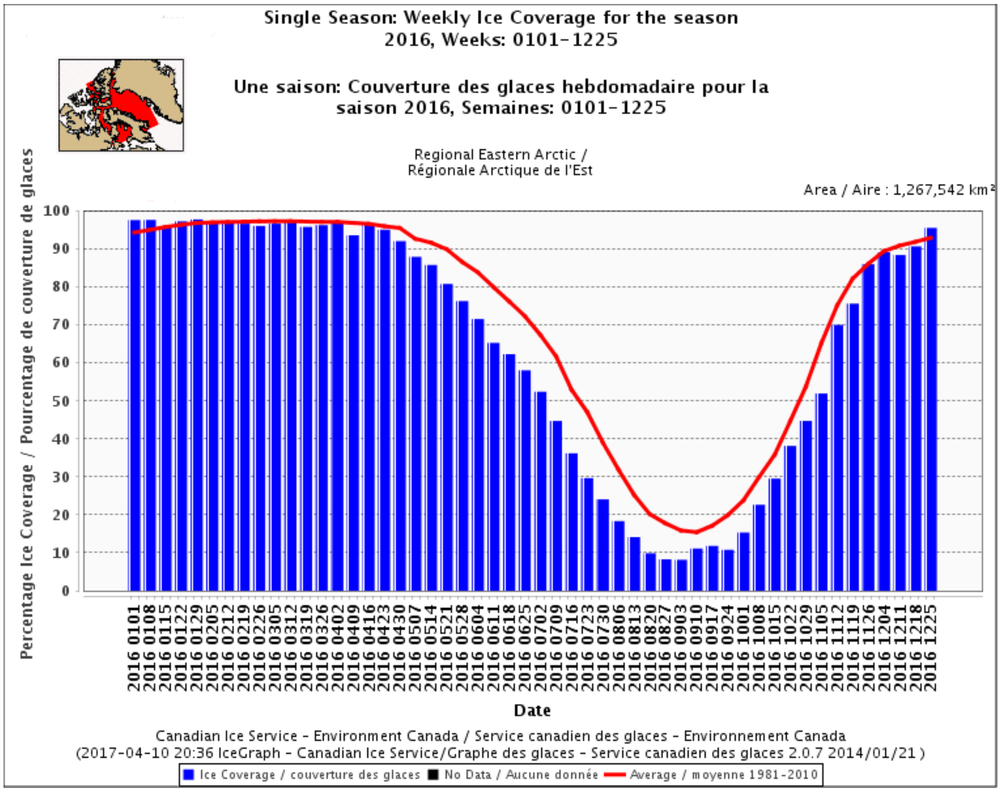


Figure 19. Regional western (upper panel) and eastern (lower panel) Canadian Arctic weekly ice cover in 2016 (Environment Canada, IceGrapgh Tool, 2016).

The roles of sea ice

Sea ice is the most dominant feature of the Arctic marine environment. It influences the climate locally and globally. Sea ice has an impact on albedo and ocean circulation via brine expulsion (Perovich, 2017). Ice melting influences the transport of cold and low salinity waters with ice drift. In addition, ice cover controls atmospheric-ocean exchanges.

Sea ice albedo is an important positive feedback process for the global climate. Albedo is a unitless measure of how well a surface reflects solar energy. A white surface has a high albedo (i.e. 1) while a black or transparent surface has a low albedo (i.e. 0) since most of the light it receives is absorbed and converted into heat. Arctic sea ice has an albedo of around 0.7 while ocean open water albedo is around 0.06 (Huard & Tremblay, 2013). Climate warming causes the sea ice cover to melt and increase the open water area. This results in the reduction of the surface albedo and decreases the amount of solar energy (light and heat) that is reflected back to space. Areas of open water absorb more solar energy and contribute to further warming and more sea ice melt (Perovich, 2017). This process contributes substantially to the Arctic amplification of climate change (Vihma, 2014).

Sea ice also affects the movement of ocean waters. When sea ice forms, brine is pushed into the ocean water just underneath the ice (Cottier et al., 2017). This water has a high concentration of salt and is denser than surrounding ocean water, thus it sinks. By this process, sea ice contributes to the ocean's global thermohaline circulation (Figure 20; Cottier et al., 2017). Changes in the amount of sea ice formed can disrupt normal ocean circulation, thereby leading to changes in the global climate. In contrast, when the sea ice cover melts in the Arctic Ocean or in Fram Strait, it creates a layer of freshwater on top of the ocean water. There have been reports of recent freshwater export events in the Davis Strait, another major pathway connecting the Arctic and the North Atlantic, and may be related to increased glacial melt events (Curry et al., 2014). Since freshwater is less dense than seawater, it tends to stay at the top of the ocean. This lower density discourages the normal process of sinking at high latitudes that supports the thermohaline circulation.

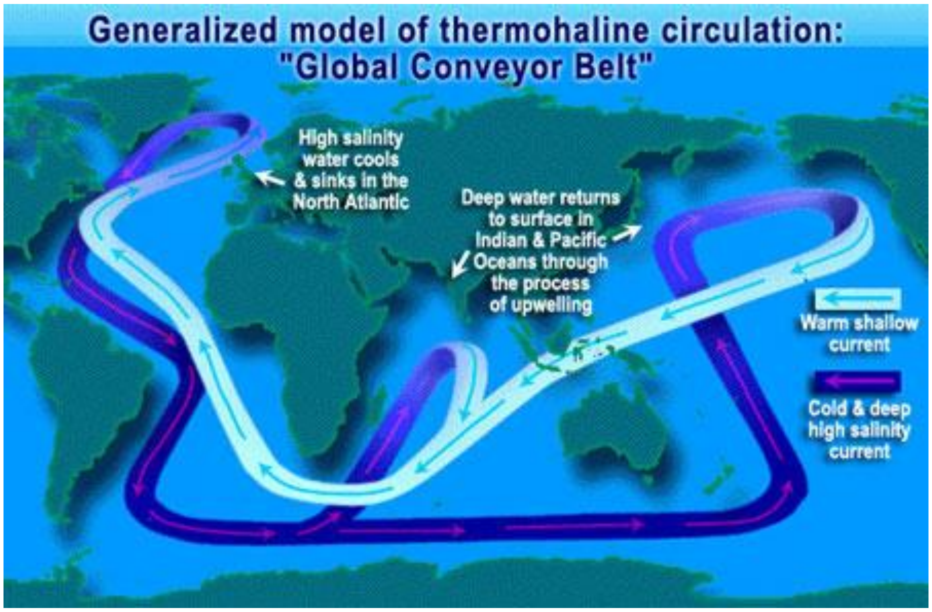


Figure 20. The thermohaline circulation (image courtesy of NASA GSFC; National Snow and Ice Data Centre, 2013a).

Ice cover also controls atmosphere-ocean exchanges. It isolates the upper ocean from direct wind forcing which physically protects the surface water from mixing and dampens surface wave motion. Ice cover also protects the coasts from wave action and associated coastal erosion. It also served as an efficient thermal insulator (McPhee, 2017). The Arctic's atmosphere is very cold during the winter while the ocean is relatively warmer. The sea ice cover prevents the heat in the ocean from warming the overlying atmosphere. Nonetheless, heat can escape from leads and polynyas (Persson

& Vihma, 2017). As the ice melts, energy and moisture move out of the ocean to the atmosphere resulting in more storms such as cyclones (cells of air that rotate in a counter-clockwise direction), characterized by high winds and precipitation (Persson & Vihma, 2017).

The sea ice cover also plays important roles for Arctic marine ecosystem. Similar to the snow cover, the ice cover influences how much light will penetrate to the under ice ecosystems and affects the timing and extent of ice algal and phytoplankton production (Arrigo, 2017). The recent thinning of the sea ice cover contributes to an increase in light transmission, which is mirrored in greater primary production by phytoplankton (see section 8.1; Arrigo et al., 2012). The different components of the Arctic marine biodiversity use and depend on sea ice in different ways. Sea ice cover is the substrate for organisms that thrive within it (see section 8.2). Two fish species use the sea ice cover as habitat, protection from predators and a place to spawn (see section 8.5). Marine mammals that live in the Arctic all year long rely on sea ice as a platform for resting, hunting or breeding (see section 8.6). Loss of Arctic sea ice will push these organisms to adapt their life cycle in order to survive, and the sea ice diversity will change as multiyear ice is replaced by first-year ice. The impacts of a reduced sea ice cover for species that use sea ice occasionally (e.g. seabirds, whales present in the Arctic only during summer) is less clear. The decline in the sea ice cover implies that islands will be separated by open water longer during summer and will prevent terrestrial animals to migrate easily between habitats.

Other impacts of a reduced sea ice cover will be more indirect. Navigation through the Northwest Passage will be easier. This could result in shipping impacts, including spills of bunker fuel oil, or hazardous cargoes (Arctic Council, 2009). Subsistence harvesting practices will have to change in some communities, as traditional over-ice routes become unstable during shoulder seasons, and prey change their patterns (Huntington et al., 2017).

7.3 Marginal ice zones, flaw leads and polynyas

Some features of the sea ice environment are of particular ecological significance since they are highly productive: marginal ice zones, flaw leads and polynyas (Figure 21).

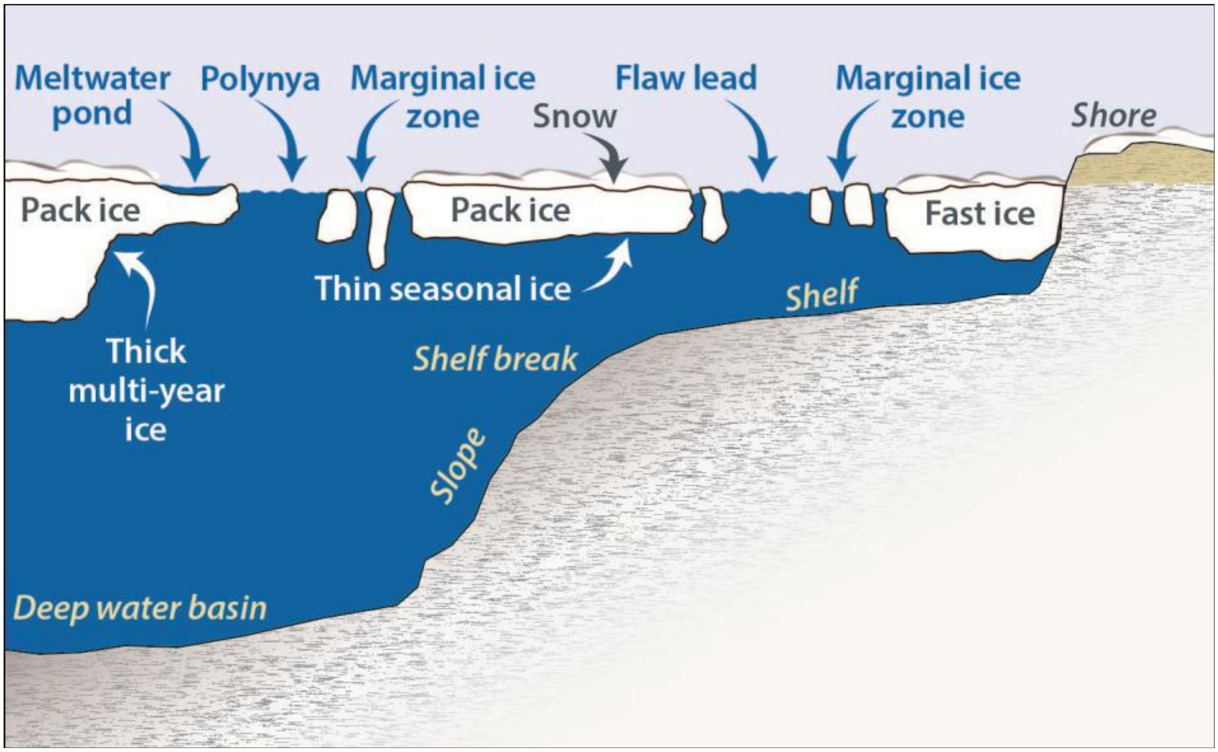


Figure 21. Some features of the sea ice environment (CAFF, 2013b).

Marginal ice zones

The marginal ice zone is the transition area from ice-covered seas to open water, where sea ice is significantly influenced by the action of waves (Persson & Vihma, 2017). Waves are responsible for the break-up of ice floes (drifting pieces of sea ice) and determine the extent of the marginal ice zone. They represent narrow zones that are 25-100 km wide (Dumont et al., 2011). These areas are complex and variable sea ice environments. Swells and waves are lower as they enter the marginal ice zone. Typical marginal ice zone conditions are found along the southern edges of the ice pack in the Bering, Greenland, Chukchi, and Barents Seas, and in Baffin Bay (Roed & O'Brien, 1983).

Marginal ice zones are recognized as biologically productive regions, where large numbers of phytoplankton, zooplankton, seabirds and marine mammals converge. In the Arctic, this is due to upwelling occurring at the sea-ice edge (Smith et al., 1987). Upwelling is the process by which deep, nutrient-rich waters rise to the surface due to the action of the winds or currents. Arctic surface waters are typically reduced in nutrient concentrations and the water column is highly stratified, which limit the growth of phytoplankton. Upwelling, created by the action of the wind on the open water, injects nutrients into the surface waters.

A significant implication of the recent decrease in sea ice extent has been the retreat of the ice edge away from the coast and continental shelves (Lee et al., 2012). At the end of the summer, when sea ice extent reaches its minimum, the marginal ice zone is located above the deep ocean, which was until recently perennially ice covered (Lee et al., 2012). As an example, the recent decrease in sea ice extent has resulted in the production of a substantial marginal ice zone in the deep Beaufort Sea (Lee et al., 2012). Extending open water conditions in the marginal ice zone permit more direct connection with the atmosphere and can have implications for the upper ocean structure and sea ice evolution. Although in the past, the LIA region did not have marginal ice areas, regions such as the Canadian Arctic Archipelago have reported increases in open water trends between June and October, and will likely see Marginal Ice Zone trends in the future (Barber et al. 2015).

Flaw leads

Flaw leads are areas of unconsolidated ice or ice-free waters between the mobile multiyear pack ice and the fixed coastal fast ice (Deming & Fortier, 2011). The circumpolar flaw lead is a perennial feature of the Arctic observed throughout the winter (Figure 22). It consists of a large crack in the ice at the periphery of the Arctic Ocean, along the coastlines of the shallow seas that surround the deep Arctic Ocean basins (Deming & Fortier, 2011). The circumpolar flaw lead in the LIA area is relatively narrow since multiyear landfast sea ice is still substantial in this area even during the summer (Meier, 2017). In some areas, the circumpolar flaw lead widens significantly in spring and summer and forms recurrent polynyas where biological productivity is increased (Deming &Fortier, 2011). Flaw leads are also areas of high ice production (Dethleff et al., 1998).

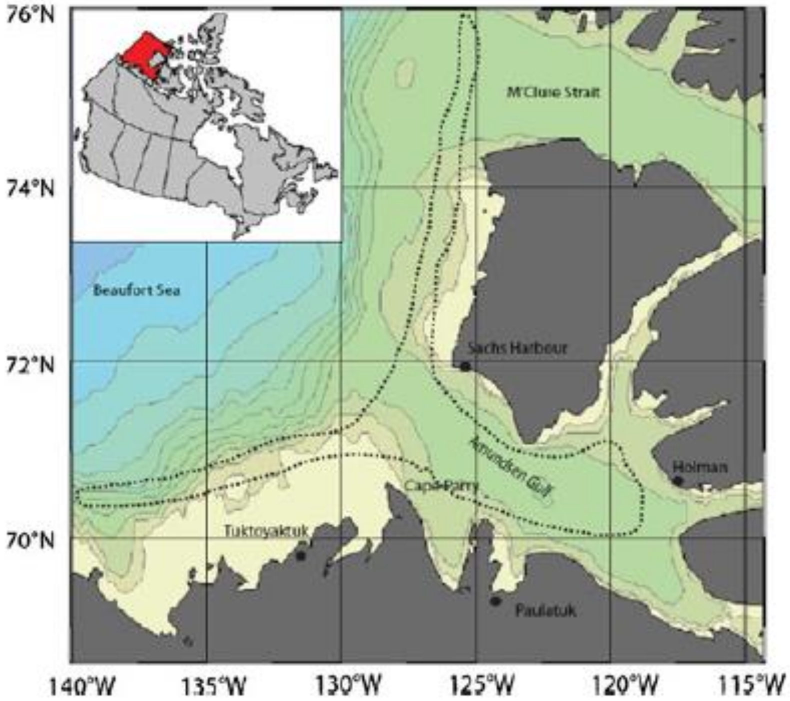


Figure 22. Map of the circumpolar flaw lead (indicated by the grey dashed line) in the Beaufort Sea and local communities (Barber et al., 2012b).

In the Fram Strait and other parts of the Arctic Ocean, leads in the ice cover provide the required amount of sunlight to initiate and sustain phytoplankton blooms (Assmy et al., 2017). The ice edges of a flaw lead are also areas of high biological productivity (Barber et al., 2012a). Upwelling is caused by strong winds which mixes water layers and introduces deeper water replete with nutrients close to the surface, making them available for biological growth (Barber et al., 2012a). As the sea ice cover and volume are decreasing with a warming climate, the open-water season at the periphery of the Arctic Ocean is lengthening and the circumpolar flaw lead is projected to enlarge and to last longer (Deming and Fortier, 2011). Ecosystem-wide enhancements in productivity are expected in these areas (Barber et al., 2012a).

Polynyas

The word Polynya originates from a Russian term for ‘ice hole’ (Cottier et al., 2017). Polynyas are large areas (10 - 90,000 km^2) of permanently or frequently open water surrounded by thick sea ice (Barber et al., 2001b). They are generated by warm water input from below or by the action of strong winds that move away sea ice as soon as it is formed (Barber et al., 2001a; Tremblay and Smith Jr, 2007). Similar to the flaw leads, polynyas produce a lot of sea ice. All polynyas are important for initiating fracturing and melt of ice cover in the spring (Cottier et al., 2017). The open water in polynyas traps heat, thereby accelerating the decay of surrounding ice (Canadian Coast Guard,2012).

Polynyas are highly productive areas and hotspots of diversity compared to other ice-covered areas of the Arctic Ocean (Barber et al., 2001a). In most Arctic waters, low winter sun and a thick ice cover limit primary production. However, the open waters associated with polynyas permit phytoplankton blooms in early spring, and this increased algal production is reflected in high densities of zooplankton (Arrigo & van Dijken, 2004). They are a very important habitat for high densities of birds and mammals that use these areas for feeding, mating, spawning and over-wintering grounds (Heide-Jorgensen et al., 2013). This high productivity at all trophic levels is mirrored by a great export of carbon and nutrients to the seafloor at the end of the bloom season (Grant et al., 2002). Polynyas are also of special significance for air-breathing Arctic organisms (Heide-Jorgensen & Laidre, 2004). They form breathing holes for narwhal, beluga whales, walrus and seal species. Areas adjacent to polynyas can form suitable hunting ground for polar bears because of the aggregation of seals. Also numerous seabirds use polynyas for hunting and major winter bird colonies in the Canadian islands are located adjacent to polynyas (e.g. the North Water Polynya). Upwelling and vertical mixing of water masses entrain nutrients from below into the surface waters that can become rapidly exhausted in nitrate during blooms (Tremblay and Smith Jr, 2007). Polynyas are often described as polar oases (Cottier et al., 2017). Archaeological records also show that Inuit used the shores of polynyas as a predictable food source since prehistoric times as Inuit settlements are often found in the vicinity of persistent polynyas (Henshaw, 2003; Pedersen et al., 2010).

Figure 23 depicts some of the recurring polynyas that have been identified in the Canadian Arctic, three of which are contained within LIA boundaries: Penny Strait, Queen’s Channel, Hell Gate/Cardican Strait and the North Water (NOW) – Canada’s largest and most famous polynya (see section 8.8 for more details). The NOW is located in northern Baffin Bay between Canada and Greenland (Figure 23), and its features are explored in greater detail in section 8.8. The former

Northeast Water polynya (NEW), off the northeast coast of Greenland, is no longer considered a polynya due to changed ice conditions (Kovacs and Michel, 2011). The NEW polynya was only moderately productive due to little replenishment of nutrients (Schneider and Budeus, 1995).

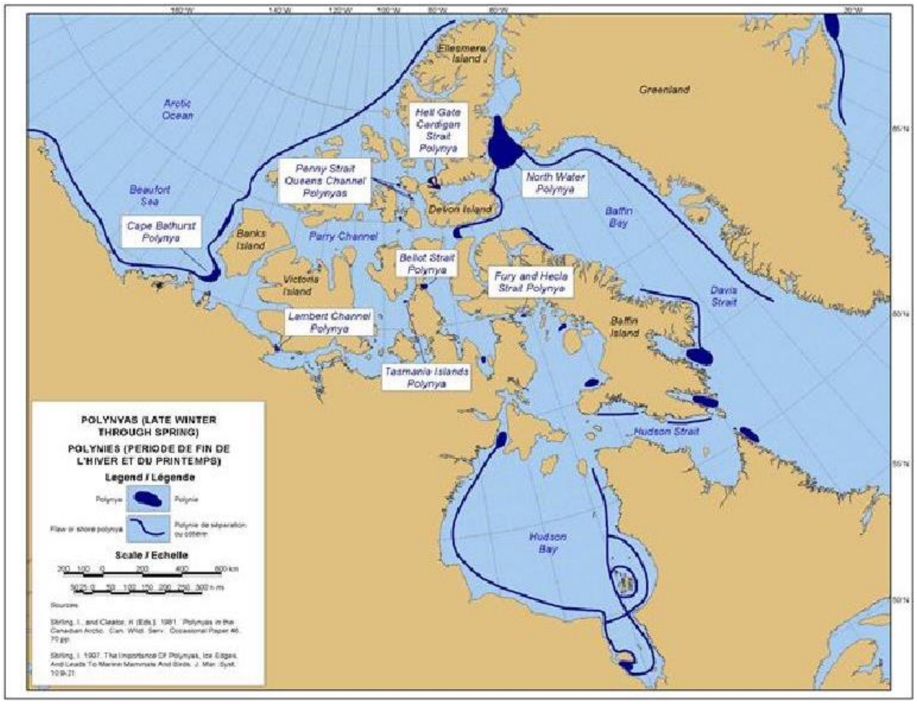


Figure 23. Map of Polynyas in the Canadian Arctic (Canadian Coast Guard, 2012).

Polynyas are dynamic features that vary in timing, extent and duration from year to year (Dumont, 2012). A warmer climate associated with a reduction in thick sea ice cover may affect polynyas in different ways, although it is expected that they will more commonly decrease in duration (Smith Jr and Barber, 2007). For instance, trends over the last 4 decades show that the NOW polynya is occurring less frequently and break-up earlier. Also, its formation is due to the presence of thick sea ice and a slightly warmer Arctic winter could lead to its demise (Dumont, 2012). In contrast, the Wrangel Island polynya, located in the Chukchi Sea, has more than doubled in extent over the last 30 years (Moore and Pickart, 2012). Additionally, new polynyas could be generated at other sites (Ingram and Carmack, 2006). Species reliant on polynyas will need to adapt to changing locations and timing of new polynyas if they are to remain connected to these areas. Alternatively, they will have to adapt to less productive habitats (Ingram and Carmack, 2006).

7.4 Ice shelves

Ice in bays and fiords can become very thick since less dynamic conditions in wind and current, compared to offshore, have permitted ice growth over periods lasting from tens to thousands of years.

Ice shelves are defined as thick (> 10 m) ancient ice attached to the coastline (multiyear landfast sea ice) and floating on the sea (Veillette et al., 2008). Ice shelves are in hydrostatic equilibrium with the ocean and hence, only ~ 10% of their total thickness is emerging above sea level (freeboard) (Mortimer, 2011). Ice shelves are a predominant feature of the Antarctic, where they border ~ 55% of the coastline (Dowdeswell and Jeffries, 2011), but they are also present in the Arctic (Eurasian High Arctic, Greenland and the Canadian High Arctic) (Dowdeswell, 2011). In the Canadian High Arctic, ice shelves are found on the northern coastline of Ellesmere Island. These are formed, on the underside, by the accretion of basal ice and, on the upper side, by the accumulation of ice from snow and rain precipitations. Ice shelves loss processes include melting and calving events that create ice islands (Jeffries, 2011; Figure 24). In Greenland and the Antarctic, however, ice shelves are composed of the floating extensions of glaciers floating off the continents (Williams and Dowdeswell, 2001).

Ice shelves along the northern coastline of Ellesmere Island have undergone rapid attrition of more than 90% in extent over the last decades. At the beginning of the 20th century, a single ice shelf covering around 8,900 km^2 was reported to fringe this coastline (Vincent et al., 2001). This ice shelf subsequently deteriorated into several smaller ice shelves and accelerated major changes occurred since 2000 (Mueller et al., 2008; Vincent et al., 2011). At the end of the summer of 2011, there were four remaining main ice shelves in Canada, totalling an area of 563 km^2, ~54% of the total area in 2005 (Figure 25; Kealey et al, 2011). In the last decade (2000-2010), most of the Serson Ice Shelf has broken away (Kealey et al., 2011), and the Ward Hunt Ice Shelf, the largest of the four, has undergone substantial fractures during the summers of 2010 and 2011 (W. Vincent, pers. comm.). Milne Ice Shelf is now the thickest in Canada with a maximum thickness over 90 m and a mean thickness of 55 m (Mortimer, 2012). Warmer air temperature, by controlling ice melt, is playing a role with the numerous calving events and the disintegration of the remnant ice shelves. Offshore winds also move fractured ice away from the coast and no longer provide a barrier to the waves that batter the ice shelves (Copland et al., 2007; Mueller et al., 2008; Veillette et al., 2008). The decline in the number, thickness and area of Canadian ice shelves may be irreversible given the current and projected climate warming and that multiyear landfast sea ice is also decreasing along the northern coastline of Ellesmere Island (Copland et al., 2007). The Canadian Archipelago and Fram Strait are the primary sinks for this type of ice (Meier, 2017).

Ice shelves provide the physical structure for unique ecosystems. Cold-tolerant microbial communities occur in association with sediments on the ice shelves' surface (Mueller et al., 2006). The surface morphology of ice shelves is characterized by undulations parallel to the coast that would be caused by the alongshore winds (Figure 26; Hattersley-Smith, 1957). During the summer, meltwater flows in the troughs of these undulations and creates long (up to 15 km), thin (10-20 m), and shallow lakes (maximum of 3 m) that are also characterized by their microbial mat communities (Mueller et al., 2006). DNA profiling demonstrated that the mat microbial communities were composed of all three domains of life (Bacteria, Archaea and Eukarya) and viruses (Varin et al., 2010, 2012).

When an ice shelf completely dams a fiord or an embayment, a lake called "epishelf" may be formed on the landward side (Veillette et al., 2008). These ice-dammed lakes are highly stratified since a layer of freshwater from snow and ice melt floats on top of seawater. The waters do not mix because of their different densities, and because the perennial ice cover stops wind from mixing them (Veillette et al., 2008). Epishelf lakes are one of the most vulnerable ecosystems the LIA region houses. There used to be as many as 17 on the Northern coast of Ellesmere Island before the ice shelf broke up over the course of the 20th century; over the years, these lakes would suddenly drain or lose their dam, and today there is only one epishelf lake left: the Milne ice-dammed lake, located behind the Milne ice shelf (Thomson, 2015). Recently, researchers set out to characterize the lakes microbial ecosystem, and noted a distinct combination of marine and freshwater taxa that are rarely reported from marine water columns (Thaler et al., 2016). However, it is expected that as the ice cover of the lake continues to break up seasonally, the increased light as well as mixing of nutrients and salt to the nutrient depleted surface freshwater will irrevocably change the microbial structure (Veillette et al., 2011; Thaler et al, 2016).

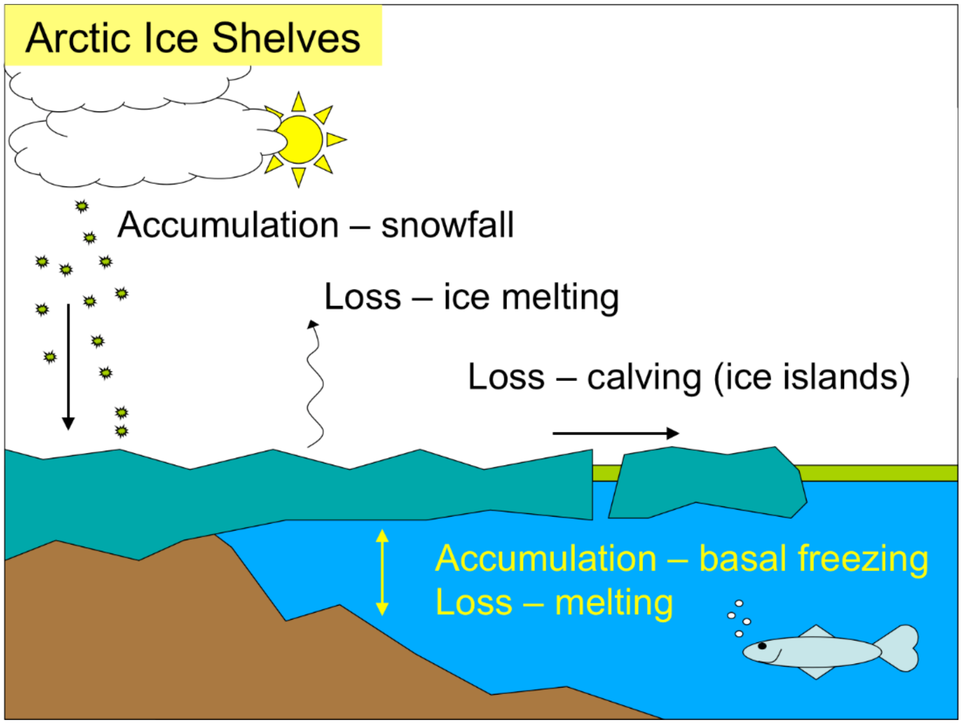


Figure 24. The formation and loss processes of most Canadian Arctic ice shelves (figure courtesy of Derek Mueller).

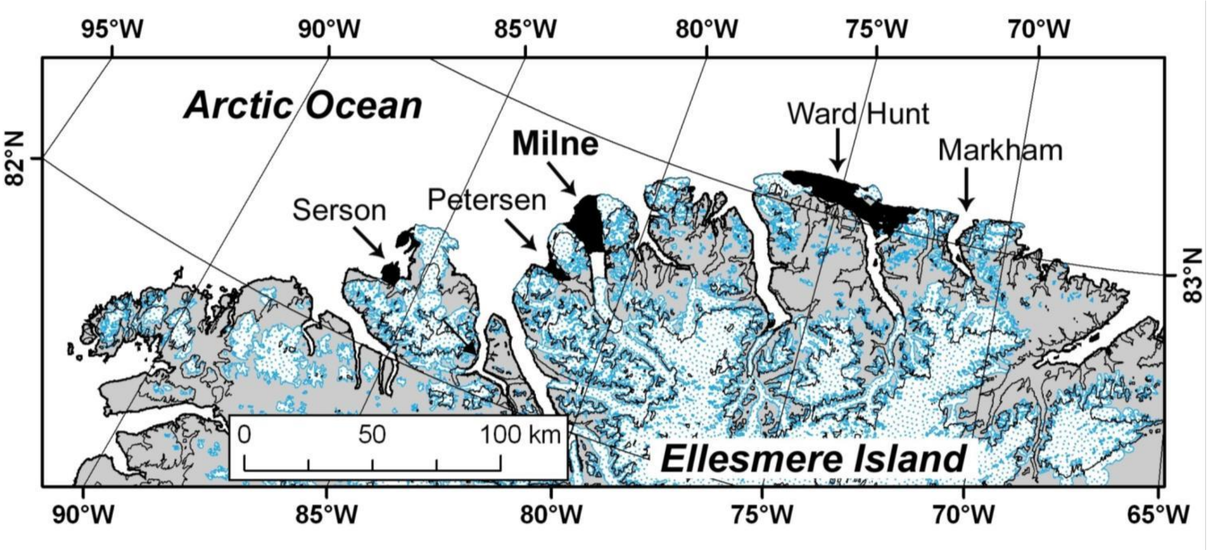


Figure 25. Map of the northern coastline of Ellesmere Island showing the location of the 4 remnant ice shelves at the end of summer 2008 (note that Markham Ice Shelf is completely lost)(figure courtesy of Warwick Vincent).

Figure 26. The Ward Hunt Ice Shelf in August 2008 when the characteristic undulations were clearly visible (Photo: J. Veillette).

8. Marine biodiversity

The Arctic Ocean provides diverse habitats for a multitude of unique life forms highly adapted in their life history, ecology and physiology to the extreme and seasonal conditions of this environment. The logistical challenges imposed by the harsh Arctic environment limit our knowledge of the marine biodiversity. This is especially true for the High Arctic where biological data are sparse and almost non-existent for some habitats (e.g. the benthos) (Piepenburg et al., 2011).

This section first presents information on Arctic marine food webs and productivity. Then, the biodiversity of the different Arctic Ocean habitats (in the ice, in the water column and on the seafloor) is reviewed. After, the biodiversity of fish, marine mammals and seabirds, and the description of key species are presented. Finally, the impacts of climate change for marine biodiversity are tackled since they are likely to affect all Arctic life on top of, within and beneath the ice, and also in the open water and on the ocean floor. A special emphasis is placed on the LIA region.

Overall, it is predicted that there will be more life in the Arctic but that it will be less diverse (Fortier et al., 2012). Only organisms that are adapted to low temperatures, strong seasonality, a perennial or seasonal ice cover, limiting nutrients in the stratified surface layer of the water column and a pulsed annual cycle of primary production have survived in the extreme climate of the Arctic over the last 3.5 million years. As marine ecosystems are exposed to environmental change driven by warming and changes in sea ice coverage and temperature, the types of species that the Arctic can support will change. This will likely lead to a redistribution of species, as southern species that thrive in the more temperate conditions will move north, and those specialized to ‘Arctic marine’ conditions will decline or be redistributed to where their specialized niche still exists (Lenoir & Svenning, 2015).

8.1 Arctic marine food webs and productivity

Structure of Arctic marine food webs

Arctic marine food webs comprise densely linked connections between microbes, algae and animals (Figure 27). Primary producers (ice algae and phytoplankton) support the base of the Arctic marine food web. They convert energy from the sun into food energy. Then zooplankton such as copepods and bacteria graze on these primary producers. In turn, carnivorous zooplankton, fish (Arctic cod) and whales feed on zooplankton (Darnis et al., 2012). Arctic cod are important prey species for many larger fish and marine mammals (Jørgensen, 2015). Top predators such as humans, polar bears, seals feed on a combination of different species. Detritus, which typically includes the bodies or fragments of dead organisms as well as faecal material and nutrients, sink to the sediments where they support invertebrates and microbial communities (Bluhm et al., 2017). The relatively short growing season implies that consumers have a narrow window of opportunity to grow and accumulate energy reserves for winter survival and/or reproduction. Arctic marine food webs involve numerous pathways but are not considered complex compared to the food webs of more temperate systems. These food webs are consequently considered vulnerable to perturbations from southern generalist species (de Santana et al., 2013; Kortsch et al., 2015).

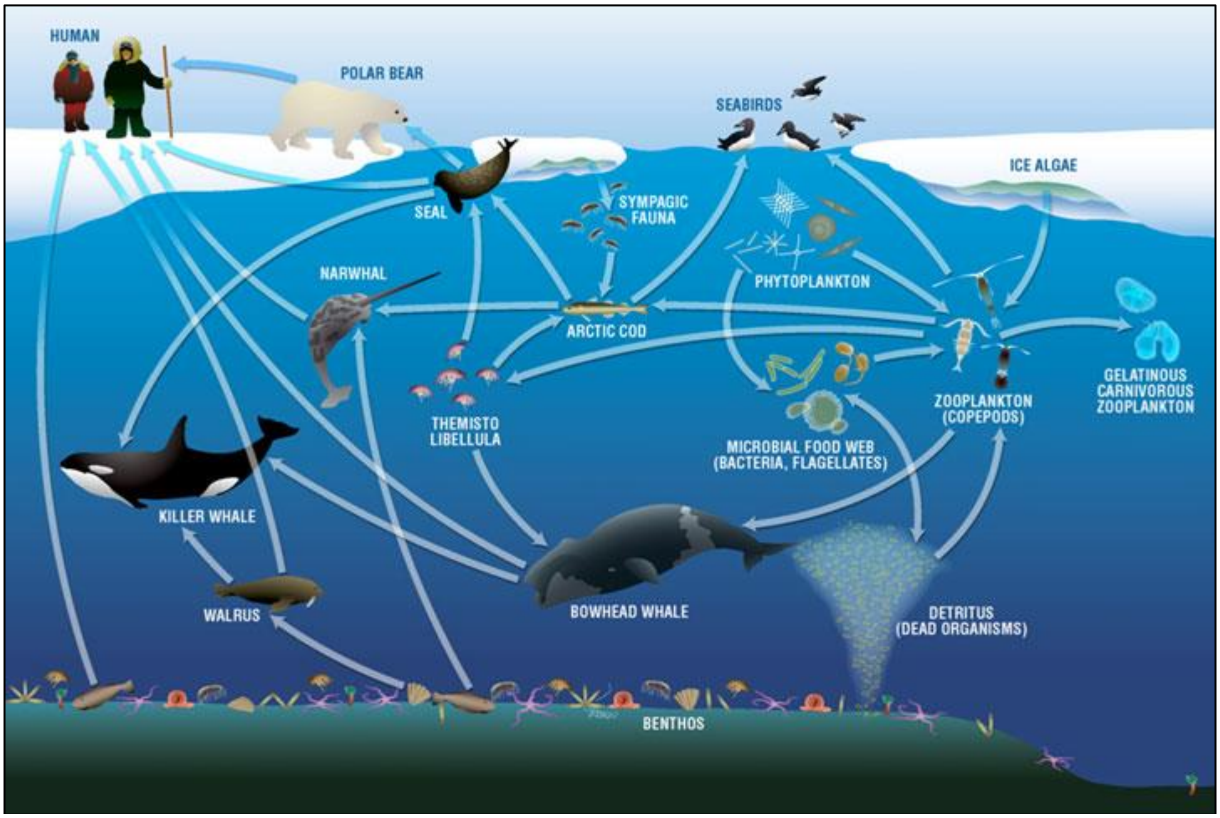


Figure 27. Representation of an Arctic marine food web (Darnis et al., 2012)

Primary production

Primary production determines the amount of food that is available to consumers. Primary producers fix the greenhouse gas CO_2, which helps to reduce its burden in the atmosphere since sinking algae and detritus remove carbon from the surface waters (a process known as the biological pump) (Nishino et al., 2011). Primary productivity is low in the Arctic Ocean and Canadian Arctic Archipelago compared to other oceanic environments located at lower latitudes (Niemi et al., 2010). This is explained by the reduced availability of light and nutrients (nitrate is usually limiting) (Arrigo, 2017). Light is a limiting factor as the sun is up only during the summer, and snow and sea ice cover control the amount of light that reaches the water column (Perovich, 2017). Thus, primary production starts with the growth of ice algae as soon as a critical amount of light reaches the ice-water interface in spring. Ice algal production then blooms and ice algae synthesize fats. At the onset of ice melt, fat-rich ice algae are released in the water column and provide high energy food for the zooplankton, and eventually to the seafloor, at a time when little food is available (Tremblay et al., 2012). Over 95% of primary production in the oceans is due to photosynthetic microbes (Pedrós-Alió et al., 2015), and ice algae contribute around 60% of the total primary production (sea ice and water column) in the central Arctic Ocean (Gosselin et al., 1997). Phytoplankton then take over as the dominant primary producers. The intensity of the late spring or early summer phytoplankton bloom is controlled by the availability of nutrients, which are readily depleted from the surface layer (Arrigo, 2017). The surface layer derived from ice melt is relatively less dense and restricts the mixing with nutrient-rich water from deeper waters. Then primary production declines during summer until the ice forms in the fall. A second bloom can occur in polynyas where ice growth is delayed (Tremblay & Smith Jr, 2007).

Up until recently, it had been assumed that regions underneath a full sea ice cover were incapable of supporting photosynthetic life. However, this classical view of the annual cycle of primary productivity in the Arctic Ocean, presented in the above paragraph, is challenged by some works that report phytoplankton blooms under the ice cover over continental shelves in Barrow Strait in the Canadian Arctic Archipelago (Fortier et al., 2002) and in other seas (Arrigo et al., 2012; Mundy et al., 2009; Strass & Nöthig, 1996). Additionally, research since 2011 has demonstrated that blooms can occur under ice where melt ponds form (Horvat et al. 2017). Melt ponds have a lower albedo than bare ice, thus are hypothesized to transmit sufficient light through the thinner ice cover and allow for primary production. Additionally, the polar night is an important stage for reproduction of many species of Arctic Benthos (Figure 28), and is characterized by a number of processes and interactions yet to be fully understood (Berg et al., 2015).

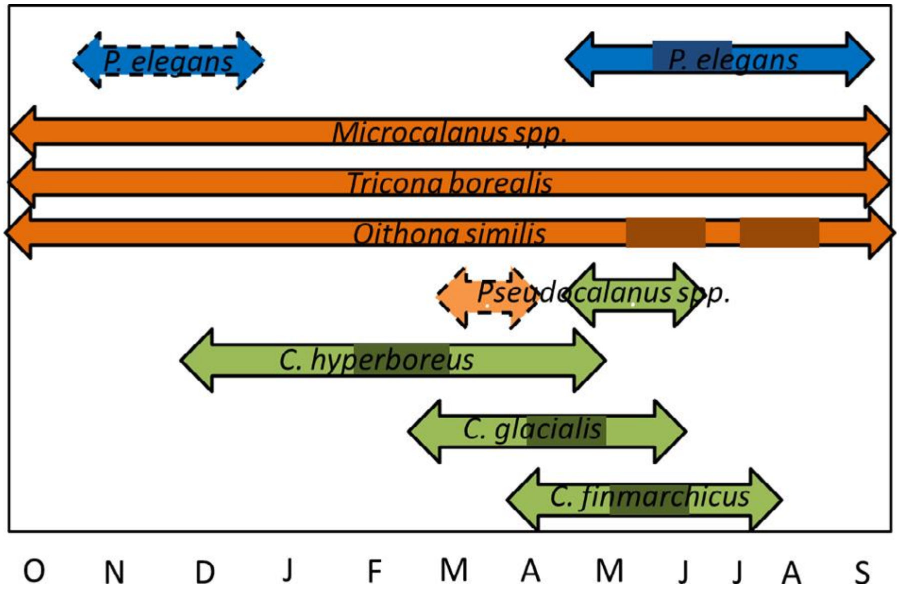


Figure 28. Time windows for reproduction for common high-latitude zooplankton. Darker colours indicate likely peaks in reproduction (Image from Berg et al., 2015).

Primary productivity is also extremely variable among different areas of the Arctic Ocean. Figure 29 illustrates spatially integrated primary production from 1998 to 2012 and demonstrates a general trend of increasing Net Primary Production (NPP) over time. The researchers attribute NPP increase to increases in open water areas, which can provide new habitat for phytoplankton growth (Arrigo & van Dijken, 2015). It is also associated with increased number of open water days, which can lengthen the phytoplankton-growing season (Arrigo et al., 2008). Over the last decade, the annual NPP in the Arctic Ocean was highly variable, ranging from 460 Tg C yr^{-1} in 2003 to 608 Tg C yr^{-1} in 2008 (Arrigo & van Dijken, 2015). Coastal seas accounted for 74% of the variability in annual primary production. This variation is further influenced by latitude, seasonal and multiyear sea ice and snow cover, depth and stability of the surface mixed layer, discharge of inorganic sediments (causing light attenuation) and nutrients from water circulation patterns (Gosselin et al., 1997; Pabi et al., 2008).

The Beaufort sector (stretches into the westernmost portion of the LIA) exhibited a large increase in annual NPP between 1998 and 2012 (53%) (Arrigo & van Dijken, 2015). Yet, despite an increase in open water days, annual NPP decreased in parts of the Canadian Arctic Archipelago, and exhibited no significant change in the Baffin Bay sector (which is dominated by outflow shelves). The Greenland Sea in fact saw a significant decline in annual NPP (Arrigo & van Dijken , 2015). It has been suggested that recent thinning of the ice cover and the proliferation of melt ponds increase light transmission and make it possible for the required amount of light to reach underneath the ice and create conditions favourable for under-ice blooms (Arrigo et al., 2012; Boetius et al., 2013). This suggests that under-ice phytoplankton blooms may be more widespread over nutrient-rich Arctic continental shelves and that satellite-based estimates of annual primary production in these waters may be underestimated by up to 10-fold (Arrigo et al., 2012). Alternatively, Arrigo & van Dijken (2015) suggest that increased NPP in upstream regions of the Chukchi and Beaufort Sea may be consuming a larger fraction of available nutrients, thus resulting in a decline in annual NPP in downstream Greenland Sea and Baffin Bay regions.

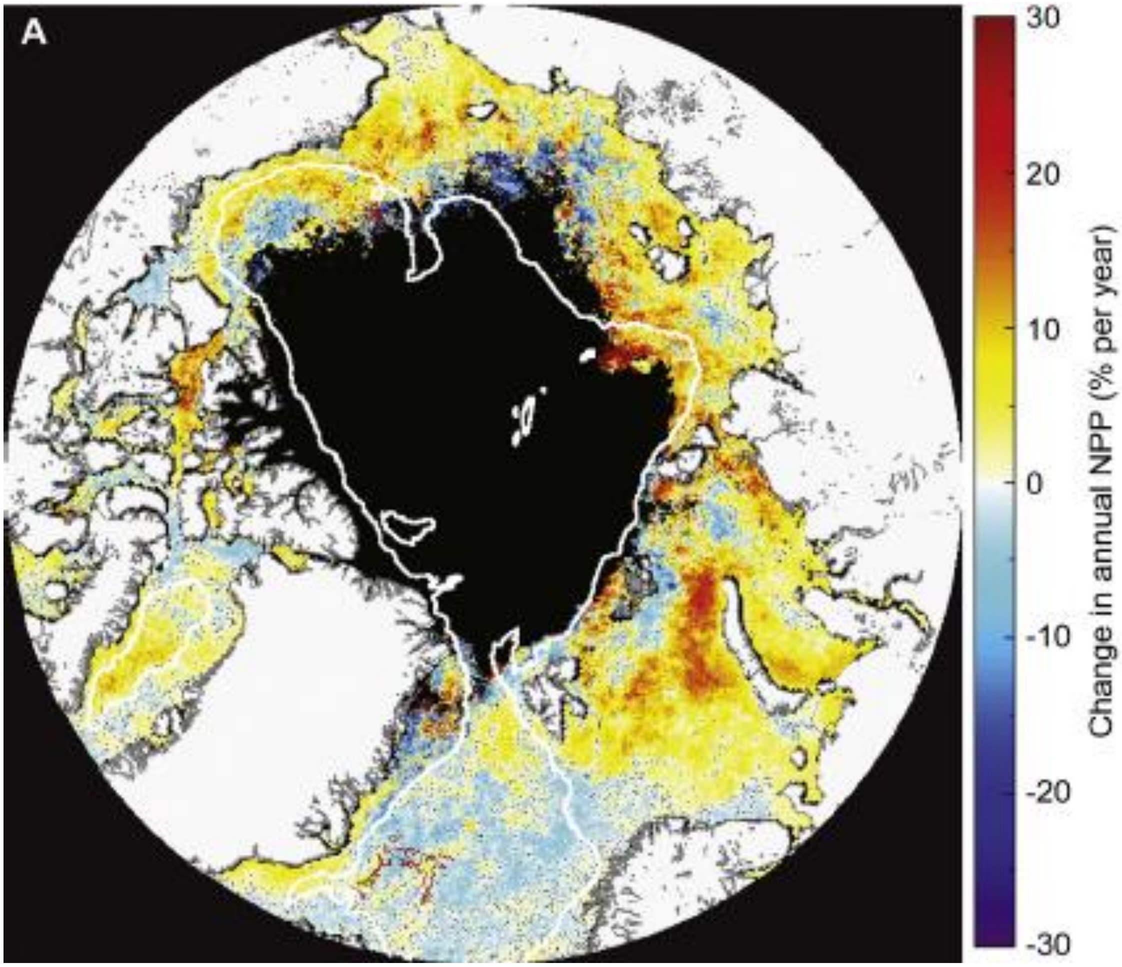


Figure 29. Rate of change in annual NPP (% yr^{-1}) from 1998 to 2012 (Arrigo & van Dijken, 2015).

Implications of a reduced Arctic ice cover for primary productivity

In the next few decades, removal of the ice cover during summers in the Arctic Ocean may increase primary productivity, especially in areas where multiyear ice was present (Arrigo et al., 2008). Primary producers have lost over 2 million km^2 of Arctic ice since the end of the last century (Kinnard et al., 2011). Michel Gosselin, a biological oceanographer specialist of the Arctic Ocean, predicts that phytoplankton production in the Arctic could increase up to 10 times in nutrient-rich regions and three times in nutrient-poor regions as climate warming continues (Gosselin et al., 2012). This increase in primary productivity is associated with a better penetration of light in the water column due to more areas of open water and to a longer phytoplankton growing season (Lange et al., 2015; Arrigo, 2017). However, this increase might slow as the surface nutrients become exhausted (Arrigo et al., 2008), unless upwelling of deep nutrient-rich waters in coastal areas become initiated as multiyear ice cover retreats offshore and favourable winds blow (Tremblay et al., 2012). Therefore, flaw leads and polynyas will continue to play a crucial role in primary production. Nonetheless, the strong stratification of the central Arctic Ocean will likely persist (Tremblay et al., 2012). Although the Arctic sea ice can be productive (Gosselin et al., 1997), the ice-free pelagic (i.e. the water column) environment is typically much more productive. Enhanced primary productivity can strongly increase the efficiency of the biological pump and counteract some of the effects of global warming (Fortier et al., 2012). These changes in primary production will have consequences for the entire Arctic Ocean marine food web and the yield of harvestable resources in the Arctic Ocean. It is predicted that there will be increased fish and marine mammals for Northerners, and exploratory small-scale commercial fisheries by local communities is underway (CBC News, 2013). However, it will most likely not be sufficient to support industrial fisheries (Tremblay et al., 2012).

Implications of a reduced Arctic ice cover for ecosystem structure

Changes in the extent and duration of the Arctic sea ice cover may influence ecosystem structure by modifying the coupling between the pelagic and the benthic (i.e. the seafloor) systems (Figure 30; Arrigo et al., 2008). Under abundant sea ice conditions, as it was observed until recently, Arctic marine ecosystems are strongly influenced by ice algal production that starts as soon as enough light reaches underneath the ice. Ice algal production then blooms and when the ice cover melts, ice algae are released in the water column and are grazed by zooplankton (Arrigo, 2017). An earlier ice break-up in Arctic spring could potentially shift the ecosystem from the current benthic dominated system towards one where more energy is directed towards pelagic food webs (Figure 30; Carroll and Carroll, 2003; Bluhm et. al., 2017). Under this scenario, the release of ice algae during ice melt would be earlier and smaller. The zooplankton could graze almost everything and little would be left to sink to the sediments (Kędra et al., 2015). Phytoplankton could subsequently be available in a less pulsed manner and the zooplankton would graze a large proportion of it, meaning that less particulate matter would be exported to benthic communities (Wassmann and Reigstad, 2011). This could potentially affect benthic feeding marine mammals and seabirds, whose foraging areas will become less productive with less prey available (Kędra et al., 2015). However, this scenario assumes that zooplankton grazers would still be synchronized with the availability of ice algae.

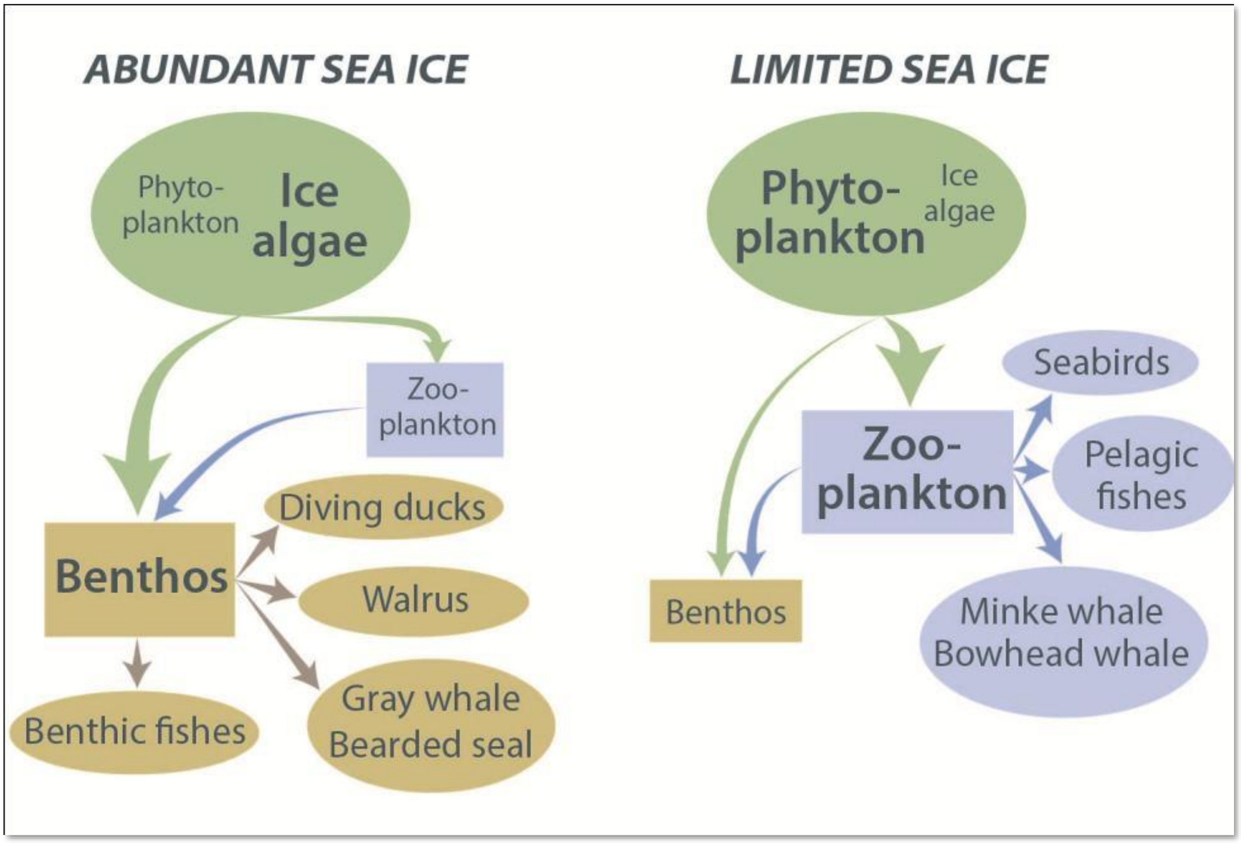


Figure 30. The diagram on the left illustrates an ecosystem strongly influenced by ice algal production under abundant sea ice conditions, while the diagram on the right shows an ecosystem dominated by phytoplankton production that may results from reduction of sea ice (figure from CAFF, 2013).

It is also possible that ice algal communities would be released in the water column at a time when zooplankton abundance is relatively low. This potential mismatch between primary production and zooplankton grazing would have negative consequences for the reproductive cycles of key zooplankton communities, and, eventually, for the entire Arctic marine ecosystem. This is explained by the reliance of zooplankton for the high-quality food that is produced during the two primary production blooms (1. ice algae bloom under the ice cover in late spring; 2. phytoplankton bloom just after the ice break-up) (Søreide et al., 2010). Nonetheless, a recent study indicated that zooplankton showed a high level of activity during winter, well before the spring release of ice algae (Darnis et al., 2012). The authors suggested that zooplankton are well adapted to variability in the timing of the primary production season and that extreme mismatch between primary production and secondary production is unlikely. Nevertheless, a mismatch between primary production and zooplankton grazing would reduce the grazing losses by the zooplankton and increase the sinking flux of particulate matter from the sea ice to the sediments, enhancing benthic production (Michel et al., 2006). Hence, the relative importance of ice algae and phytoplankton for zooplankton and benthic communities would depend on the rate at which the algae are released from the sea ice or the phytoplankton produced in the water column and on the abundance of zooplankton at specific times. At higher trophic levels, seabirds and mammals have evolved to use the seasonal pulse in productivity by migrating to the Arctic at the most productive time of the year to breed, raise their young and feed. They will have to adapt to the changing conditions (Arrigo et al., 2008).

8.2 Biodiversity in the sea ice

Sea is a substrate for diverse and abundant microbial communities (Figure 31; Krembs & Deming, 2011). The sea ice biota consists of a complete food web and observed taxa include viruses, archaea, bacteria, protists, and multicellular organisms (worms and crustaceans small enough to navigate the brine channels) (Bluhm et al., 2011b). Microorganisms, nutrients and other constituents are incorporated into sea ice as the ice is formed. Larger organisms are selectively scavenged from the water column into the sea ice at the time of its formation (Kovacs and Michel, 2011). Sea ice organisms are assumed to be the founding members for the development of the ice-algal bloom that occurs in spring with the seasonal increase in solar radiation (Yergeau et al., 2017).

Multiyear and first-year sea ice communities differ substantially (Bowman et al., 2012). First-year ice supports more organisms than multiyear ice (Aslam et al., 2016). This is due to the greater presence of pores and brine channels that offer more habitats than does multiyear ice (Kovacs and Michel, 2011 ; Caron et al., 2017). Dramatic decreases in the extent of Arctic multiyear ice suggest that this environment may disappear in the next decades and be replaced by ecologically different first-year ice (Bowman et al., 2012). This may result in higher biomass of sea-ice associated organisms available for upper trophic levels before light reaches the surface waters in spring (Poulin et al., 2011). Lange et al. (2015) note that future refugia for multi-year ice associated species will be in the Canadian Arctic and north of Greenland (LIA region) where this ice persists.

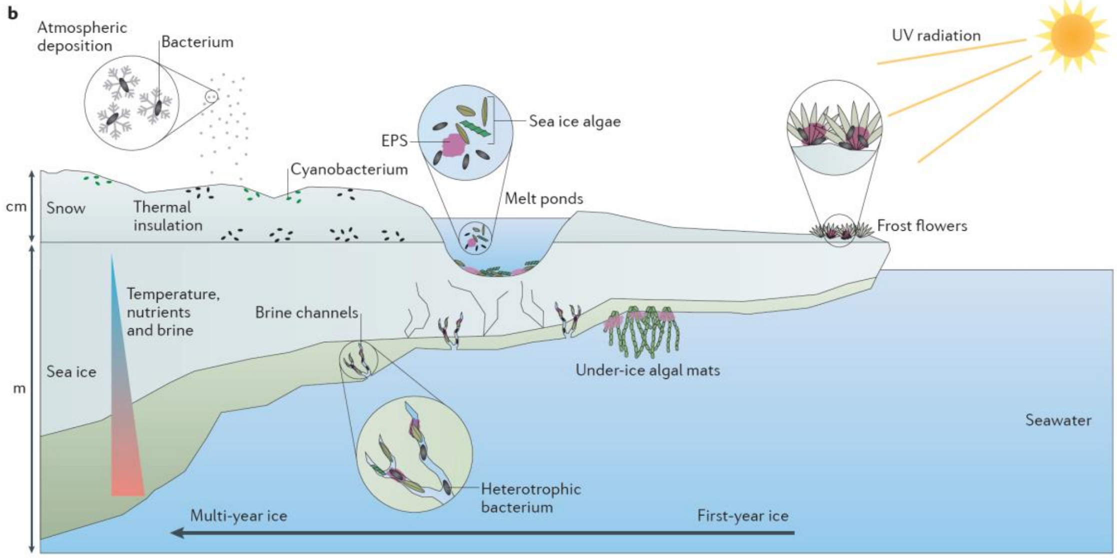


Figure 31. The flourishing life within the briny habitat of sea ice. The ice specific ecosystem includes bacteria, viruses, unicellular algae, diatom chains, worms and crustaceans (from Boetius et al., 2015).

Sea ice is important as a habitat for photosynthetic algae. They can be present on the upper and lower surfaces of the ice as well as in brine channels. In the Arctic, sea ice algae flourish mainly at the ice-water interface, where they are bathed in seawater nutrients to form under-ice algal mats (Kovacs & Michel, 2011; Boetius et al., 2015). Ice algal communities in the Canadian Arctic Archipelago are diverse (Michel et al., 2006). Marine single celled eukaryote (algae and other non-autotrophic organisms) associated with sea ice were recently surveyed and the authors reported 1,027 taxa (Poulin et al., 2011). Many of the invertebrates within the ice feed on ice algae. Invertebrates and fish feed on ice algae on the underside of the ice when the water column does not support phytoplankton growth. Ice algae are grazed by zooplankton when benthic communities release them from the ice cover, and also if they sink to the sediments (Bluhm et al., 2017). Some algal species, such as the diatom *Melosina arctica*, grow meter-long filaments that are not used as food by zooplankton and sink rapidly to the seafloor. A recent cruise reported widespread deposition of this ice algae to the deep seafloor of the central Arctic basins and feeding by opportunistic megafauna (Boetius et al., 2013).

8.3 Water column biodiversity

The open water of the Arctic Ocean harbours a multitude of habitats that include coastal and oceanic regions, downwelling or upwelling areas and polynyas. The water column food web is composed of phytoplankton, zooplankton, bacteria and archaea, and other tiny organisms such as various animal larvae and other floating animals like jellyfish. “Plankton” describes the organisms that are drifting with the currents in contrast to other pelagic organisms that are able to propel themselves (e.g. fish and whales). “Phytoplankton” comprises single-celled algae that mostly photosynthesize and other protists between 0.2 and 200 μm (Poulin et al., 2011). “Zooplankton” are small animals that feed on other zooplankton, phytoplankton or particles of organic matter. Many common phytoplankton and zooplankton species are not Arctic specialists and are also found in other oceans (Bluhm et al., 2011b).

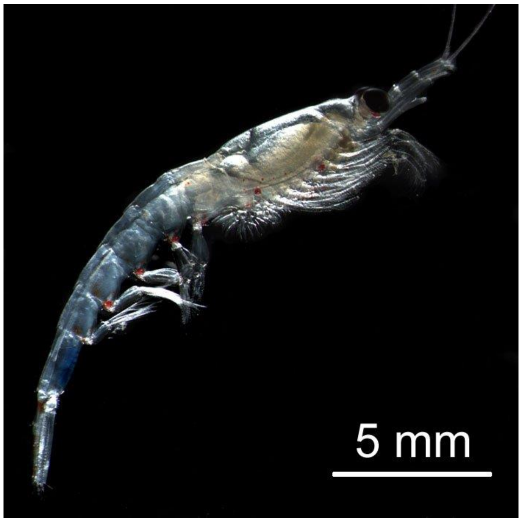
Phytoplankton

A recent pan-Arctic assessment of marine phytoplankton reported 1,874 single-celled types (Poulin et al., 2011). This number is indicative of a well-diversified group of organisms (Poulin et al., 2011). Pennate and centric diatoms, dinoflagellates and prymnesiophytes are the most frequently reported marine phytoplankton groups in the Arctic (Poulin et al., 2011). The vast majority of the identified microorganisms consist of large cells (>20 μm) because of the magnification capability of light microscopy. Recent major technological advances in molecular biology permitted identification of most major groups of marine microbes in the three domains of life (Bacteria, Archaea and Eucarya) in Arctic marine waters (Lovejoy et al., 2011). Communities of phytoplankton are dynamic and change with the seasons (Terrado et al., 2009).

Climate change has already had impacts on phytoplankton communities. Park et al. (2015) note that warming-induced sea ice melting could result in a longer phytoplankton growing season in the Arctic. This increase in Arctic phytoplankton could warm the ocean surface layer through direct biological heating, and amplify positive feedbacks to warming in the Arctic. The warming and freshening of the surface layer could also lead to increased stratification and nutrient depletion. Small picoplankton (<2 µm diameter), have a large surface-area-to-volume ratio that provides effective acquisition of nutrients as well as hydrodynamic resistance to sinking. Hence, these small cells are thriving and displace the larger cells (Li et al., 2009). Increased ice-free conditions may also favour and extend northwardly the intrusion of Atlantic phytoplankton species (Hegseth & Sundfjord, 2008).

Zooplankton

Zooplankton communities are much better characterized than phytoplankton communities. Despite a relatively low sampling effort, they reveal a surprisingly high diversity (Darnis et al., 2012). The inventory of Arctic metazoan (multicellular) zooplankton is around 350 species with nearly 200 species largely restricted to the shelves and 174 listed from the central basins (Bluhm et al., 2011b; Kosobokova et al., 2011). Arctic crustaceans dominate in terms of species number with copepods being the most diverse group, followed by the Cnidaria. However, zooplankton diversity of the Arctic has not been exhaustively characterized (Archambault et al., 2010). Recent evidence indicates increasing reproductive success of Atlantic species (Kraft et al., 2013), and may indicate that physiological effects related to climate change may be shifting functions in the ecosystem (Jørgensen et al., 2015). As climate change modifies oceanographic conditions, the number of zooplanktonic species will likely increase in this region (Archambault et al., 2010).



Arctic krill (Thysanoessa raschii). Photo: Dr. Russell R. Hopcroft, Institute of Marine Science, University of Alaska Fairbanks

Large suspension feeders, such as the copepods *Calanus glacialis* and *Calanus hyperboreus*, dominate the biomass of zooplankton in the Arctic (Darnis et al., 2012). These species feed on large phytoplankton and build huge lipid reserves that are essential for all animals, making them key drivers of the transfer of energy through Arctic marine ecosystems (Jørgensen et al., 2015). These species perform long-range seasonal vertical migrations to depths of several hundred meters where the late developmental stages overwinter (Darnis et al., 2012). Small, numerically dominant copepods (*Oithona similis*, *Triconia borealis*, *Pseudocalanus* spp., and *Microcalanus* spp.) are active year-round and feed opportunistically throughout the winter on variable food sources (Darnis et al., 2012).

8.4 Seafloor biodiversity

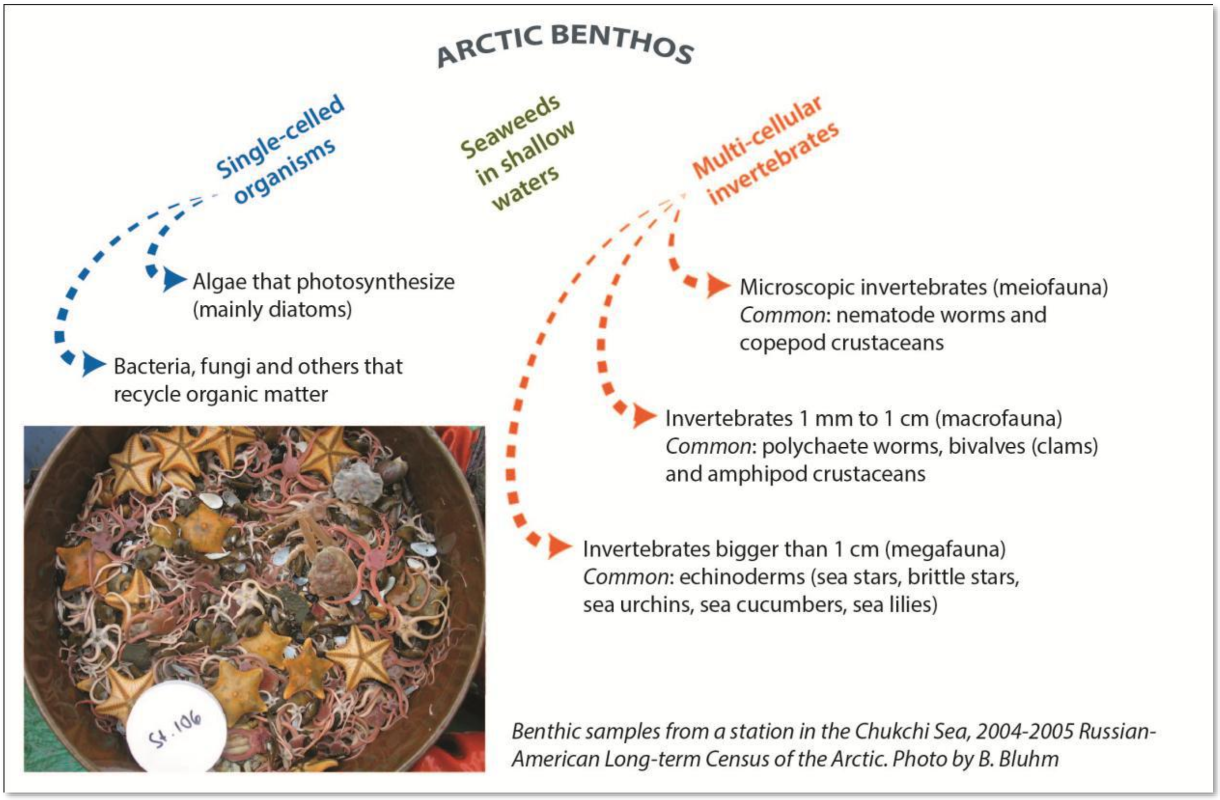
The benthos is the community of organisms dwelling on the seafloor. Arctic benthos range from unicellular life in the spaces among sediment particles to large invertebrates (Figure 32). The Arctic seafloor presents a multitude of habitats that include intertidal areas, fiords, estuaries, an expanded shelf zone, and the deep sea with several basins separated by deep-sea ridges (Josefson & Mokievsky, 2013; Jørgensen et al., 2015). At smaller scales, benthic areas contain different sediment habitats such as sand and mud as well as harder substrates like boulders and bedrocks. Nearshore locations are affected by ice scouring and present impoverished benthic diversity. Macroalgae (seaweed) are found in shallow waters.

Much remains unknown about what species are found in the Arctic benthos, particularly in deep waters, where new species are still being described and where half of the species were observed at only one or two locations (Bluhm et al., 2011a). An inventory of benthic species colonizing the central Arctic deeper than 500 m resulted in 1,125 species (Bluhm et al., 2011a). Crustaceans, foraminifers, annelids and nematodes dominated this inventory. A recent study on macrofauna (large enough to be retained on sieves with a mesh size of 0.5 mm, mostly fauna that live in the mud) and megafauna (larger than 1 cm, mostly live on the surface of the substrate and are visible on seafloor images) colonizing the seafloor of Arctic shelves suggest an intermediate biodiversity (Piepenburg et al., 2011). A total of 2,636 species were listed and the highest species numbers were for crustaceans, annelids, molluscs and echinoderms (Piepenburg et al., 2011). The authors of this work also estimated that the entire benthic macro- and megafauna (excepting fishes) of the Arctic shelves could numbered up to 4,700 species (Piepenburg et al., 2011). It is worth noting that the number of reported benthic species is influenced by the sampling methods and the sampling frequency. Notably, the Canadian Archipelagos have not been compiled due to lack of data (Jørgensen et al., 2015). Bacteria and algae (in shallow waters) are also present on the seafloor (Bluhm et al., 2011b).

Most benthic communities are supported by the food supplied from the water column. Plankton, ice algae, and organic matter sink through the water column and fuel benthic food webs (Bluhm et al., 2017). Amounts of phytoplankton and zooplankton production and the timing of algal blooms and peak zooplankton production are important to determine the coupling of the benthic and pelagic communities (see section 8.1). The location, timing and duration over which food from the water column drifts to the seafloor affects the distribution and biomass of benthic communities. For instance, the North Water (NOW) polynya has high primary production and tends to be associated with enriched benthic biomass due to a longer period over which the benthos receive food (Darnis et al., 2012; Grant et al., 2002). The macrofauna and megafauna of the Arctic shelves provides major feeding grounds for fishes, mammals and seabirds.

It is expected that the benthic fauna may show increased diversity, due to a combination of anticipated increased food availability and immigration of faster-growing species adapted to warmer waters in the southern areas of the Arctic (Josefson & Mokievsky, 2013; Caron et al., 2017). Moreover, fisheries of commercially relevant species might become more important in the LIA. Commercial shrimp fisheries for Northern (*Pandalus borealis*) and striped (*Pandalus montagui*) shrimp began in the late 1970s off Baffin Island and expanded southward to the area of Resolution Island (Hudson Strait) in the mid-1990s, where the main fishery remains to date (DFO, 2008). The

Northern shrimp is the most important marine resource in Greenland, and represents 70% of the total fisheries revenues (Dahl-Jensen et al., 2011). The snow crab fishery is also important in Greenland (Boertmann et al., 2009). Increased fisheries pressure of course can have a negative impact on the seafloor structure and benthic communities due to passage of fishing gears and frequent by-catch (Jørgensen et al., 2015).



Benthic samples from a station in the Chukchi Sea, 2004-2005 Russian-American Long-term Census of the Arctic. Photo by B. Bluhm

Figure 32. Arctic seafloor diversity (CAFF, 2013b).

8.5 Fish

Nearly 250 marine fish species are known from the Arctic Ocean, but this number rises to 633 fish species if the adjacent Arctic seas are included (Christiansen & Reist, 2013). These 633 species represent 2.2% of the fish species on the planet (Christiansen & Reist, 2013). Of these, 63 species are restricted to Arctic waters (Christiansen & Reist, 2013). Additionally, approximately 92% of Arctic species are bony fishes (bony skeleton), and only 8% are cartilaginous fishes (skeleton is entirely or mostly made from cartilage) like sharks and skates (Lynghammar et al., 2013). Polar seas are considered species-poor compared with more temperate latitudes. Most Arctic marine fishes are living on or closely associated with the seafloor (benthic and demersal fish respectively).

Two species are ecologically dependent on sea ice, using it as habitat, protection from predators and a place to spawn: Arctic cod (*Boreogadus saida*, also called polar cod) and ice cod (*Arctogadus* *glacialis*) (Christiansen & Reist, 2013). Arctic cod is considered a keystone species and is particularly abundant and widespread in marine waters throughout the Arctic (Christiansen & Reist, 2013). Conversely, the ice cod is much less abundant and is primarily found in fiords and Arctic shelves (Christiansen & Reist, 2013). Arctic cod are the dominant fish on the Arctic shelves and the central element of the pelagic food web of the Arctic Ocean (Welch et al., 1992). They feed mainly on copepods, amphipods and mysids (small shrimp-like animals), and they play a key role in the diet of many Arctic marine mammals, seabirds and fish. The distribution of Arctic cod varies seasonally in habitats ranging from coastal brackish waters to regions deeper than 200 m, and from just above the seafloor to under sea-ice habitat. They can occur in a dispersed state all year round but schools often appear in nearshore waters during summer (Welch et al., 1992). Large schools of Arctic cod are present at the productive ice edge during late spring-early summer where they would hide from predators (Gradinger and Bluhm, 2004) and to feed on zooplankton and other ice-associated taxa (Bradstreet & Cross, 1982). They can conduct large horizontal displacement to find more favourable habitat in the winter months, such as migrating from shallow west depths of the Barrow Strait to the deeper and warmer depths (under ice cover) in the west (Kessel et al., 2017). Arctic cod is also dependent on zooplankton for food. The changes in sea ice will likely impact the developmental life cycles of zooplankton and thereby influence the diet composition of Arctic cod. Northward shifts in marine boreal fish distribution have already been documented as a consequence of climate warming (Renaud et al., 2012; Hollowed et al., 2013). Fossheim et al. (2015) note that recent warming in the Barents Sea has led to a change in spatial distribution of fish communities, with boreal communities such as Atlantic Cod (*Gadus morhua*) and Haddock (*Melanogrammus aeglefinus*) expanding northwards. They term this the “borealization” of the Arctic ecosystem and note that in the near future, Arctic fish species will face increased competition from boreal species and thus retract northwards.

An 11-foot Greenland shark, Somniosus microcephalus, and an ice ledge, Arctic Bay, Baffin Island, Northwest Territories, Canada © National Geographic Stock / Nick Caloyianis / WWF

Other common marine fish species include the Greenland halibut (*Reinhardtius hippoglossoides*), Sculpins (Cottidae), and the Greenland shark (*Somniosus microcephalus*). The Greenland halibut is a subarctic and Arctic species and occurs in deep water along continental slopes. It is a flatfish but lives and feeds mainly in the water column. Sculpins are benthic fishes that occur mostly in shallow waters. Their pectoral fins (i.e. fins located on each side of the body) are smooth on the upper edge and webbed with sharp rays along the lower edge, which make them well adapted for gripping the seafloor substrate. Sculpins are an important food source for other fishes but are not consumed by humans. The Greenland shark is the northernmost species of shark and is native to the North Atlantic Ocean and waters around Greenland and Iceland. This shark species is large (up to 7 m in length), and feeds mostly on other fish but occasionally on seals as well. Greenland sharks occupy deep environments where the temperature is cold and they swim very slowly (Campana et al., 2015). The flesh of this shark is poisonous unless it is boiled in several changes of water, dried or fermented.

Herring and Greenland halibut are important for subsistence fishing in the Canadian Archipelago (Niemi et al., 2010) and essential to the economy of Greenland (Tejsner & Frost, 2012). Greenland halibut has been fished commercially since 1986 in Cumberland Sound (in southwest Baffin Island) (see references in Niemi et al., 2011) and around Greenland (Kovacs & Michel, 2011). This Arctic species is expected to decline in response to warming temperatures (Albert & Høines, 2003).

The impacts of climate change and of Arctic fisheries on Arctic marine fish will act in concert. New commercial fisheries in the Arctic are imminent and they will affect species of boreal origin that are already commercially harvested, and fishes native to Arctic waters (Christiansen & Reist, 2013). As previously mentioned, boreal fish species like Atlantic cod are projected to spread northward, which could lead to greater populations and enhanced fisheries values (Christiansen & Reist, 2013; Drinkwater, 2005). There are currently 59 species that are fished in the Arctic and sub-Arctic waters (Christiansen & Reist, 2013). Demersal fish are collected by bottom trawls, affecting significantly the sea bed and producing considerable bycatch of non-targeted fish (species and sizes not desirable by the industry) (Christiansen & Reist, 2013). The LIA region may become more important for several marine fish species. However, while enhanced primary productivity could result in increased fish harvests for Northerners, it will probably be insufficient to sustain large-scale commercial fisheries in the Canadian Arctic (Tremblay et al., 2012).

8.6 Marine mammals

Eleven marine mammal species (including three cetaceans, seven pinnipeds and the polar bear) live in the Arctic all year long and many other species occupy Arctic waters seasonally (see Appendix II) (Laidre et al., 2015). Arctic marine mammals use several specific types of ice habitats and feed on diverse food sources (Table 2). Changes in the Arctic climate may challenge the adaptive capacity of these species. Sea ice plays a crucial role for these animals either as a platform, marine ecosystem foundation or as a barrier to non-ice-adapted marine mammals and human commercial activities (Moore & Huntington, 2008). A clear example is that reduction in sea ice cover removes the hunting platform of polar bear and likely reduces the survivorship of their primary prey, the ringed seal (Kovacs et al., 2011). The fitness of Arctic marine mammals is therefore influenced by changes to the dynamic balance among sea ice effects on ecosystem structure and prey availability.

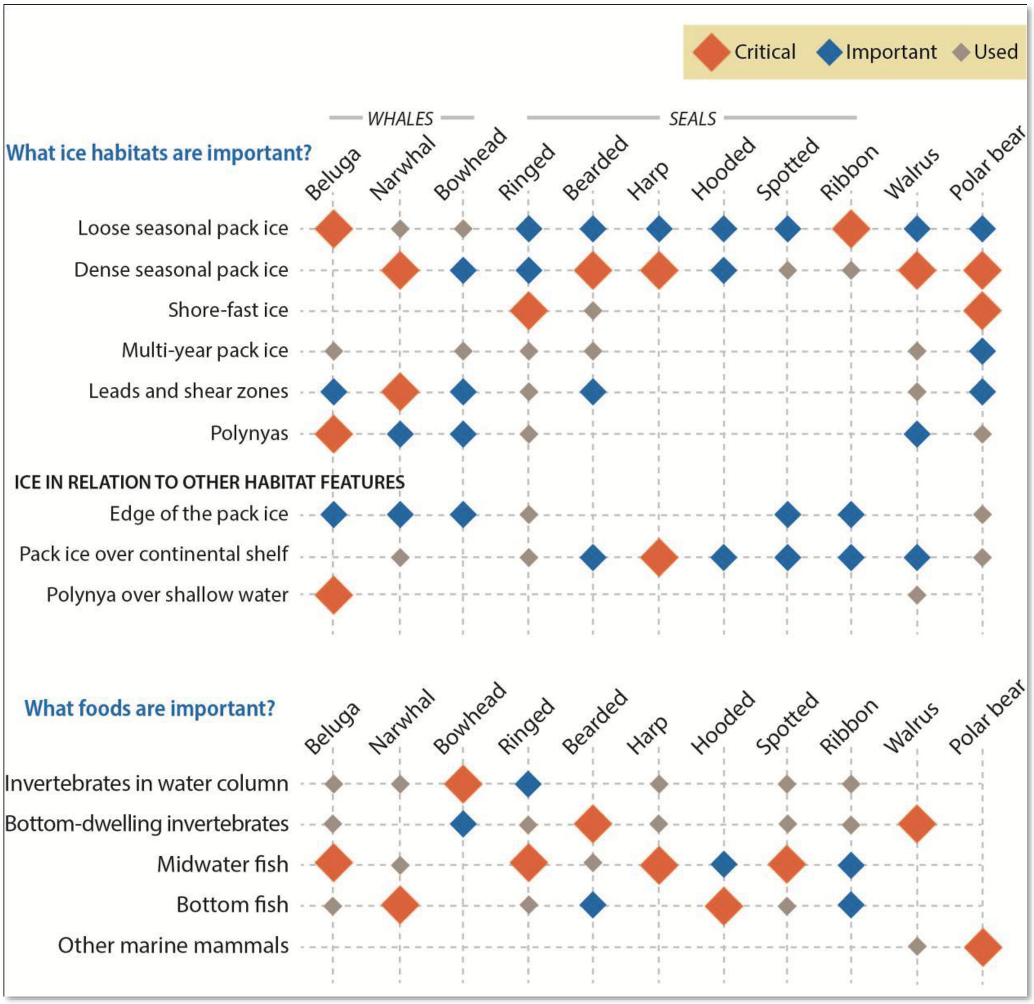
One approach to quantify marine mammal resilience to climate change is to classify them with regard to the species relationship to the ice (Figure 33; Moore & Huntington, 2008). Polar bear, walrus, bearded seal and ringed seal are classified as ice-obligate species since they are reliant on sea ice as a platform for resting, breeding or hunting (Kovacs et al., 2011; Laidre & Regehr, 2017). Harp seal, hooded seal, ribbon seal, spotted seal, beluga, narwhal and bowhead whale are ice-associated species since they are adapted to marine ecosystems of which ice is predominant. Fin, minke, humpback, gray and killer whales are seasonally migratory species that encounter sea ice in parts of their migration (Laidre et al., 2008). Ice-obligate species are especially vulnerable to changes in the sea ice cover (Moore & Huntington, 2008; Kovacs et al., 2011). The scenario for ice-associated species is harder to predict but decreases in the sea ice cover will have negative impacts on these species (Figure 33), except perhaps reduced risk of sea ice entrapment (Moore & Huntington, 2008). The five migrant whale species are likely to benefit from loss in sea ice since the pelagic system will be more accessible (Kędra et al., 2015).

Another approach to assess the sensitivity of marine mammals to climate change is to use an index that includes the species' narrowness of distribution and specialization of feeding in addition to the seasonal dependence on sea ice and reliance on sea ice as a platform to access prey and predator avoidance (Laidre et al., 2008). This index suggests that the hooded seal, the polar bear, and the narwhal are the three most sensitive Arctic marine mammal species, primarily due to reliance on sea ice and specialized feeding. The least sensitive species were the ringed seal and bearded seal, primarily due to large circumpolar distributions, large population sizes, and flexible habitat requirements.

Overall, climate change is forecast to have serious negative impacts on Arctic marine mammals by altering the seasonal patterns, the extent and the quality of sea ice habitat (Laidre & Reghr, 2017). Species seasonally occupying the Arctic might stay north longer, and compete for food resources with existing Arctic species (Laidre et al., 2008). Also, temperate marine mammals are expanding their distribution northward, which are likely to cause competitive pressure on Arctic endemic species and to put them at greater risk of predation, disease and parasite infections (Kovacs et al., 2011).

Since the LIA is predicted to hold the last remaining ice during summer, the area may become increasingly important for ice-obligate and ice-associated marine mammal species. This is why WWF scientists are in discussion with Inuit and governments located in the LIA region in order to plan the future management of this area to ensure the resilience of all life forms dependent on sea ice. A recommendation of the Arctic Biodiversity Assessment (CAFF, 2013a) states the importance of developing and implementing mechanisms to conserve Arctic biodiversity under the deteriorating trend of sea ice, glaciers and permafrost.

Table 2. The diversity of ice habitats and prey items for Arctic marine mammals species (from CAFF, 2013).



🔶 Critical 🔷 Important ◆ Used

	WHALES			SEALS						
What ice habitats are important?	Beluga	Narwhal	Bowhead	Ringed	Bearded	Harp	Hooded	Spotted	Ribbon	Walrus	Polar bear
Loose seasonal pack ice	🔶	◆	◆	🔷	🔷	🔷	🔷	🔷	🔶	🔷	🔷
Dense seasonal pack ice		🔶	🔷	🔷	🔶	🔶	🔷	◆	◆	🔶	🔶
Shore-fast ice				🔶	◆						🔶
Multi-year pack ice	◆		◆	◆	◆					◆	🔷
Leads and shear zones	🔷	🔶	🔷	◆	🔷					◆	🔷
Polynyas	🔶	🔷	🔷	◆						🔷	◆
ICE IN RELATION TO OTHER HABITAT FEATURES											
Edge of the pack ice	🔷	🔷	🔷	◆				🔷	🔷		◆
Pack ice over continental shelf		◆		◆	🔷	🔶	🔷	🔷	🔷	🔷	◆
Polynya over shallow water	🔶									◆	

What foods are important?	Beluga	Narwhal	Bowhead	Ringed	Bearded	Harp	Hooded	Spotted	Ribbon	Walrus	Polar bear
Invertebrates in water column	◆	◆	🔶	🔷		◆		◆	◆		
Bottom-dwelling invertebrates	◆		🔷	◆	🔶	◆		◆	◆	🔶	
Midwater fish	🔶	◆		🔶	◆	🔶	🔷	🔶	🔷		
Bottom fish	◆	🔶		◆	🔷		🔶	◆	🔷		
Other marine mammals										◆	🔶

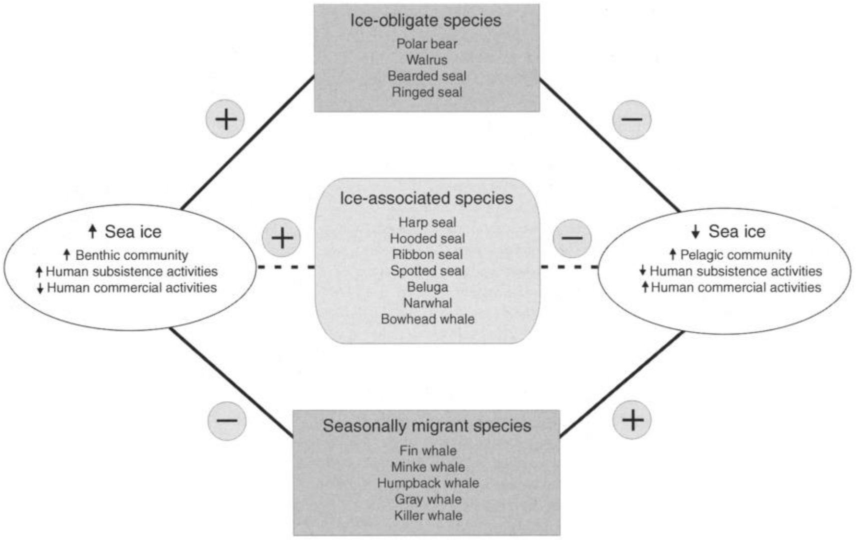


Figure 33. Conceptual model of sea ice impacts on ice-obligate, ice-associated and seasonally migrant marine mammals. Positive impacts are indicated by (+) signs and negative impacts by (-) signs. From Moore & Huntington (2008).

Cetaceans

Only three species of cetacean live year round in the Arctic. These are: the bowhead whale (large baleen whale), the beluga (middle-sized toothed whales) and the narwhal. The bowhead whale and the beluga have a circumpolar distribution while the narwhal only occupies the Atlantic sector of the Arctic (Figure 34; Reeves et al., 2013). Thirteen other whale species (baleen whales: blue, fin, sei, humpback, minke, North Atlantic right and gray whales; toothed whales, sperm, Sowerby’s beaked and killer whales, Atlantic white-sided and white-beaked dolphins, and harbour porpoise) seasonally occupy Arctic and Subarctic waters. The loss of summer sea ice cover is allowing an increasing number of killer whales to use the Canadian High Arctic as a hunting ground (Darnis et al., 2012), and may be forcing narwhal to redistribute closer to shore where they are presumably less vulnerable (Breed et al., 2017). The stronger presence of this apex predator species is also likely affecting the populations of the bowhead and beluga whales (Higdon & Ferguson, 2009). The three Arctic whale species are described in the following paragraphs.

Bowhead whale © naturepl.com M. Holmes WWF-Canon

Bowhead whales (*Balaena mysticetus*) measure between 15 and 18 m and weigh up to 100,000 kg. They live in Arctic waters during summer but migrate to Subarctic seas during winter (Laidre et al., 2008). This whale species occurs within the LIA region in Baffin Bay and in the eastern side of the Canadian Arctic Archipelago (Figure 34a). The pre-whaling population of bowhead whales has been estimated at about 50,000 individuals (COSEWIC, 2009). Commercial whaling ended around 1910 and reduced the population to less than 3,000 animals. From this low point, populations have recovered to approximately 25000 individuals worldwide and are subject to limited hunting by Canadian Inuit and Greenlanders (Laidre et al., 2015). The population abundance of the Eastern Canada West Greenland stock is estimated at around 7660 individuals (Frasier et al., 2015). The bowhead whale is listed as “least concern” on the IUCN Red List, since the population appears to be increasing (Reilly et al., 2012); however, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) lists it as “special concern” (COSEWIC, 2009). This whale species is well adapted to ice-covered waters and can move through areas of nearly solid ice cover. They prefer areas of low ice coverage in winter, presumably to reduce risk of ice entrapment while remaining within the ice (Ferguson et al., 2010). In contrast, during summer, these whales select high ice coverage regions to reduce risk of killer whale predation while providing enriched feeding opportunities (Ferguson et al., 2010). The Hudson Strait may be an important wintering ground for Baffin Bay bowhead whales (Heide-Jørgensen et al., 2006), but they also inhabit polynyas and the marginal ice zone during winter and early spring, feeding on zooplankton throughout the water column (Laidre et al., 2008).

Beluga © K. Schafer WWF-Canon

Beluga whales (*Delphinapterus leucas*) or white whales occur in estuaries, at the continental shelves and in deep ocean basins. They measure between 4 and 6 m and weigh between 900 and 1,300 kg. Beluga whales are divided into 19 discrete populations around the Arctic, depending on their summering (fiords or estuaries, to which they show high fidelity) and wintering (shallow or coastal areas) grounds (see references in Laidre et al., 2008, 2015; Figure 34b). Ice edges serve as important feeding grounds for belugas as their primary prey is Arctic cod (Laidre et al., 2008). The global population estimate is well over 150,000 animals and has been divided into 29 different populations (or stocks) by the International Whaling Commission (Jefferson et al., 2012a). DNA studies have indicated genetic differences between some of the populations (de March & Postma, 2003). Two populations are present within the LIA for at least parts of the year: the North Water winter (North Baffin Bay) stock, with an estimated population size of 21,213 belugas (based on 1996 surveys by Innes et al., 2002), and the West Greenland winter stock, with an estimated population size of 10,595 (based on 2006 surveys from Heide-Jørgensen et al., 2010). This species is listed as “near threatened” on the IUCN Red List because there is large uncertainty about population numbers and trends over parts of the species range, and because its survival relies on national and international conservation programs that monitor and manage hunting (Jefferson et al., 2012a).

The different populations of belugas are subject to different levels of threat which call for individual assessments (Jefferson et al., 2012a). Hauser et al. (2016) report that Chukchi belugas migration timing is occurring later than past trends due to delayed regional sea ice freeze-up timing in the Beaufort, Chukchi and Bering Seas. However, this trend was not observed for Beaufort belugas in the same time period. Thus, it still remains uncertain how belugas migration timing will respond to changing ice conditions in the future.

Narwhals. © P. Nicklen National Geographic Stock / WWF-Canada

Narwhals (*Monodon monoceros*) are medium sized (4 to 6 m, 1,600 kg) toothed whales that occupy waters of the eastern Canadian Arctic Archipelago, West and East Greenland, Svalbard and Franz Joseph Land (Figure 34c). They are the most ice-associated whale, and are highly dependent on leads and cracks in the ice during migrations (Laidre et al., 2008). They are also the Arctic whale with the most restricted distribution; however, they are widely present in the LIA region, forming large aggregates in the winter to feed predominantly on Greenland halibut (Watt et al., 2013).

Narwhals perform annual migrations over long distances. During summer (June-September), Baffin Bay narwhals migrate to northeastern fiords and inlets in Canada as well as north-western inlets of Greenland (Watt et al., 2016). They overwinter in offshore, deep, ice-covered habitats along the continental slope in more southern locations such as the Davis Strait (Heide-Jørgensen & Dietz, 1995). Narwhals feed mainly during winter on benthic organisms and Greenland halibut in offshore deep ocean basins (Laidre et al., 2008). The narwhal is listed as "near threatened" on the IUCN Red List, although there is uncertainty about numbers and trends in large parts of the species range and evidence of decline for specific subpopulations (Jefferson et al., 2012b). A Canadian 2013 survey estimated the total population to be greater than 80,000 individuals (Doniol-Valcroze et al., 2015). Within the LIA there are three Canadian stocks: Somerset Island (45,768 individuals), Jones Sound (12,694 individuals) and Smith Sound (16,360 individuals) (Doniol-Valcroze et al., 2015). On the Greenland side, there are the Inglefield Bredning (8000 individuals) and Meliville Bay (6000 individuals) stocks (Heide-Jørgensen et al., 2013).

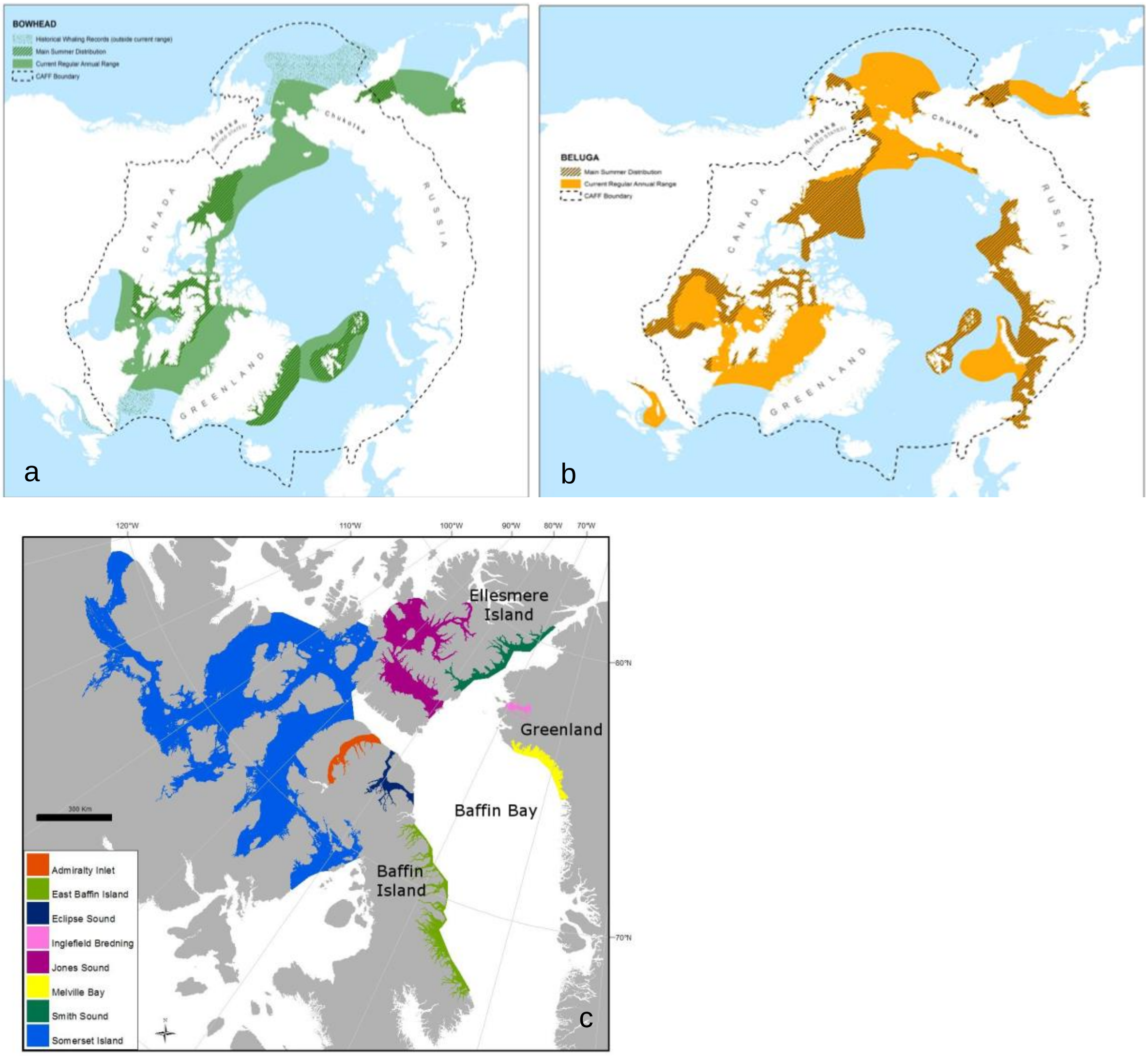


Figure 34. Distribution of a) bowhead whales,(Reeves et al., 2013 b) belugas and (Reeves et al., 2013) c) narwhals (Doniol-Valcroze et al., 2015).

Pinnipeds

Arctic ice-associated pinnipeds with a circumpolar distribution are the ringed seal, the bearded seal and the walrus (Laidre et al., 2008). Other seal species that can be found in Arctic waters are the spotted seal, the harp seal, the ribbon seal and the hooded seal (Greenland Institute of Natural Resources, 2012; Laidre et al., 2008). These latter species depend on sea ice only for some parts of their life cycle, especially for birthing, molting, mating and resting during spring. In contrast to Arctic ice-associated species, they do not occupy the Arctic year round and rely on sea ice only seasonally (Stenson & Hammill, 2014). The ribbon seal and the spotted seal only occur in the North Pacific and peripheral seas (Bering, Chukchi and Okhotsk seas) while the harp seal and the hooded seal are distributed throughout the Northwest Atlantic (Greenland Institute of Natural Resources, 2012; Laidre et al., 2008). The three Arctic ice-associated seal species found year round in the Arctic occur within the LIA region, but only ringed seals are reported to occur along the northern coastline of the Canadian Archipelago and Greenland (Figure 35). These species are briefly described in the next paragraphs.

Ringed seal. © WWF-Canon S. Kinnerød

The ringed seal (*Pusa hispida*) is the most common and widely dispersed marine mammal of the Arctic. It is the smallest of the seal species (up to 1.65 m and up to 70 kg) (Kovacs et al., 2011), and gets its name from the light-coloured circular patterns that appear on their darker grey back (Hammill, 2009). It has a circumpolar distribution (Figure 35a) and is the only seal species that is able to occupy large areas of consolidated sea ice, since they are able to maintain breathing holes (Norwegian Polar Institute, 2013). They are dependent on sea ice for all aspects of their lives: for giving birth, as a staging area for breeding, for moulting, resting and aquatic predator avoidance (Norwegian Polar Institute, 2013). Landfast ice over the continental shelves would be their favoured habitat for breeding and giving birth (Laidre et al., 2008). The ringed seal is listed as “least concern” on the IUCN Red List (Kovacs et al., 2008). Five subspecies are recognized: Arctic Ringed Seal (*P. h. hispida*), Baltic Sea Ringed Seal (*P. h. botnica*), Lake Ladoga Ringed Seal (*P. h. ladogensis*), Lake Saimaa Ringed Seal (*P. h. saimensi*), and Sea of Okhotsk Ringed Seal (*P. h. ochotensis*). The global population estimate would be between 3 and 8 million but the population size of the different subspecies varies greatly (Kovacs et al., 2008). Climate change, contaminants and bycatch in fishing gear are the current threats to this species (see references in Kovacs et al., 2008). Ringed seals feed on Arctic cod and a variety of large zooplankton (crustaceans) under the ice or in the first 50 m of the water column (Laidre et al., 2008). They are a keystone species in the Arctic since they compose the majority of the polar bear diet, especially in spring, and they are a major food source for Arctic communities (Norwegian Polar Institute, 2013).

Bearded Seal. © Wild Wonders of Europe O. J. Liodden WWF

The bearded seal (*Erignathus barbatus*), named so because of their long whiskers, measure between 2.0 and 2.5 meters and weigh between 260 and 360 kg. They have a circumpolar distribution and two subspecies of bearded seals are widely recognized: *E.b. barbatus* in the Atlantic sector, and *E.b. nauticus* in the Pacific sector (Figure 35b). Only the subspecies *E. b. barbatus* can be found with the LIA, and are usually found in shore leads or polyyas. A minimum estimate for Canadian waters of 190,000 animals was suggested by Cleator (1996), but Laidre et al., (2015) estimates the global abundance to range from 500,000 to 750,000 animals. The species is also listed under the category of "least concern" on the IUCN Red List (Kovacs & Lowry, 2008). Bearded seals are found mainly over the shallower waters of the continental shelves and usually in association with moving ice or leads and polynyas (Laidre et al., 2008). The seasonal movements and distribution of bearded seals are linked to seasonal changes in ice conditions. The seals generally move north in late spring and summer, as the ice melts and retreats, and move south in the fall, as sea ice reforms to remain associated with their preferred ice habitat. Bearded seals are closely associated with sea ice, particularly during the critical life history periods related to reproduction and moulting, and they can be found in a broad range of different ice types (see references in (Cameron et al., 2010). Ice provides a platform on which the seals haul out, bear and nurse pups, and rest and moult. Bearded seals feed primarily on benthic organisms that include epifaunal (are attached to substrates) and infaunal (live in the substrate/ soft sea bottom) invertebrates and demersal fishes (fish that live near the seafloor). Polar bears and walruses are the main predators of bearded seals (Laidre et al., 2008).

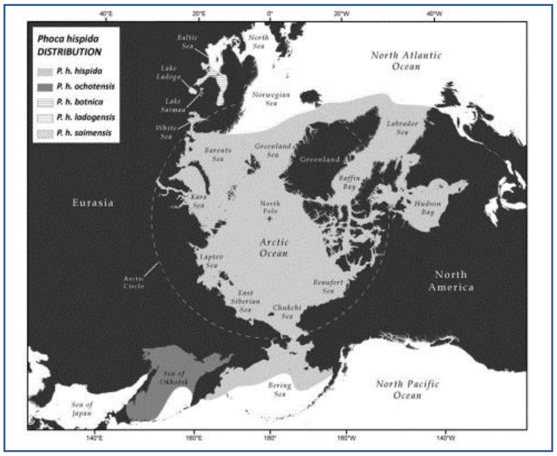
Walrus (*Odobenus rosmarus*) is the largest species of pinniped in the Arctic, measuring between 3.0 and 3.6 meters and weighing between 600 and 2,000 kg. Walruses have a discontinuous circumpolar Arctic and Subarctic distribution (Figure 35c). Two subspecies are distinguished: the Pacific walrus (*Odobenus rosmarus divergens*) and the Atlantic walrus (*Odobenus rosmarus rosmarus*), with a divergent group within the pacific subspecies called Laptev walrus (*Odobenus rosmarus laptevi*) (unpublished data). Only the Atlantic subspecies is found within the LIA. The population estimates that are available have a low precision (Lowry et al., 2008). Nevertheless, the Pacific population is estimated at around 135 000 individuals (Laidre et al. 2015). Within the Canadian Arctic Archipelago, there are three recognized stocks of Atlantic Walrus: Baffin Bay (1251 individuals in 2009), West Jones Sound (470 individuals in 2009) and Penny Strait-Lancaster Sound Stock (727 individuals in 2009) (Stewart et al. 2014; Stewart et al. 2015), Additionally, approximately 1408 Atlantic walrus were documented in West Greenland in 2012

(Witting and Born, 2013) The walrus was once threatened by commercial hunting but today the biggest danger it faces is climate change. It is currently listed under the category of "data deficient" in the IUCN Red List (Lowry et al., 2008).

Walrus. Photo: Tom Arnbom / WWF

Walruses in the Atlantic display sex-specific distribution and movement patterns. Females with young and males move to separate areas during summer but they occupy the same areas during winter (see references in Laidre et al., 2008). Walruses show high fidelity to their terrestrial haul-out sites (beaches on islands or remote stretches of mainland coastlines) and wintering areas from year to year (Laidre et al., 2008). They can overwinter close to polynyas (including the North Water Polynya) that provide access to seafloor food resources. All subspecies of walruses are found in relatively shallow continental shelf areas and seldom occur in deep waters (maximum of 200 m). They are benthic feeders and shallow divers; they generally feed on molluscs and other invertebrates in depths around 20-30 m. In response to the earlier and more extensive sea ice retreat in June to September, Pacific walruses have been reported to arrive earlier and occupy more northern areas of the continental shelf than in the past (Jay et al., 2014). This also allows them to forage near shore areas in contrast to offshore foraging in the past.

A



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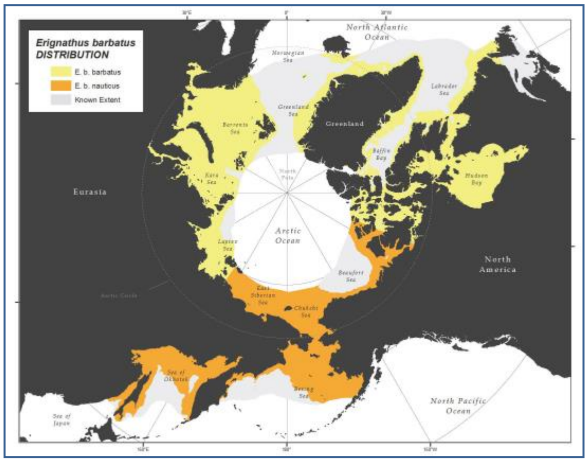


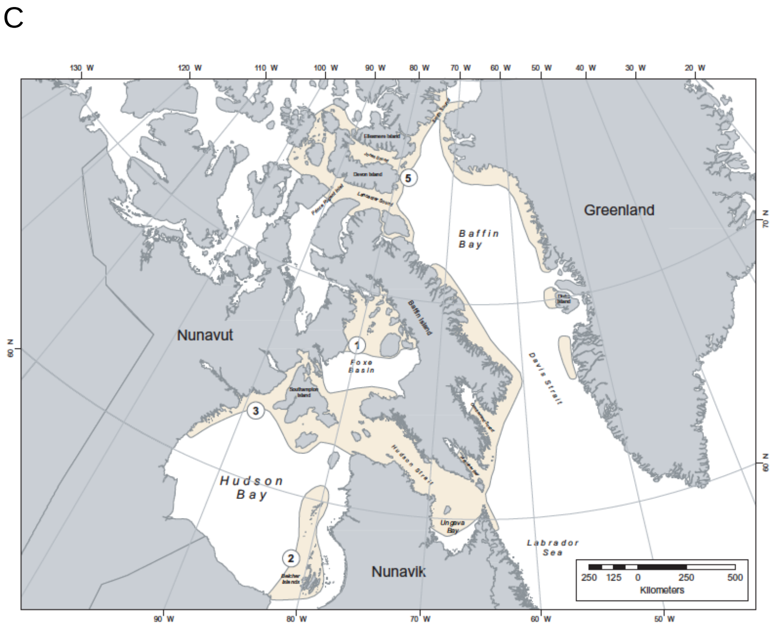


Figure 35. Distribution of a) ringed seals (Kelly, 2001), b) bearded seals (Cameron et al., 2010) and c) walrus (Stewart, 2008).

Polar bear

Polar Bear © Geoff York

Polar bears (*Ursus maritimus*) are an iconic Arctic species. They are considered marine mammals because they live predominantly on the sea ice throughout the Arctic. They are an ice-obligate species, using the sea ice as a platform for hunting seals. Polar bears are 2-3 m in length and can weight up to 680 kg. They have a circumpolar distribution (Figure 36) and are found mainly in areas of annual ice cover over the continental shelf and the inter-island channels of various archipelagos (Durner et al., 2009). Polar bears prefer to forage on seasonal sea ice (due to greater hunting opportunities) but will also use multiyear sea ice in the summer so that they do not need to wait as long for new ice to form (Hamilton et al. 2014; Pilford et al. 2014). In more southern locations, such as Hudson Bay and Davis Strait, where annual ice melts completely, bears are forced on land where they remain until freeze up in the late fall or early winter, surviving on stored reserves from hunting seals (Obbard et al., 2016). Polar bears have annual movement patterns within their home ranges and they show high fidelity to denning and spring feeding areas (Wilson et al., 2016; McCall et al., 2016). Sea ice also facilitates seasonal movements, mating, and in some cases, maternal denning (Auger-Méthé et al., 2016). They are opportunistic hunters, and feed mainly on ringed and bearded seals but they also eat belugas, narwhals and walruses (Laidre et al., 2008). They can also feed on land, eating eggs, berries, and whatever they can scavenge.

The global polar bear population is divided into 19 subpopulations (Figure 36) and four ecological regions have been described (Figure 37). This species is listed as "vulnerable" on the IUCN Red List with an estimated global population size of 25,000 individuals, and certain regions are seeing a decline in population trends (Obbard et al., 2010). In 2008, the polar bear was listed as a species of "Special Concern" under the Federal Species at Risk Act of Canada (Government of Canada, 2013c). Out of the 19 subpopulations, one (Southern Beaufort Sea) is considered to be declining in numbers, but many more are of unknown status due to difficulty in surveying such widespread distributions in remote marine areas (Vongraven & York, 2014; Laidre et al., 2015). Recent surveys actually indicate that Kane Basin and Baffin Bay populations are increasing (SWG, 2016). The main threat to the polar bears long-term survival is the loss of sea ice habitat (Stirling & Derocher, 2012; Hamilton et al., 2014). The critical feeding time occurs in late spring and early summer, when they feed on ringed seal pups that are born in early April and weaned about six week later. At that time, pups are up to 50% fat, naïve about predators and accessible from the surface of the ice. After the ice break-up, seals are mostly inaccessible to the bears. A reduced extent in sea ice and an earlier sea ice break-up in spring results in less time to access prey, longer periods of fasting, less healthy body condition and lower survival of cubs (Rode et al., 2010; Stirling & Derocher, 2012; Hamilton et al., 2014). While all bear species have adapted to changes in their environment in the past, the adaptive capacity of polar bears is limited since they are highly specialized for life in the Arctic, and they exhibit low reproductive rates with long generational spans.

Reductions in sea ice may force polar bears to redistribute geographically (Chen et al., 2011). During sea ice minimums, Rode et al. (2015) report observations of individuals from the Foxe Basin and Hudson Bay subpopulations retreating inland and supplementing their diet with terrestrial foods such as eggs and adults of murres and common eiders. This lead to complete reproductive failure at some of these bird colonies (Iverson et al., 2014). These sources of food do not satisfy the energy requirements for a polar bear like lipid rich marine mammals do. Thus, the nutritional contribution of terrestrial foods to polar bear diets will probably remain negligible, and in fact, this behaviour could have important ecological consequences for local bird populations.

The pace of Arctic sea ice habitat loss may be too fast for polar bears to adapt. Projections of polar bear habitat losses for this century are the greatest in the southern seas of the polar basin (e.g. Chukchi and Barents seas) and least along the Arctic Ocean shore included in the LIA region, from Banks Island to Greenland (Durner et al., 2009). On the basis of these projected losses in essential habitats and if climate warming continues, a research team argued that two thirds of the global polar bear population could disappear by 2050 (Amstrup et al., 2008). For the other third, the LIA is likely to be prime habitat. The Canadian Arctic Archipelego and Greenland are thought to have the greatest likelihood of sustaining polar bears to the end of the 21st century (Amstrup et al., 2008; Hamilton et al., 2014). A global coordinated monitoring framework of polar bear subpopulations is proposed as this would provide a better circumpolar understanding of ongoing patterns and future trends in polar bear subpopulations, and would improve the monitor of the effects of stressors on polar bears (Vongraven et al., 2012).

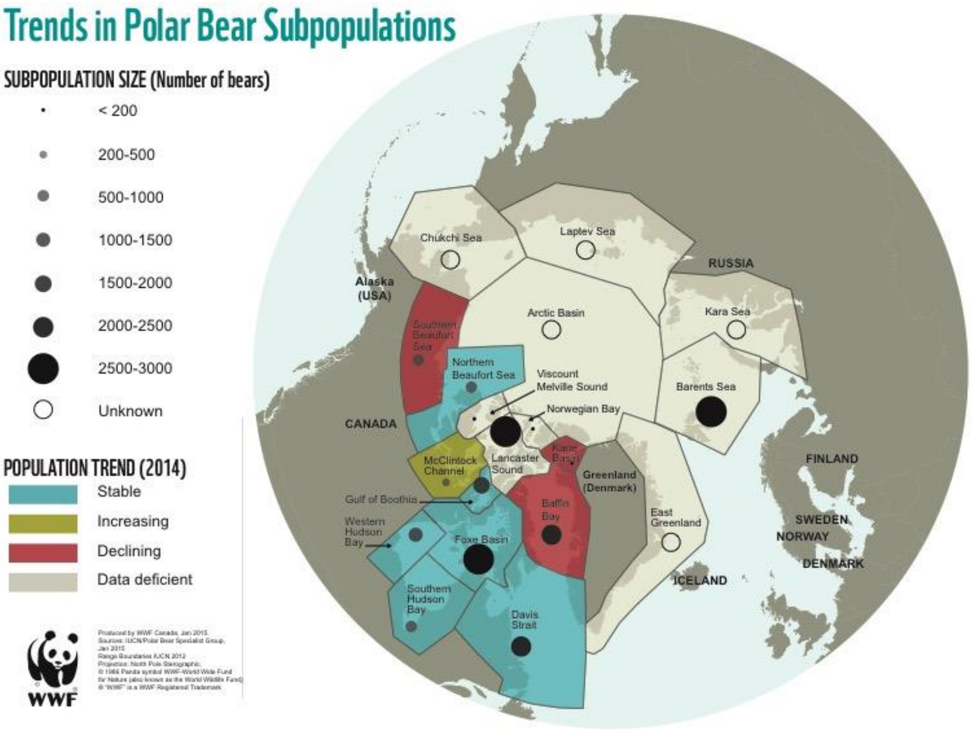


Figure 36. Map of location, size and trends of polar bear subpopulations between 2010-2014 (WWF, 2015). Data from Canada's Polar Bear Technical Committee. Foreign country sub-population status provided by the IUCN/SSC Polar Bear Specialist Group. Note that recent surveys indicate that the subpopulations of the Kane Basin and Baffin Bay are increasing; however, their status has not yet been officially changed (SWG, 2016)

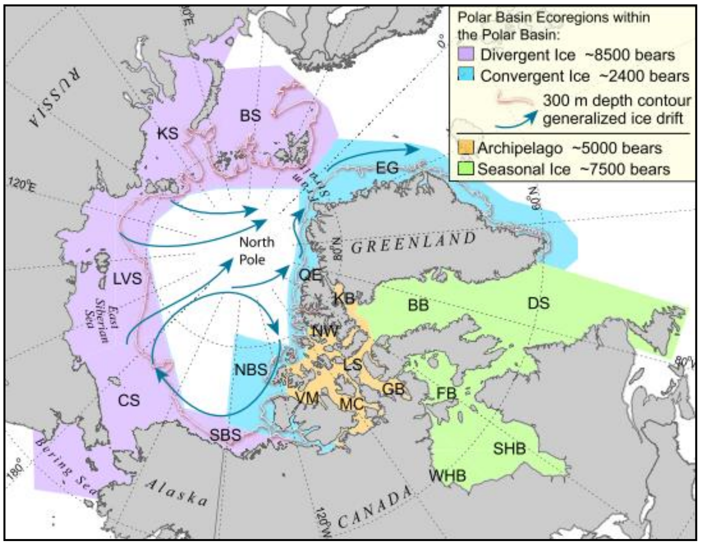


Figure 37. Ecoregions used in analysis of the future global status of polar bears. Ecoregions include the 19 Polar Bear management units (black initials) as defined by the IUCN Polar Bear Specialists' Group, and blue lines represent general ice flow patterns (Amstrup, 2011).

The LIA is home to six polar bear subpopulations (Figure 37; Table 3). Two subpopulations from the Archipelago and Seasonal ice ecoregions (Baffin Bay and Kane Basin) were considered declining until recently updated estimates, although a revision of subpopulation trend has not yet been made (SWG, 2016). Within LIA, thick multiyear ice will be replaced by annual ice, which is associated with greater productivity, and may create more favourable habitats for polar bears over the short term (in the next three to four decades), acting as potential refugia. However, this region is also predicted to become ice-free during summer in the foreseeable future. Although the long-term viability of polar bears is uncertain, the LIA will remain the best habitat available for polar bears as this region will retain ice the longest. (Stirling & Derocher, 2012).

Table 3 . Numbers and trends of the polar bear subpopulations found in the LIA region (data are from Laidre et al.,2015; SWG, 2016).

Ecoregions	Subpopulation	Number (year of estimate)	Trend
Seasonal ice	Baffin Bay (BB)	2826 (212-2013)	Increasing
Archipelago	Kane Basin (KB)	357 (2012-2014)	Increasing
	Norwegian Bay (NW)	203 (1997)	Data deficient
	Lancaster Sound (LS)	2541 (1997)	Data deficient
Convergent Ice	Arctic Basin	Unknown	Data deficient
	East Greenland (EG)	Unknown	Data deficient

8.7 Seabirds

Thick-billed murre.© Kevin Schafer / WWF-Canon

Seabirds are birds that frequent coastal waters and the open ocean. Arctic waters are host in the summer to many millions of marine birds including: Loons, petrels, cormorants, jaegers/skuas, gulls, terns and auks (Jørgensen et al., 2015). Birds are important components of Arctic ecosystems, and are culturally and economically important for local communities. They are also frequently used as indicators of environmental changes. The Arctic is an important region for seabird diversity. Ganter & Gaston (2013) list 44 species that breed in the arctic, of which 23 species of seabird, seven sea ducks and the brant occurring in the high Arctic. West Greenland (24 species) and eastern Canadian Arctic (Nunavut, northern Quebec and Labrador, 22 species) are recognized as biodiversity hotspots (Gaston, 2011). Appendix III describes 42 species that can be found within LIA.

Many seabirds are very conservative in their breeding sites. Large breeding colonies of seabirds can be found on cliffs and islands (see Appendix III) and some are associated with highly productive areas such as the North Water Polynya. Sea ice is also used as a platform for social activities, to escape from marine predators and for resting. Major breeding seabird colonies of the Canadian portion of LIA include: Prince Leopold Island (murres, kittiwakes, fulmars and guillemots), Coburg Island (Thick-billed Murres and Black-legged Kittiwakes), Cape Hay and Cape Graham on Bylot Island (thousands of seabirds and geese), Hell Gate and Cardigan Strait (Black Guillemot, Northern Fulmar, Common Eider), eastern Devon Island (Ivory Gull, Iceland Gull and Glaucous Gull colonies), Hobhouse Inlet on Devon Island (Northern fulmar), Cape Liddon and Radstock Bay on Devon Island (Northern fulmar), Baillie-Hamilton Island (Black-legged Kittiwakes), and Browne Island (Black-legged Kittiwakes) (Figure 38). Breeding seabird colonies are present in northwest Greenland (Appendix III). Melville Bay (just south of the core area of LIA), has been explored in detail for breeding seabird colonies and this area revealed low density of breeding colonies and low numbers of breeding seabirds (Figure 38; Boertmann & Huffeldt, 2012).

Some Arctic marine bird populations provide valuable subsistence resources in the Arctic. The eggs and down of Eiders are harvested throughout the region and are important for traditional food and lifestyle. Auks are also harvested by native peoples in Alaska and Canada (Jørgensen et al., 2015). Most Arctic seabirds have large population sizes and many species are represented by millions of individuals (Gaston, 2011). However, a number of populations have shown declining trends in recent years (Ganter & Gaston, 2013). Stressors to Arctic seabirds include overharvesting, fisheries activities, pollution and climate change (Gaston, 2011; Karnovsky & Gavrilo, 2017). The contribution of climate change to the decline in population trends is generally linked to the food chain as seabirds rely on ice edges and polynyas as key foraging locations (see references in Ganter & Gaston, 2013). The timing of breeding initiation with seasonal peak food (mainly fish and invertebrates) influences the reproductive success. Changes in sea ice cover conditions also allow northward spread of predominantly temperate or Low Arctic species (see references in (Ganter & Gaston, 2013)), at the expense of High Arctic species. As an example, the range of the High Arctic ivory gull is contracting in North Nunavut while most colonies located at the southern edge of its distribution are deserted (Environment Canada, 2013d). Southern colonies of ivory gull are also decreasing in Greenland (Gilg et al., 2009).

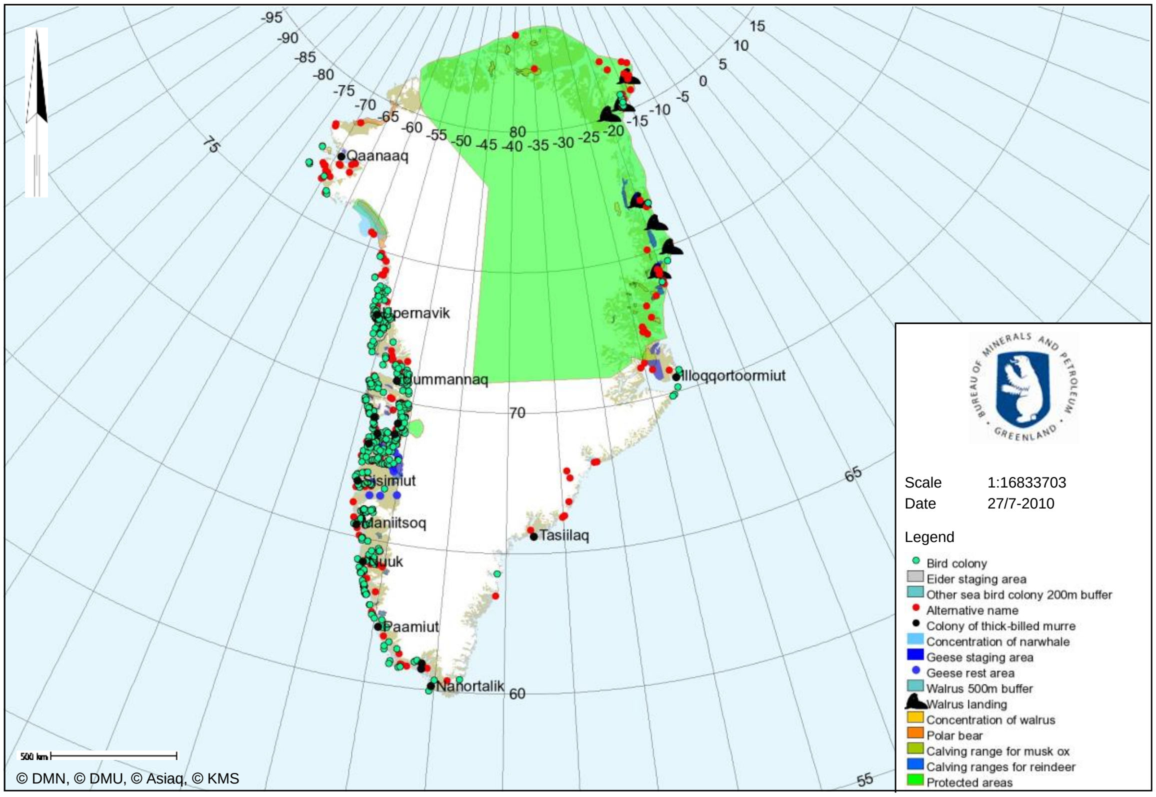


Figure 38. Seabird colonies and other important wildlife areas in Greenland.

8.8 North Water Polynya

Polynyas are large areas (10 - 90,000 km^2) of permanently or frequently open water surrounded by thick sea ice (see section 7.3 for general overview of Polynyas). The North Water Polynya is Canada largest and most productive recurring polynya in the Arctic, and is located in northern Baffin Bay (Figure 39) (Deming et al., 2002). Its formation is due to a combination of factors: strong northerly winds blow ice downstream of an ice bridge that forms at the constriction point between Greenland and Ellesemere Island and meets with the warmer northward flowing West Greenland current (Stirling, 1980). The NOW is the most productive region in the Arctic as it involves the mixing of different water masses that come from the Atlantic and Pacific Oceans (WWF, 2014). In most Arctic waters, the polar winter night and thick ice cover limit primary production. However, the open waters associated with polynyas allow for phytoplankton blooms in early spring, and consequently higher densities of zooplankton (Figure 40; Arctic Biodiversity Assessment, 2013). This is a key factor in making the NOW the most biologically productive region in the Arctic.

As a result of high productivity and presence of Arctic cod (key prey species for arctic marine mammal), the NOW hosts many marine mammals throughout the year. In the summer, it is home to most of the global Narwhal population, and year round is home to a third of North America Beluga population (Laidre & Regehr, 2017). It is also important habitat for Bowhead whale, Ringed seal, Bearded seal, Harp seal, Walrus and Canadian polar bear among others (WWF, 2014). Additionally, the NOW hosts at least 14 species of sea birds that total millions, including the largest single species colony on the planet - more than 100,000 little auks (WWF, 2014). Seabirds that use recurring polynyas have evolved the life history trait to time their migration in order to arrive after the polynya has opened and the food web has developed (Karnovsky & Gavrilo, 2017). An estimated abundance was reported for the following mammals in the NOW: Belugas (2245), Narwhals (7726), Walrus (1499), Bearded Seals (6016) and Ringed Seals (9529), and polar bears (60) (Heide-Jørgensen, 2013).

Like other polynyas, the threat of human disturbance such as an oil spill would devastate a number of species in the area (Sitrling, 1980), and thus the NOW requires careful management. Marchese et al. (2017) depict the NOW polynya as a climate-sensitive region in which the pelagic marine ecosystem may be heading towards decline in chlorophyll-a concentrations (indicator of the amount of algae growing in the water body). Should these changes persist, the NOW polynya may no longer act as a productive regional oasis that supports populations from all trophic levels.

Figure 39. Location of the Northwater Polynya between Greenland and Ellesmere Island in Baffin Bay in May/June (map from Campbell et al., 2005).

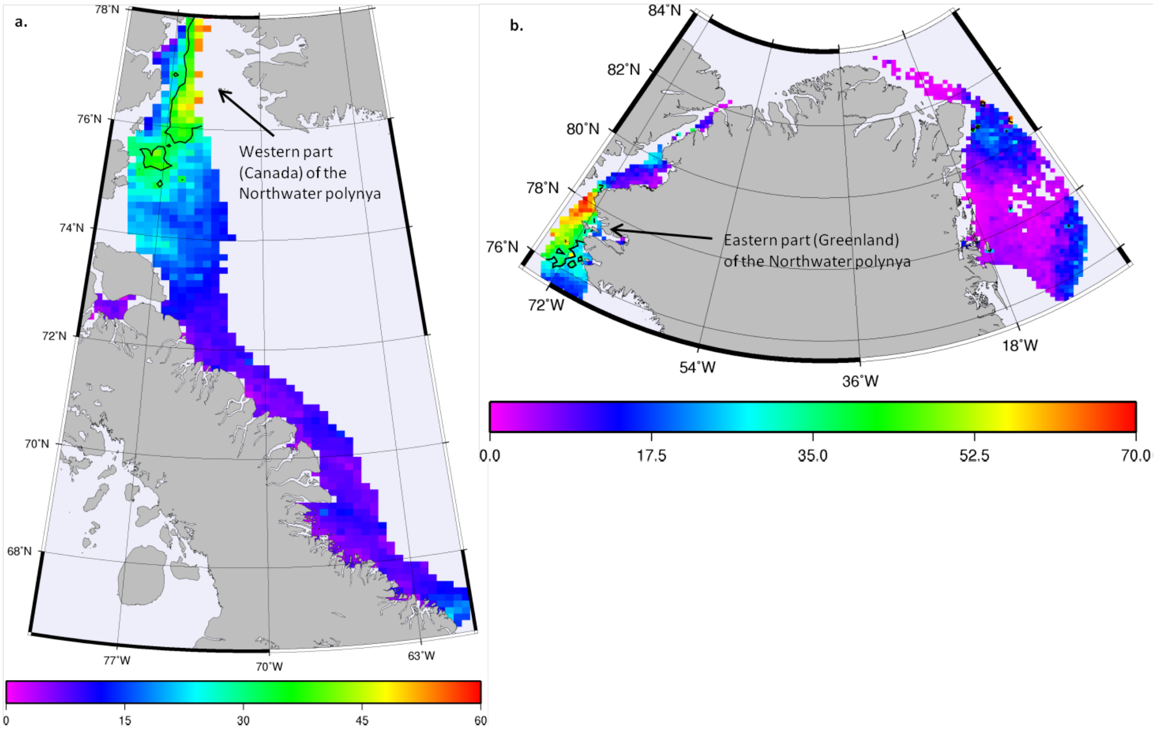


Figure 40. Primary production rates (g C m-2 y-1) of the Baffin Bay – Canadian Shelf (a) and North Greenland (b). Contour lines indicate the 10% most productive pixels. Based on data collected over a thirteen-year period from 1998-2011. Image from WWF (2014).

9. The terrestrial environment

The Arctic terrestrial environment is characterized by numerous lakes that dot the landscape and by the predominance of snow and ice in the form of glaciers, ice caps, ice sheets and permafrost (permanently frozen ground).

9.1 Lakes and rivers

The Arctic contains an abundant and wide range of freshwater ecosystems, including lakes, rivers, ponds, streams and a complex array of wetlands and deltas. These aquatic environments are habitats for diverse biological communities (see section 10.4) and are important for hunting and fishing by indigenous communities. They also provide drinking water supplies to communities and are a key resource for industries such as transport and mining. Moreover, Arctic aquatic environments have global significance as sentinels of climate change and as sources of greenhouse gases. Large rivers also bring major inputs of freshwater and organic materials to the Arctic Ocean (Vincent et al., 2008). Four sites within LIA are important for lake ecological studies: Cornwallis Island (Char Lake, Meretta Lake, Amituk Lake), Ellesmere Island (Lake Romulus, Cape Hershel ponds), Ward Hunt Lake and northern Ellesmere Island meromictic lakes, and Peary land in northern Greenland (Vincent et al., 2008).

Arctic lakes are very diverse. Their salinity ranges from freshwater to hypersaline, and their ice cover can be perennial or seasonal (Vincent et al., 2008). This diversity leads to different mixing regimes; some lakes mix fully during open water conditions in summer, others mix at spring and fall and stratify strongly during summer (as most temperate lakes), and others never mix (Vincent et al., 2008). These physical differences bring large variations between lake chemical characteristics, such as oxygen concentration, and even within the same lake at different depths or times. Some lake types with unusual features are found exclusively in the polar regions, such as solar-heated perennially ice-capped lakes of northern Ellesmere Island (Veillette et al., 2008), and epishelf lakes (see section 7.4). The Arctic also harbours a diversity of streams and river ecosystems, from spring-fed streams to large rivers.

Most Arctic lakes are ultra-oligotrophic (have very low levels of nutrients) and are therefore relatively unproductive, but some are greatly enriched by human activities (e.g. Meretta Lake (Schindler et al., 1974). Several variables would control biological production in Arctic aquatic ecosystems (Vincent et al., 2008). First, the availability of liquid water is essential for aquatic life. For some ecosystems (e.g. meltwater lakes on ice shelves), this limits biological activity to only a few weeks each year. However, liquid water persists all year round under snow and ice cover for most aquatic ecosystems. Streams and rivers are fed by melting snowpack and glaciers, and their flow is the most important during the peak snowmelt in spring (Bring et al., 2016). Second, the reduced irradiance, since the sun is up only during the summer, compounded with the attenuating effects of snow and ice cover on the underwater irradiance strongly limits the annual production in Arctic aquatic ecosystems. However, the primary variable controlling daily primary production by phytoplankton during summer would be nutrient availability (eg. phosphorus, nitrogen, and carbon) (Vincent et al., 2008; Wrona et al., 2016). Nutrient delivery for biological production to plankton communities in lakes and rivers is low in the Arctic. The release of nutrients from the catchments by soil microbes is limited due to low temperature, low moisture, and freezing which reduces biological activity (Wrona et al., 2016), Also, low temperatures would likely slow the metabolic rate and growth of many of the organisms colonizing Arctic aquatic ecosystems. Hence, it is suggested that nutrient supply exerts a strong control on phytoplankton production with the interplay of light and temperature (Vincent et al., 2008).

Lake floor communities of many Arctic aquatic ecosystems flourish and dominate the ecosystem biomass and productivity (Vincent et al., 2008). They take advantage of the more stable environment and of the enhanced supply of nutrients by sedimentation of particles from above and by more active bacterial decomposition and recycling processes, compared to the water column environment (Daniels et al., 2015). Thus, lake floor photosynthetic communities may be more limited by light than by nutrients (Bonilla et al., 2005; Daniels et al., 2015).

Climate change is the major environmental driver affecting Arctic freshwater ecosystems (Prowse & Reist, 2013). The duration of freshwater ice cover is strongly controlled by climate. The lake ice cover duration in the Northern Hemisphere (1846-1995) has declined: freeze-up comes later, break-up comes earlier and the ice cover duration has decreased (Prowse et al., 2011). The most rapid change has occurred in the most recent 30 year period, with freeze-up 1.5 days/decade later, breakup 1.9 d/decade earlier and ice duration 4.3 d/decade shorter (Bring et al., 2016). Rivers are also showing a trend towards earlier breakup, but no strong trend for freeze up (Beltaos & Prowse, 2009; Bring et al., 2016) Hence, lakes with seasonal ice cover have a longer ice-free season while lakes with perennial ice covers are becoming ice free during summer (Prowse et al., 2011). These reductions in lake ice cover duration modify thermal conditions that may lead to enhanced evaporation and, in some cases, the loss of shallow lakes (Prowse et al., 2011; Smol, 2016). In addition, these conditions can lead to enhanced mixing, making Arctic lakes sinks for contaminants (Prowse et al., 2011). Loss of ice cover will also likely lead to increased methane emissions, particularly in Arctic ponds (Smol, 2016), and expose the biota to an increased level of ultraviolet radiation (Prowse et al., 2011). Apart from climate change, other environmental stressors are increasingly relevant for Arctic aquatic ecosystems such as pollution (point source and long-range atmospheric transport), altered hydrologic regimes related to impoundment and diversion of freshwater, water quality degradation due to enhanced mining, and oil and gas activities, and anthropogenic introduction of invasive species via more transport in the North (Prowse & Reist, 2013; CliC/AMAP/IASC, 2016). Specifically, increasing river flows will raise the transport of nutrients, sediment and carbon in Arctic Rivers (Bring et al., 2016), and older carbon will be increasingly mobilized (Aiken et al., 2014). Additionally, microbes breaking down organic matter in wetlands, lakes or waterlogged soil, where there is no oxygen, will produce methane rather than carbon dioxide, which is more potent but spends less time in the atmosphere (CliC/AMAP/IASC, 2016).

9.2 Glacier ice

Arctic glacier ice comprises mountain glaciers (i.e. ice bodies whose shape and size are controlled by bedrock topography), ice caps (i.e. dome-shaped ice bodies that entirely submerge the underlying rock) and the Greenland Ice Sheet (i.e. an ice sheet is an ice cap) (Bring et al., 2016). If all glaciers, ice caps and the Greenland Ice Sheet were to completely melt, the global sea level would rise by 7.9 m (Dahl-Jensen et al., 2011; Sharp et al., 2011). 250,000 km^3 of ice is locked up in mountain glaciers and ice caps (Sharp et al., 2011). The LIA region contains glaciers and ice caps in the mountains on Devon and Ellesmere islands, which are nourished in part by moisture from the NOW polynya, and glaciers at the periphery of Greenland (these glaciers are not connected to the Greenland Ice Sheet). These glacial features drain ice mass away from the accumulation areas, where snowfall exceeds surface melt, to ablation areas where melting exceeds accumulation. Where the ablation areas of ice reach the ocean, icebergs are calved. The Greenland Ice Sheet is a massive ice cap, with an area of 1.71 million km^2, making it the second largest glacial ice mass on earth (second only to the Antarctic ice sheet) (Tedesco et al., 2014). It is composed of 2.85 million km^3 of ice, and stores the global sea level equivalent of 7.4m of freshwater (Tedesco et al., 2014). The Greenland Ice Sheet gains ice by snow falling onto its surface, and loses ice either at the surface, where it is melted by warm air and winds, or from the edge, where it breaks off as chunks of solid ice or flows into the ocean as meltwater (Tedesco et al., 2014). In contrast to sea ice, glacier ice is formed on land but may end up in the ocean. Glaciers and ice sheets contribute to the river and lake systems of the Arctic to which they provide freshwater while melting. Nutrients and sediment are carried with the melting ice into rivers, lakes and the ocean (Bring et al., 2016).

Similar to trends observed for sea ice, lake and river ice cover, glacier ice is also rapidly declining (Dahl-Jensen et al., 2011; Sharp et al., 2011). Almost all Arctic glaciers have retreated over the past 100 years and the rate of loss has increased during the last decade across most regions (Sharp et al., 2011). The Greenland Ice Sheet is also losing ice in a series of fast-flowing glaciers that discharge to the ocean through fiords along the coast. These glaciers have increased their rate of flow and discharge an increased volume of ice (Dahl-Jensen et al., 2011; Nick et al., 2013). The mass loss of Arctic glaciers and the Greenland Ice Sheet are currently the biggest contributors to global sea level rise (Bring et al., 2016). The warming of the ocean water that is in contact with the outflowing end of these glaciers would play a role in these rapid changes. Mass loss from the Greenland Ice Sheet has accelerated in the last few years, with recent estimates of 375 ± 24 km^3 yr^{-1} for 2011-2014, which equates to a factor of 2.5 higher volume loss than for the time period between 2003 and 2009 (Figure 41; Helm et al., 2014). Additionally, the proportion of the ice sheet melting has been increasing, with enhanced melt occurring in the southwest and northeast regions.

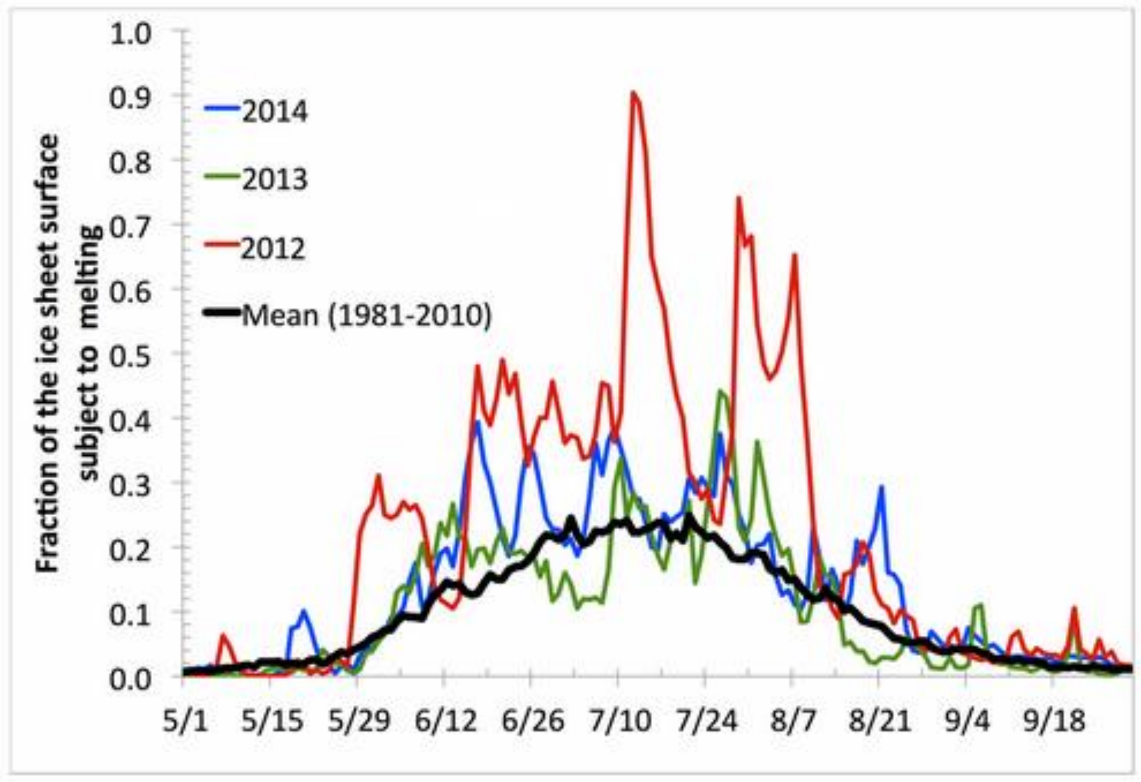


Figure 41. The annual cycle of melt extent, expressed as fraction of total ice sheet area where melting was detected (Tedesco et al., 2014).

The implications of land ice melt are numerous (Dahl-Jensen et al., 2011; Sharp et al., 2011). Fresh water is added to the ocean, which reduces the salinity and density of the surface water, and thereby enhances the water column stratification, especially in fiords and in coastal locations (CliC/AMAP/IASC, 2016). These physical changes may have implications for marine food webs and thereby fisheries (Wrona et al., 2016). The composition and production at the base of the food web will be altered and these changes will ultimately affect fish, birds and marine mammals. Moreover, new land areas are exposed and the global sea level is rising, affecting the populations living close to the coast (Dahl-Jensen et al., 2011; Sharp et al., 2011). Global mean sea level rose by 0.19 m over the period 1901-2010 (IPCC, 2013). Global mean sea level rise will keep continue throughout this century and at an increasing rate compared to those observed over 1971-2010 due to increased ocean warming (thermal expansion) and increased loss of mass from glaciers and ice sheets (IPCC, 2013). By 2100, the rise in the global sea level is projected to be between 0.52 and 0.98 m (IPCC, 2013). Glacier run-off will increase in the short term (CliC/AMAP/IASC, 2016), but decline after a few decades in many parts of the Arctic, as glacier area will be greatly reduced (IPCC, 2013). This will have implications for water supplies, water quality, hydroelectric power generation, coastal habitats and ocean circulation patterns (Sharp et al., 2011). Finally, iceberg production represents hazards to shipping and offshore activities.

9.3 Permafrost

Permafrost, or permanently frozen ground, is soil, sediment, or other rock material that remains at or below 0°C for two or more consecutive years (National Snow and Ice Data Centre, 2013c). Permafrost underlies the vast majority of the surface of the terrestrial Arctic and it can occur beneath offshore Arctic continental shelves (National Snow and Ice Data Centre, 2013c). At the soil surface, there is an active layer that freezes and thaws seasonally. Under this active layer, a transient layer can remain frozen in some summers and, underneath it, there is permafrost (Callaghan et al., 2011a). Taliks, unfrozen zones within permafrost, can occur, for example, under large water bodies (Callaghan et al., 2011a). Terrestrial permafrost thickness ranges from less than 1 meter to greater than 1,500 meters in the north of the Arctic region (National Snow and Ice Data Centre, 2013c). The active layer thickness is influenced by climate and local factors and vary from less than 0.5 m in vegetated, organic terrain to more than 10 m in areas of exposed bedrock (Callaghan et al., 2011a). The proportion of the landscape underlain by permafrost becomes greater with increasing latitude from the southern limits of the permafrost zone to the High Arctic (Callaghan et al., 2011a). The LIA is located well north of the continuous (90-100% of area) permafrost boundary.

Permafrost is intimately linked with biodiversity and ecosystem processes in the Arctic (Callaghan et al., 2011a). On one hand, permafrost influences soil temperature, drainage, nutrient availability, rooting depth and plant stability. It also provides a habitat for viable ancient microorganisms that live within permafrost. On the other hand, vegetation moderates ground surface temperature by insulating and protecting permafrost directly or indirectly by trapping snow. The presence of permafrost is playing a key role in plant species composition as it restricts the types of plants that can grow. Permafrost is important for maintaining the integrity of many ecosystems. Thawing of the permafrost can convert terrestrial ecosystems (e.g. tree or shrub dominated forests) into aquatic ecosystems (bogs, thermokarst lakes), due to flooding of roots that would lead trees or shrubs to collapse (Wrona, 2016).

Some of the implications of permafrost thaw for arctic environments can be seen in Figure 42. Increasing temperatures and changing snow cover are driving permafrost warming. Permafrost temperatures have risen by up to 2 °C since the 1970s, although there is large regional variability (Callaghan et al., 2011a), and the southern limit of permafrost has moved northward in Russia and Canada (Callaghan et al., 2011a). The integrity of low Arctic and sub-Arctic permafrost is currently under greater threat than colder permafrost in the high Arctic (Vaughan, 2013). However, this thawing trend is projected to continue, with some projecting the area currently underlain by permafrost near the surface (upper 3.5 m) would decrease by 37-81% by 2100 (IPCC, 2013).

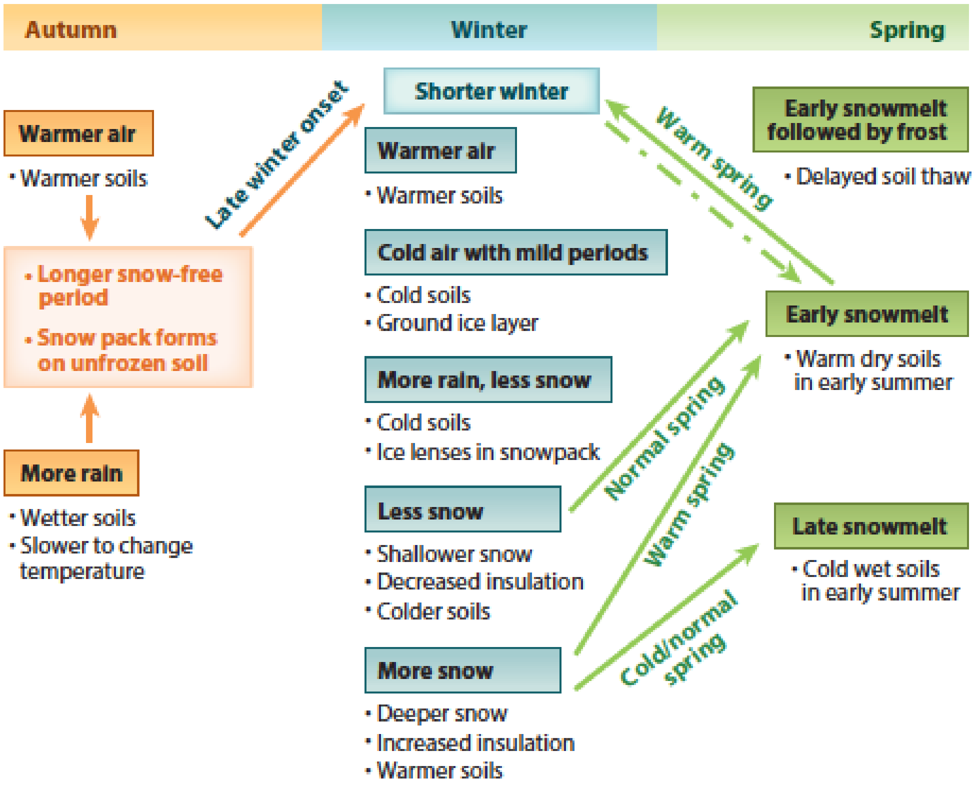


Figure 42. Overview of seasonal climate changes in the terrestrial Arctic (taken from Cooper, 2014)

Permafrost thawing is having drastic impacts on the built and natural environments (Callaghan et al., 2011a). Arctic infrastructure (e.g. schools, hospitals, roads, airports) is greatly damaged and the design of any future development will need to take into account the instability of the permafrost. Also, permafrost thawing on mountain slopes can lead to rock slope instability and landslides. In addition, coastal erosion is enhanced since the Arctic coastline is composed of unconsolidated material rich in ice. With permafrost thawing during summer, the coasts are especially sensitive to the action of waves and experience high annual erosion rate. Moreover, the outcomes of thawing permafrost are at the opposite for hydrology; landscape dryness is increasing in the boreal forest and ponds are drying, while waterlogging occurs in some flat areas of the sub-Arctic (Wrona et al., 2016). This is because permafrost degrades in a continuum from rising temperatures in frozen ground (which increases the unfrozen water content and reduces the load-bearing strength of the ground) to complete thawing of ice-rich ground (which causes the surface to subside and creates depressions in the ground, termed ‘thermokarst’). Thawing permafrost would increase nutrients to hydrological systems, potentially leading to greater algae blooms that reduce water quality. This would have implications for species diversity and food webs in the Arctic (CliC/AMAP/IASC, 2016). Finally, permafrost thawing has an important impact on greenhouse gases emissions. Recent research has demonstrated that permafrost soils (both terrestrial and beneath continental shelves) hold large pools of carbon (mostly in the form of methane (CH_4)) and nitrous oxide (N_2O). The emission of these two powerful greenhouse gases from thawed permafrost could greatly accelerate climate-warming feedbacks (Callaghan et al., 2011a). However, it is more likely that carbon will enter the atmosphere gradually, over the decades to come, and at smaller volumes compared with emissions caused by human use of fossil fuels (CliC/AMAP/IASC, 2016).

10. Terrestrial biodiversity

This section examines Arctic terrestrial biodiversity. Soil microbial biodiversity, vegetation and animal biodiversity for terrestrial ecosystems (except aquatic ecosystems) are first described, then, aquatic biodiversity is presented.

10.1 Soil microbial biodiversity

Arctic soils are generally shallow and have relatively low productivity. The heterogeneity of the soil cover is substantial and greatly influences the distribution of the soil biota occurring in relation to the small-scale topographic variations (Callaghan, 2005; Blaud et al., 2015). The soil biota comprises invertebrates, fungi and prokaryotes (bacteria and archaea). Despite the critical role that these organisms play for the functioning of ecosystems by being responsible of carbon and nutrient fluxes, they are still poorly understood in the soil of the tundra compared with other species (Callaghan, 2005).

Until recently microbial diversity in Arctic soils was believed to be low, and was based on the analogy with plants and animals in which diversity decreases with increasing latitude and altitude (Blaud et al., 2015). Recent progress in molecular ecology have rarely been applied to Arctic terrestrial studies. Nevertheless, a molecular technique investigated the upper limit for variation of prokaryote diversity as compared with other systems. This technique revealed that Arctic polar desert and tundra soils contain a considerable level of prokaryote diversity; similar to boreal forest soils and much higher than arable soils (Callaghan, 2005; Chu et al., 2010). Within soils, microbial diversity differs between Arctic ecosystems (eg. peat vs. hummock tundra) and decreases with soil depth or soil horizons within the active layer (eg. from tundra to peats) (Blaud et al., 2015). Microbial activity is generally lower in permafrost than the active layer. Soil microbial communities in the tundra vary seasonally; it is dominated by fungi during winter while certain bacteria become more important during spring, summer and fall, and the importance of fungi declines (Buckeridge et al., 2013). The soil nutrient status and environmental differences between winter and the other seasons explain these community differences (Buckeridge et al., 2013). The harsh Arctic climate limits the metabolic activity of Arctic soil microorganisms.

Microorganisms are highly adaptive, tolerant of most environmental conditions and have short generation times that help to adapt to changes in environmental conditions. The main impact of climate change on Arctic soil microorganisms will likely be an increase in metabolic activity, to a similar level as the one of the boreal soils (Callaghan, 2005). Warmer temperatures, increase in atmospheric CO_2 concentration and a higher availability of nutrients will likely contribute to this (Blaud et al., 2015). Increases in microorganism activity also implies accelerated soil organic matter decomposition (Koyama et al., 2013).

10.2 Vegetation

Vegetation in the Arctic

Environmental and climatic conditions are extreme for Arctic vegetation and control the plant communities that can grow. Summer temperature is the most important factor that influences Arctic vegetation (CAVM Team, 2003). The mean July temperatures are near 0˚C on the northernmost Arctic islands. At these low temperatures, plants are at their metabolic limits, and small differences in the total amount of summer warmth make large differences in the amount of energy available for maintenance, growth, and reproduction. Higher summer temperatures cause the size, horizontal cover, abundance, productivity, and variety of plants to increase. Environmental factors such as landscape, topography, soil chemistry, soil moisture, and the history of plant colonization also influence the distribution of plant communities in the Arctic (CAVM Team, 2003; Walker et al., 2016). Most plants found in the Arctic are dwarf shrubs, herbs, lichens and mosses that grow close to the ground, and they cover the land surface that is not ice-covered (5.05 millions km^2 are covered by vegetation out of 7.11 millions km^2 of total land surface) (Walker et al., 2005). With decreasing latitude (moving from the High Arctic to the Low Arctic), the amount of warmth available for plant growth increases significantly, allowing the size, abundance, and variety of plants to increase as well (CAVM Team, 2003).

The circumpolar Arctic is subdivided along latitudinal subzones (Table 4) and longitudinal floristic provinces (Figure 43). The latitudinal north-south axis reflects the present climate and vegetation gradient divided into five different subzones. A, B and C delineate bioclimate subzones of the High Arctic, while D and E are located in the Low Arctic (Table 4). Very steep bioclimate gradients occur in mountains and these areas are therefore mapped as elevation belts (CAVM Team, 2003). There is a clear increase in species numbers from the northernmost High Arctic subzone A (102 species) to the southernmost Low Arctic subzone E (2180 species) (Daniëls et al., 2013). The longitudinal east-west axis reflects different conditions in the past such as glaciations, land bridges and north-south trending mountain ranges (particularly in Asia) (Walker et al., 2016). These influences have limited the exchange of species between parts of the Arctic (Daniëls et al., 2013). Species numbers per floristic province vary widely from approximately 200 species for the heavily glaciated and northern floristic province Ellesmere – North Greenland to more than 800 species for Beringian Alaska (Daniëls et al., 2013; Walker et al., 2016).

Table 4. Vegetation properties in each bioclimate subzone from CAVM Team (2003). Note that the subzone A is also known as polar desert, subzone B as Arctic tundra, subzones C and D as typical tundra and, subzone E as southern tundra. Alternatively, subzone A can also be named the Arctic herb subzone (absence of sedges and woody plants); B, the northern Arctic dwarf shrub subzone; C, the middle Arctic dwarf shrub subzone; D, the southern Arctic dwarf shrub subzone and E, the Arctic shrub subzone.

Subzone	Mean July Temp[1] (°C)	Summer warmth index[2] (°C)	Vertical structure of plant cover[3]	Horizontal structure of plant cover[3]	Major plant growth forms[4]	Dominant vegetation unit (see Detailed Vegetation Descriptions for species)	Total phyto-mass[5] ($t\ ha^{-1}$)	Net annual production[6] ($t\ ha^{-1}\ yr^{-1}$)	Number of vascular plant species in local floras[7]
A	0-3	<6	Mostly barren. In favorable microsites, 1 lichen or moss layer <2 cm tall, very scattered vascular plants hardly exceeding the moss layer	<5% cover of vascular plants, up to 40% cover by mosses and lichens	b, g, r, cf, of, ol, c	B1, G1	<3	<0.3	<50
B	3-5	6-9	2 layers, moss layer 1-3 cm thick and herbaceous layer, 5-10 cm tall, prostrate dwarf shrubs <5 cm tall	5-25% cover of vascular plants, up to 60% cover of cryptogams	npds, dpds, b, r, ns, cf, of, ol	P1, G1	5-20	0.2-1.9	50-100
C	5-7	9-12	2 layers, moss layer 3-5 cm thick and herbaceous layer 5-10 cm tall, prostrate and hemi-prostrate dwarf shrubs <15 cm tall	5-50% cover of vascular plants, open patchy vegetation	npds, dpds, b, ns, cf, of, ol, ehds* * in acidic areas	G2, P2	10-30	1.7-2.9	75-150
D	7-9	12-20	2 layers, moss layer 5-10 cm thick and herbaceous and dwarf-shrub layer 10-40 cm tall	50-80% cover of vascular plants, interrupted closed vegetation	ns, nb, npds, dpds, deds, neds, cf, of, ol, b	G3, S1	30-60	2.7-3.9	125-250
E	9-12	20-35	2-3 layers, moss layer 5-10 cm thick, herbaceous/ dwarf-shrub layer 20-50 cm tall, sometimes with low-shrub layer to 80 cm	80-100% cover of vascular plants, closed canopy	dls, ts*, ns, deds, neds, sb, nb, rl, ol *in Beringia	G4, S1, S2	50-100	3.3-4.3	200 to 500

[1] based on Edlund (1996) and Matveyeva (1998).
[2] Sum of mean monthly temperatures greater than 0°C, modified from Young (1971).
[3] Chernov and Matveyeva (1997).
[4] b - barren; c - cryptogam; cf - cushion or rosette forb; deds - deciduous erect dwarf shrub; dls - deciduous low shrub; dpds - deciduous prostrate dwarf shrub; g - grass; ehds - evergreen hemiprostrate dwarf shrub; nb - nonsphagnoid bryophyte; neds - nondeciduous erect dwarf shrub; npds - nondeciduous prostrate dwarf shrub; ns - nontussock sedge; of - other forb; ol - other lichen; r - rush; rl - reindeer lichen; sb - sphagnoid bryophyte; ts - tussock sedge. Underlined codes are dominant.
[5] Based on Bazilevich, Tishkov and Vilcheck (1997), aboveground + belowground, live + dead.
[6] Based on Bazilevich, Tishkov and Vilcheck (1997), aboveground + belowground.
[7] Number of vascular species in local floras based mainly on Young (1971).

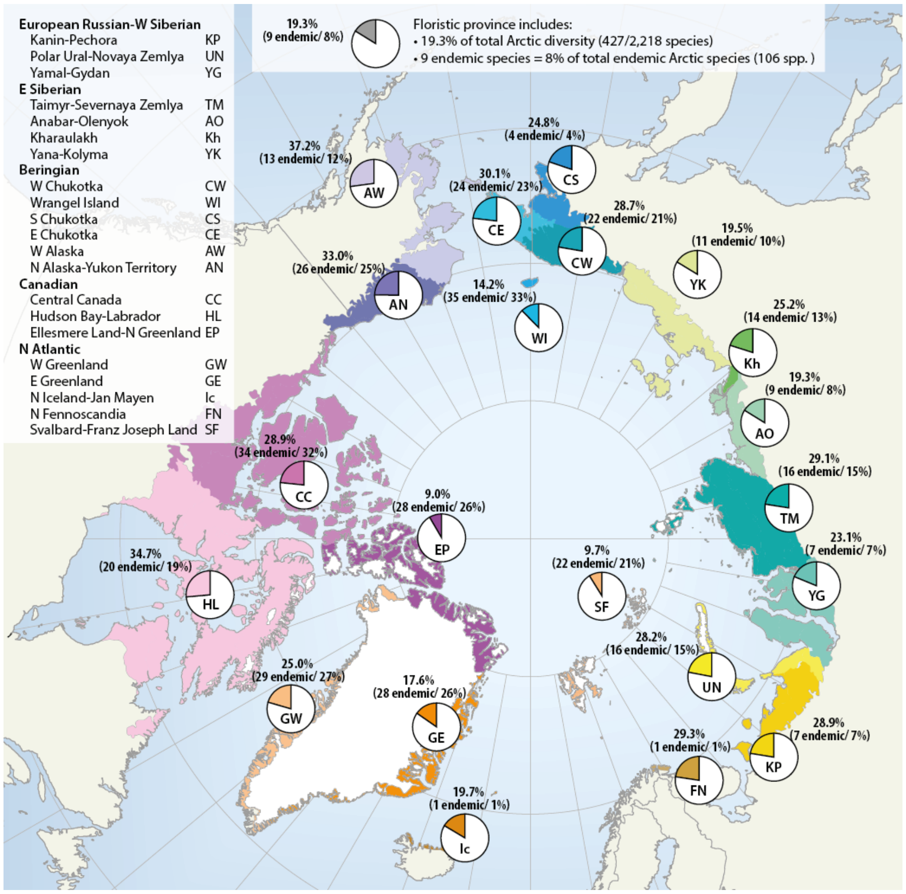


Figure 43. Vascular – plant species richness within each floristic province (colour coded on map) as a percentage of the total Arctic species richness (2,218 species). The number of endemic species is shown in parentheses with percentage of the total arctic endemic species (106) (taken from Daniëls et al., 2013).

Approximately 3% (~5900 species) of known plant species occur in the Arctic (Callaghan, 2005). Vascular plants (2,218 species), bryophytes (mosses and liverworts; 900 species) and lichens (1,750 species) are the main structural components of terrestrial vegetation and ecosystems (Daniëls et al., 2013). Vascular plants and bryophytes are the two main groups of terrestrial plants and as primary producers, they perform photosynthesis and support all organisms of higher trophic levels. Vascular plant diversity of the Arctic is relatively poor. Approximately 2,218 vascular plant species are recognized in the Arctic which represent less than 1% of the known vascular plant species in the world (Elven et al., 2011). The majority of these Arctic vascular plant species have a circumpolar distribution (Daniëls et al., 2013). Lichen and Bryophytes combined cover more land surface than vascular plants in the high Arctic (Blaud et al., 2015), and bryophytes strongly differ in life cycle, structure and physiology (Daniëls et al., 2013). Turfs dominate the bryophyte growth form in the Arctic (Schofield, 1972). Bryophyte diversity is moderate in the Arctic although species number could increase in the course of future studies. Although on a fine scale (few square kilometres), bryophyte species diversity is higher than vascular plants, the estimated species number of Arctic bryophyte is 900 species, significantly less than 1,750 lichen species and 2,218 vascular plants (Daniëls et al., 2013). High Arctic sites have fewer species of bryophyte than Low Arctic areas (Daniëls et al., 2013). Also, almost 80% of these species have a circumpolar distribution (Daniëls et al., 2013). Bryophytes contribute to vegetation biomass in stable, wet-to-moist sites, and they add to species richness of many vegetation types in other habitats as very few vegetation types in the Arctic occur without bryophytes (Daniëls et al., 2013). Single shoots occur almost everywhere, and particularly in the High Arctic (Daniëls et al., 2013). Vascular plant endemism is low, only 5% of the Arctic vascular plant species are endemic to any of the floristic provinces, and there is an overall low level of genetic diversity (Daniëls et al., 2013; Eidesen et al., 2013). Interestingly, the relative percentage of vascular plant species endemic to the Arctic decreases from the High Arctic to the Low Arctic (Daniëls et al., 2013). In contrast, Arctic endemism is not strongly pronounced for bryophytes (Daniëls et al., 2013). No species in the Arctic are currently considered as invasive, although some are at risk of becoming it with increasing human traffic combined with climate change (Daniëls et al., 2013).

Plants have always played a central role in the lives and cultures of Arctic indigenous peoples (Daniëls et al., 2013). Vascular plants are consumed and used for medicines. The use of bryophytes is little known and therefore, probably very restricted.

Vegetation in the LIA

The LIA region encompasses three bioclimate subzones: A, B and C (Daniëls et al., 2013). Islands between the Peary Channel and the M’Clure Strait, at the northwestern margin of the Canadian Arctic Archipelago, are characterized by subzone A. The northern coast of Ellesmere Island and Greenland, and territories on each shore of the Parry Channel, by subzone B. The interior of Ellesmere Island and Devon Island, by subzone C. Two floristic provinces are found within LIA (Figure 43). Northern Greenland, Ellesmere Island, Axel Heiberg Island and Devon Island are part of the Ellesmere – North

Greenland province. The other islands of the Canadian Arctic Archipelago north of the Parry Channel are included in the central Canada province. Appendix IV presents a detailed overview of all sub-categories of vegetation types found in the LIA.

Climate change impacts on vegetation

The main implications of climate change for Arctic vegetation is greening, shrub expansion and floristic changes (Daniëls et al., 2013; Epstein et al., 2016). Greenness is measured by indices such as the Normalized Difference Vegetation Index (NDVI), a measure of vegetation photosynthetic capacity. Between 1983-2013, most studies reported a significant increase in greenness in the circumpolar Arctic that correlates with the general warming of this region (Bhatt et al., 2013). Increases in greenness are linked to the loss of coastal sea ice (Bhatt et al., 2010). When there is less ice, air temperatures warm over land and the primary production of tundra ecosystem increases. This greening is accompanied with shifts in vegetation communities. Key plant events (such as leaf bud burst and flowering) and growth are stimulated by warmer temperature (Aft et al., 1999). Warming also increases shrub cover and height in the tundra ecosystems along the southern Low Arctic (Myers-Smith et al., 2011, 2015). This shrub expansion may result in important feedbacks effects. For instance, the darker and denser canopy will lower the albedo, increasing the amount of solar radiation absorbed, and will lead to increased warming (Chapin et al., 2005). Also, taller shrubs enhance snow depth, which insulate the soil during winter, which result in greater microbial activity and greater nutrient availability (Sturm et al., 2005; Epstein et al., 2016). In addition, the increased presence of shrubs can have implications for herbivores such as the caribou that feed on lichens, herbaceous and woody plants (Henry et al., 2012). There is no clear evidence of treeline advance; however, seedlings and saplings show the potential for increases in tree density within and beyond this zone of transition (Henry et al., 2012; Phoeneix & Bjerk, 2016). The heterogeneity of habitats in the Arctic and the high genotypical and phenotypical variability of Arctic plants will certainly result in the evolution of adaptations to benefit from higher temperatures and longer growing seasons.

Arctic greening has received much attention as it has a number of implications for biodiversity, but so can the reverse. Phoenix & Bjerke (2016) note that although there has been a clear greening trend for most of NDVI satellite record's 33-year history, there appears to be an overall decline in greenness from 2011 to 2014. Long-term trends (1982-2015) show greening in southern Canadian tundra, but browning (decrease in tundra greenness) occurring in the Canadian Archipelago (part of LIA) (Epstein et al., 2015; Phoenix & Bjerke, 2016). Browning may be attributed to deeper winter snowpack and snow cover duration or events such as extreme winter warming (Bjerke et al., 2014). Other extreme events such as permafrost degradation can lead to browning where thaw features expose ground (Phoenix & Bjerke, 2016). Although it is unclear whether the Arctic will experience a browning or greening trend in the future, it is worth noting that vegetation shows evidence of rapid recovery from extreme events like fire or winter warming (Bokhorst et al., 2011; Bret-Hart et al., 2013). There is no evidence that any Arctic plant species has become extinct in the last 250 years (Elven, 2011). However, species with a very low abundance and a restricted distribution are the most vulnerable to ongoing climate change. Also, the loss of habitats induced by climate change may reduce the range of many plant species. This could cause losses of genetic diversity within species and therefore hamper their capacity to adapt and persist in a changing climate (Alsos et al., 2012).

10.3 Terrestrial fauna

Biodiversity of Arctic terrestrial fauna

The species richness of Arctic terrestrial animals (6,000 species) is similar to the one of Arctic plants (~5900 species), and accounts for around 2% of the global total (Callaghan, 2005). The most diverse group of Arctic animals are insects with 3,300 species. Vertebrates are less diverse with 322 species in total, of which 75 are mammals, 240 are birds, 2 are reptiles and 5 are amphibians. Spiders (300 species), mites (700 species), springtails (400 species), nematodes (500 species), oligochaetes (700 species), molluscs (a few species) and protozoans (an unknown number of species) are also present. Similar to Arctic plants, diversity of Arctic animals declines with latitude and temperature (Callaghan, 2005). However, patterns of animal distribution are more diverse than for plants. As a consequence of the lower number of species present at high latitudes, dominance is more important in these regions (Callaghan, 2005). Arctic terrestrial food chains are short and simpler than further south. There are typically a couple of plant species involved (mainly grasses, sedges and willows), along with an herbivore (mammal or bird) and a top predator (mammal or bird) (Jensen & Christensen, 2003).

Terrestrial Arctic animals possess different adaptations that enable them to cope with low winter temperature and conserve energy. As an example, warm-blooded animals have thick coats of fur or feathers, they store fat and they reduce metabolism during winter (Callaghan, 2005). Numerous vertebrate animals escape harsh conditions by moving over long or short distances (Callaghan, 2005). Moreover, Arctic animals would be mostly generalists in terms of food and habitat selection, and this might be explained by the low presence of competitors and the unpredictable food resource availability (Callaghan, 2005). Some predators scavenge if and when opportunities arise. In winter, carrion is the mainstay of Arctic foxes. They trail polar bears on the sea ice to eat the remains of seal kills, and they trail wolves on land.. These activities must be pursued circumspectly, as both polar bears and wolves will kill and eat Arctic foxes (Sale, 2006). Ivory gulls scavenge on carrion from polar bear kills (Sale, 2009).

Terrestrial fauna of the LIA

Terrestrial mammal species reported for LIA are listed at Appendix II. The terrestrial predator community of the LIA consists of Arctic wolf (*Canis lupus arctos*), Arctic fox (*Vulpes lagopus*), (red fox, Vulpes vulpes, on Devon Island) and stoat (*Mustela erminea*). Aerial predators in the LIA are rough-legged hawk (*Buteo lagopus*), gyrfalcon (*Falco rusticolus*), peregrine falcon (Falco peregrinus), snowy owl (*Bubo scandiacus*), jaegers and skuas (Stercorariidae), gulls (Laridae) and raven (Corvidae). There are many species of shorebirds that prey on invertebrates and molluscs on land, shorelines and tidal mud flats. Polar bears are summer season terrestrial predators and scavengers in the seasonal sea ice regions.

Caribou

Caribou. © P.Nicklen National Geographic Stock WWF-Canada

Rangifer tarandus is called caribou in North America America and reindeer in Europe. It is a conspicuous Arctic terrestrial species with a circumpolar distribution in the tundra and taiga zones of northern Europe, Siberia and North America (Figure 44). They have supported many cultures for thousands of years through meat and fat, and skins for clothing. Caribou is found throughout LIA; the subspecies Peary caribou (*Rangifer tarandus pearyi*) is found on the islands of the Canadian Arctic Archipelago and coastal northwestern Greenland (Government of Canada, 2013b; Jensen and Christensen, 2003). This subspecies is small (males measure 1.7 m in length on average), have relatively short legs, they are almost completely white and they have small antlers (Government of Canada, 2013b). Peary caribou migrate seasonally between islands to maximize their use of the available habitat. During summer, they feed on dense vegetation in the slopes of river valleys and upland plains, while during winter they occur in areas where the snow is shallow. Caribou is an important prey species for many Arctic carnivores such as the golden eagles, wolves, and polar bears. In 2015, the caribou was listed under the IUCN red list category of 'vulnerable' due to a decreasing population trend across circum-Arctic countries (Gunn, 2016).

The number of mature individuals of Peary caribou in the population of the Queen Elizabeth Islands is 2100 (Government of Canada, 2013b), the Inglefield/Pruhoe Land population and the Olrik Fiord population in Greenland had an estimated population size of 2,300 in 1999, and an unknown number, respectively (Greenland Institute of Natural Resources, 2013). The best current estimate of the total Peary Caribou population, including calves, is 7890 (Government of Canada, 2013b). The Peary caribou population is declining (Figure 45); the total population has declined by 72% since 1980, and the population on the Queen Elizabeth Islands has declined by about 37% (Government

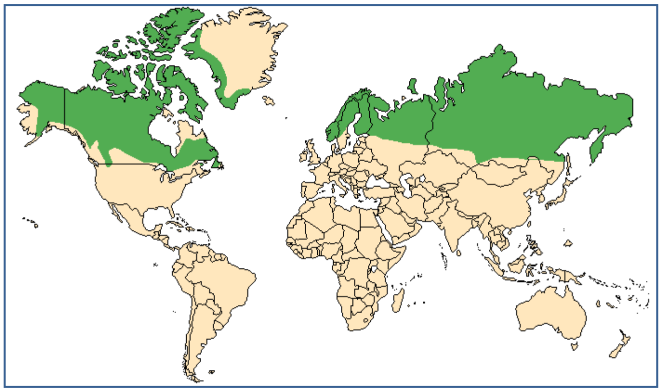


Figure 44.Distribution of caribou (Ultimate ungulate.com, 2012, compiled from Burt and Grossenheider, 1976; Whitehead, 1993).

of Canada, 2013b). The Peary caribou has been assessed as endangered under both the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and the Species At Risk Act (SARA) (Government of Canada, 2013b). The main threat to this caribou population would be winters with heavy and persistent snow accumulation, in association with freezing rain and warm periods that cause the formation of ice crusts over vegetation. For this reason, climate change could lead to the disappearance of this population (Government of Canada, 2013b). Industrial development is still absent in the Queen Elizabeth Islands and northwestern Greenland. However, future industrial operations could hamper seasonal migrations and cause disruptions during critical periods of their life cycle (Government of Canada, 2013b). Certain Peary caribou herds are characterized by low number and low genetic diversity, which reduce their ability to adapt to environmental stresses (Government of Canada, 2013b).

Figure 45. Distribution of different herds of caribou in Arctic Canada and their trends (taken from Gunn et al., 2011)

Lemming

The Northern Collared (or Arctic) lemming (*Dicrostonyx groenlandicus*) is an important species in the High Arctic ecosystem and it is widely distributed throughout the LIA. It copes with the severe winters by positioning its nest and tunnels under the snow. The Arctic lemming feeds on willow and grasses, and it is the most important prey species for Arctic fox, stoat and snowy owls. Skuas, jaegers, gyrfalcon and raven also feed on lemmings. The lemming population follows a cyclical pattern and crashes at times, which especially influences the stoat population, as well as other predators of. As an example, two varieties of Arctic foxes occur in Greenland: the white Arctic foxes are found primarily inland, and the blue Arctic foxes are associated with the coastal zone (Jensen and Christensen, 2003). The white Arctic foxes feed on lemmings and show much greater population fluctuations than the blue Arctic foxes that feed on more stable food sources (Jensen and Christensen, 2003).

Musk ox

Muskox (*Ovibos moschatus*) have lived in the Arctic for many thousands of years and they are survivors of the last ice age. They live in the Arctic tundra in Canada, Alaska, and Greenland (throughout LIA). These animals are well adapted to the Arctic climate with their long thick, shaggy fur that keeps them warm. Additional adaptations to the harsh Arctic climate are short legs and large, rounded hooves that allow them to move easily through shallow snow. These large mammals (up to 360 kg) feed on roots, mosses and lichens and they supplement their diet with Arctic flowers and grasses during summer. Muskox live in herds of two to three dozen animals and they use cooperation to deal with predation by wolves and dogs. When they are threatened, they form a circle, protecting their young in the middle, and they show their sharp horns outward. They are an integral part of the Inuit lifestyle as they provide large quantities of meat, and warm, versatile, insulating hair.

Impacts of climate change on terrestrial fauna

Current climate change is having observed impacts on Arctic terrestrial animals. Among them, alterations of freeze-thaw cycles lead to ice-crust formation that reduce the insulating properties of the snowpack, and alter temperature, oxygen and CO_2 conditions for animals living below the snow (Callaghan, 2005). In addition, ice crusts make vegetation inaccessible to herbivores, such as the caribou (Callaghan, 2005; Langlois et al., 2017). Inuit are also reporting changes in animal behaviours (WWF, 2013a).

Future climate change will impact terrestrial animals in several ways (Callaghan, 2005). A projected deeper snow cover in winter is likely to limit the ability of the caribou to access winter pastures and to escape from predators (Callaghan, 2005). Migrant species may also be particularly vulnerable if climate change interferes with migration routes and staging sites. Some animal species time their reproduction to the seasonal peak in food resource availability. Future climate change might lead to mismatch if there is disruption in animal behaviour or change in timing of food availability. With future increase in summer temperature, interspecific interactions (competition, predation and parasitism) may be intensified (Callaghan, 2005). Species with temperate distributions will likely invade the Arctic and compete with Arctic species. The large and aggressive red fox would likely spread north, probably at the expense of the Arctic fox (Tannerfeldt et al., 2002). In addition, generalist predators that are currently absent in the Arctic are likely to move northward as ecosystem productivity increases (Callaghan, 2005). Also, longer growing seasons may be an advantage for species that come to the Arctic during the short summer season to feed and reproduce.

The rate of climate change would be too rapid for Arctic vertebrates to adapt through evolution. The main response of Arctic animal species to climate change impacts would be relocation rather than adaptation (Callaghan, 2005; Lenoir and Svenning, 2015), since the geographic ranges of terrestrial species are generally well correlated with bioclimatic variables. Relocation possibilities vary from one region to another and are also restricted by geographical barriers (Lenoir and Svenning, 2015). With the increasing length of the open water season, crossing between islands will become harder and will reduce the connectivity in habitats and isolate local populations. For example, caribou have been observed swimming across open water bodies, but this type of movement is energetically costly. Consequently, caribou tend to adjust their migration route according to ice availability and conditions (Leblond et al., 2016). Additionally, hybridization of Arctic species will likely increase with melting sea ice as Arctic species spend more time with more temperate species (i.e. polar bears spend more time in the same environment that grizzlies). However, in most cases, hybridization tends to reduce individual genomic diversity and species diversity (Kelly et al., 2010).

10.4 Aquatic biodiversity

Arctic aquatic biodiversity

Aquatic biodiversity is known to decrease with increasing latitude, likely reflecting the increasingly harsh conditions (Prowse & Reist, 2013). Also, Arctic aquatic environments often have a simplified food web structure compared to temperate latitudes (Vincent et al., 2008). They range from simple with flagellates, ciliates and rotifers at the highest trophic level, to more complex with well-developed zooplankton and fish communities (Vincent et al., 2008). Shallow lakes and ponds exhibit extreme seasonality in temperature, water levels and light conditions, which preclude the presence of higher trophic levels (Prowse & Reist, 2013). The level of nutrients available in the lake (if it is oligotrophic, mesotrophic or eutrophic) and biogeography would likely influence the food web structure and diversity (Vincent et al., 2008). The microbial water column diversity of some Arctic lakes was reported to be very rich despite their extreme locations (Charvet et al., 2012; Comeau et al., 2012).

At the base of the food web, phytoplankton in polar lakes include bacteria, eukaryotic algae and ciliated protists (Lizotte, 2008). Between 20 to 150 species of phytoplankton are found per lake in the Arctic and species number was found to be correlated with latitude, altitude or water temperature (Moore, 1979; Prowse and Reist, 2013). Species composition would be mainly determined by water chemistry (Forsström et al., 2009). Chrysophytes were reported to dominate the phytoplankton communities of High Arctic lakes (Charvet et al., 2012). However, picocyanobacteria could be the most abundant cell types in these waters (Van Hove et al., 2008). Zooplankton are important components of Arctic lakes as they represent the highest trophic level of the foodweb in lakes without fish. Their abundance is therefore only controlled by food supply and their ability to survive in cold conditions (Rautio et al., 2008). Rotifers, copepods, cladocerans, fairy shrimps (Anostraca) and mysids are the main components of the zooplanktonic community of Arctic lakes and ponds (Rautio et al., 2008). The distribution of zooplankton species in Arctic lakes is largely dependant on geographic location and correlates with the distance from locations that escaped glaciation in the Pleistocene period (Rautio et al., 2008). Zooplankton feed preferably on phytoplankton but they can also feed on benthic microbial mats in shallow lakes (Rautio et al., 2008). Some species live on the edge of their environmental tolerance while others have adapted to life at low temperatures, short growing season, long periods of ice cover, and low food supply (Rautio et al., 2008). In lakes with fish, predation controls the zooplankton community, as fish are size-selective in their feeding. Zooplankton therefore tends to be small and transparent in order to escape predation in these lakes (O'Brien et al., 2004; Rautio et al., 2008). Different species of fish have different impacts on the zooplanktonic community (O'Brien et al., 2004).

Arctic lakes display low fish abundance and diversity. Within the Arctic, eastern Canadian Arctic and Greenland are the regions with the lowest diversity because they were deglaciated last during the last ice age and still retain large ice sheets (Christiansen & Reist, 2013). Five fish families (carps and minnows, trouts and salmons, sculpins, perches, and lampreys), out of the 17-19 present in this region, comprise most of the Arctic freshwater diversity (Christiansen & Reist, 2013). Some lampreys, trouts and salmons are anadromous, meaning that they undertake regular migrations between marine waters (to benefit from the productive marine coastal environments for feeding), and freshwater (for reproduction, juvenile growth and over-wintering). These species are especially important for subsistence fisheries in Arctic communities. Approximately 127 species of fish occur in freshwater Arctic and sub-Arctic environments, which represent around 1% of the global fish estimate on the planet (Christiansen & Reist, 2013). Nonetheless, much research likely underestimates Arctic freshwater fish diversity, as it does not account for the important diversity that occurs below the species level. Out of these 127 species, 83-85 are obligate freshwater forms, 39 are anadromous and 2 species are catadromous (fishes which migrate from freshwater into the sea to spawn) (Christiansen & Reist, 2013). Arctic char (*Salvelinus alpinus*) is the freshwater fish the most northerly distributed as it is the only species to occur north of 75°N latitude, and in the LIA (Christiansen & Reist, 2013). Lake A, a coastal lake located at 83°N on the northern coast of Ellesmere Island hosts an anadromous Arctic char population (Veillette et al., 2012). This fish species is widely distributed throughout many habitats and exhibits different life-history strategies that vary with latitude, resulting in high adaptability (Power et al., 2008). Some populations are resident in lakes and show a complex variety of life-history tactics: they vary in growth and feeding patterns, and occupy distinct niches. Other populations are anadromous. Lake char (*Salvelinus namaycush*) are also present in many lakes in the south of the Canadian Arctic Archipelago (Power et al., 2008).

The well-developed benthic microbial mats at the bottom of Arctic lakes, streams and ponds are dominated by cyanobacteria, but other algal groups such as chlorophytes and chromophytes are also present (Jungblut et al., 2009). The benthic invertebrate community is abundant in Arctic lakes and is mostly composed of insect larvae (chironomids), oligochaete worms, snails, mites and turbellarians (Rautio et al., 2008). The only macrophytes present in Arctic lakes are benthic mosses (Jungblut et al., 2009).

Impacts of climate change on aquatic biodiversity

Climate change has been identified as the main threat to Arctic freshwater ecosystems, and to their related biological and functional diversity (Prowse & Reist, 2013). Since freshwater biodiversity typically declines sharply poleward (because of lower temperatures), the northward migration of aquatic organisms in response to climate change is likely to be straightforward (Prowse & Reist, 2013). As an example, freshwater fish would move northward along river corridors and anadromous fish would migrate in marine waters northward as the climatic constraints lessen (Christiansen & Reist, 2013; Fossheim et al., 2015). This will increase fish diversity of Arctic lakes and rivers. Increased summer air temperature and precipitation would have positive effects on the condition of anadromous fish and would increase their overall abundance, survival and growth, mainly because of increased marine productivity (Reist et al., 2006). Shifts in ice cover regimes will have cascading effects on the biological communities. The longer duration of ice-free conditions may increase primary productivity due to improved light conditions, and to enhanced nutrient availability caused by wind-induced mixing and entrainment of nutrients into the euphotic zone (the surface layer with enough light for net photosynthesis), and catchment geochemical inputs (Prowse et al., 2011). However, excessive nutrient inputs could lead to development of toxic cyanobacterial blooms that affect drinking water quality and lead to bioaccumulation within aquatic organisms (Instanes et al., 2016). Shifts in algae and invertebrates are also associated with decreased ice cover conditions (Smol et al., 2005). Changes in the timing of freeze-up and break-up of lakes will affect biological factors linked with seasonality. As an example, the seasonal succession of plankton is strongly coupled with the freeze-up and the break-up of ice cover and summer thermal stratification. Also, an earlier break-up may advance spring phytoplankton bloom and the associated zooplankton biomass peak. These effects may be offset by projected increases in surface accumulations of snow and formation of white ice, which impairs light penetration to waters beneath (Wrona et al., 2016). Finally, reductions in river ice cover will likely result in fewer ice-dam flood events and less severe break-up ice scouring (Wrona et al., 2016). However, cold-water fish species, such as the Arctic char, will likely reduce their habitat as temperature warms (Prowse & Reist, 2013).

11. Protected areas

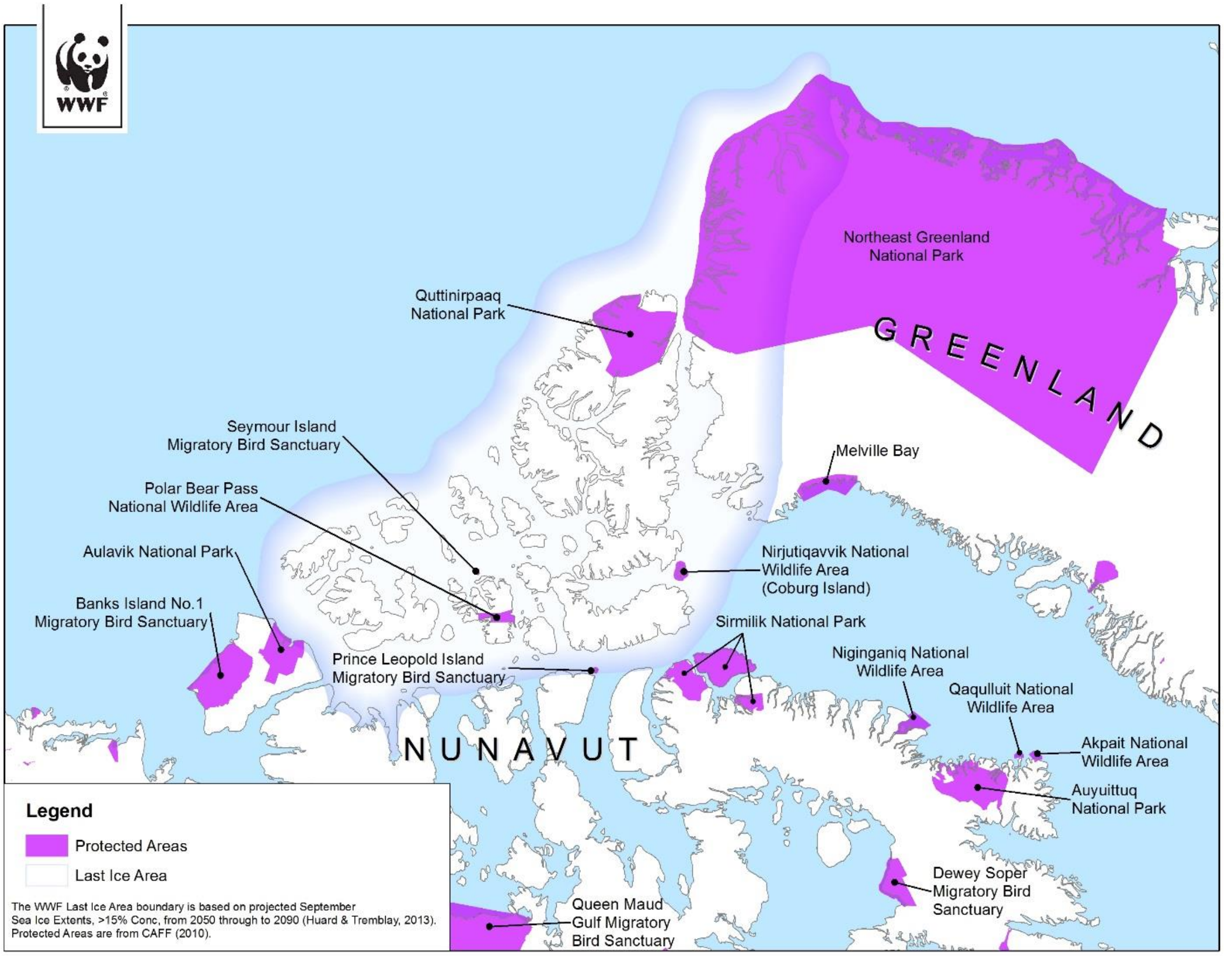
Certain terrestrial, coastal and marine areas of the Arctic are currently under some form of protected status. Interactive mapping platforms showing these areas are available online at www.protectedplanet.net (the World Database on Protected Areas (WDPA), a joint project of IUCN and UNEP), and at www.arkgis.org (Arctic Geographical Information System, by WWF). Protected areas are a key tool to maintain and conserve Arctic biodiversity and the functioning landscapes upon which species rely on for survival (Barry & McLennan, 2010). They have been established in strategically important and representative areas in order to help to maintain crucial ecological and physical features (e.g. seabird colonies, caribou migration and calving areas) (Barry & McLennan, 2010). Arctic protected areas are also important for global biodiversity conservation as Arctic habitats provide essential resources for many bird and mammal species that migrate to the Arctic seasonally (Barry & McLennan, 2010). Arctic protected areas also play a role in holding values for societies and allowing traditional uses and lifestyles (CAFF, 2002). In many Arctic countries, protected areas are co-managed with indigenous and local peoples, through which access to resources is maintained and knowledge is shared (Barry & McLennan, 2010). Arctic protected areas provide significant long-term economic benefits, for example by tourism, in term of revenues and employment to the countries and to local communities (CAFF, 2002). These areas are also important for education and recreation (Livingston, 2011). The Arctic contains most of the last remaining pristine and undisturbed landscapes. Protected areas in this region are therefore critical for research and monitoring as they can be used as benchmarks where human-induced changes are minimal (Livingston, 2011). However, increasing pressures from industrial development including the oil, gas, mining, forestry and transportation sectors, might modify the situation. Protected areas will face the challenge of resisting industrial pressures even if they offer economic benefits and job opportunities (CAFF, 2002).

Around 11% of the Arctic (including both marine and terrestrial environments) has some form of protected status. This covers 3.5 million km^2 and is divided into 1,127 protected areas (Barry & McLennan, 2010). Obviously, the nature and level of protection, and governance of these areas vary between the different Arctic countries. Although this level of protection is considerable, it is important to note that the North-East Greenland National Park accounts for over a quarter of the protected territory, and that, although over 40% of Arctic protected areas have a coastal component (Barry and McLennan, 2010), yet the marine environment is not well represented (CAFF, 2002). Therefore, the area of Arctic protected areas should be increased, with the International Aichi Biodiversity Target aiming for at least 17% of terrestrial and inland water, and 10% of coastal and marine protected areas worldwide by 2020 (Convention on Biological Diversity, 2013). The Aichi Biodiversity Target also stresses the role of areas of particular importance for biodiversity, such as High Arctic environment, and the importance of connectivity between protected areas to facilitate species migration.

With ongoing climate change and increasing human impacts in the Arctic, it is urgent to assess the effectiveness of protected areas as a conservation tool. Also, a changing climate motivates the identification and the advancement of the protection of large areas of ecologically important marine, terrestrial and freshwater habitats (CAFF, 2013a). It is critical to ensure environmental conservation outside of the actual protected areas boundaries as the northward shift of species or greening of the Arctic may move the target ecological features outside of the original protected area (Barry and McLennan, 2010). Areas critical for sensitive life stages of Arctic species may also be located outside of protected areas (CAFF, 2013a). Arctic biodiversity associated with sea ice, glaciers and permafrost is especially vulnerable to changing environmental conditions and CAFF recommend to safeguard areas where High Arctic species have greater chance to survive in the future for climatic and geographical reasons, such as certain islands and mountainous regions (CAFF, 2013a, b). These areas would act as a refuge for these specialized species. This recommendation is one of the main raison d'être of the Last Ice Area (LIA) project.

There are a total of 7,864 protected areas in Canada, 28 of which are in Nunavut (Canadian Council on Ecological Areas, 2016). Protected areas in the LIA and its vicinity, which cover terrestrial and marine environments are identified in Figure 46. As of 2015, Canada has designated 10.6% of its terrestrial areas as protected and less than 1% in the marine environment (CCEA, 2016). These areas are protected under different jurisdictions including Parks Canada, Environment and Climate Change Canada, Indigenous and Northern Affairs, Fisheries and Oceans Canada and the National

Capital Commission (Environment and Climate Change Canada, 2016). Moreover, Canada is currently in the process of establishing a national marine conservation area near Lancaster Sound (Parks Canada, 2013a, 2017). Lancaster Sound is the eastern entrance to the Northwest Passage, the sea route through Canada's Arctic Archipelago. This area is crucial for marine mammals including seals, narwhals, belugas, bowhead whales, walrus and polar bears. Lancaster Sound is also bordered by huge seabird breeding colonies, with populations in the hundreds of thousands. Additionally, in 2017 the International Union for Conservation of Nature (IUCN) in partnership with the U.S. Based Natural Resources Defence Council and World Heritage Centre identified two sites within the LIA that warranted protection and could qualify for World Heritage Status: Remnant Arctic Multi-Year Sea Ice and the Northeast Water Polynya Ecoregion and The North Baffin Bay Ecoregion (Figure 47; Speer et al., 2017). If afforded World Heritage Status, these sites will receive extra resources and support for management and conservation initiatives. The following paragraphs briefly describe each of the nationally designated protected areas located in the LIA.



The WWF Last Ice Area boundary is based on projected September Sea Ice Extents, >15% Conc, from 2050 through to 2090 (Huard & Tremblay, 2013). Protected Areas are from CAFF (2010).

Figure 46. Protected areas in LIA and its vicinity (Protected Planet, 2013).Note this map does not include the recently designated Qausuittuq National Park.

The Northern Baffin Bay Ecoregion

Remnant Arctic Multi-Year Sea Ice and the Northeast Water Polynya Ecoregion

Map: Marine Geospatial Ecology Lab, Duke University (2016)

Figure 47. Sites nominated for UNESCO World Heritage Status. Top. Northern Baffin Bay Ecoregion. Bottom. Remnant Arctic Multi-year Sea Ice and the Northeast Water Polynya Ecoregion. Taken from (Speer et al., 2017)

North-East Greenland National Park

The North-East Greenland National Park is the largest (with an area of 972,000 km^2) and most northerly national park in the world. It extends three nautical miles into the adjacent sea. The Greenland Government established it in 1992, 15 years after it was appointed a UNESCO biosphere reserve. Mineral exploration is possible within this park (Tejsner and Frost, 2012). It is the only national park in Greenland and it encompasses the entire northeastern coastline of 18,000 km, and interior sections of Greenland. The Sirius Dog Sledge Patrol, Danish Navy, monitors the coastline of the park and is stationed at Daneborg, located in the National Park. Also, the research station Zackenberg is located within the park. There are no permanent Inuit settlements within the park.

Melville Bay Nature Reserve

This reserve borders with LIA. It is a large bay off the coast of northwestern Greenland. It is located to the north of the Upernavik Archipelago and opens to the southwest into Baffin Bay. It was established in 1977. Melville Bay Nature Reserve has an area of 7,957 km^2, of which 5,193 km^2 are marine (Wood, 2007). The Greenland Government is currently drafting a new regulation for the nature reserve with a clearer definition of activities allowed within the reserve (e.g. traditional hunting) (Tejsner and Frost, 2012).

Quttinirpaaq National Park

The Quttinirpaaq (“top of the world” in Inuktitut) National Park is located on the northeastern part of Ellesmere Island. It is the northernmost park in Canada and the second largest, after Wood Buffalo National Park. It covers 37,775 km^2, of which 2,670 km^2 are marine (Wood, 2007). It was established as Ellesmere Island National Park Reserve in 1988, and the name was changed to Quttinirpaaq in 1999, when Nunavut was created, and became a national park in 2000 (Parks Canada, 2013b). Quttinirpaaq is pending an application as a UNESCO world heritage site (UNESCO, 2013). Most of Quttinirpaaq National Park is classified as an Arctic desert.

Qausuittuq National Park

Qausuittuq was recently designated as a national park in 2015, and means “place where the sun doesn't rise” (Parks Canada, 2015). Qausuittuq includes most of Bathurst Island and a number of islands west of Bathurst Island, and is north of the Polar Bear Pass National Wildlife area (Parks Canada, 2012). This area has been chosen to represent the Western High Arctic Natural Region. This park will help to protect the endangered Peary caribou and other terrestrial and marine wildlife.

Sirmilk National Park

Located near Pond Inlet, Sirmilik (“the place of glaciers” in Inuktitut) National Park is composed of three separate areas at the north end of Baffin Island: most of Bylot Island, the area between Oliver Sound and Paquet Bay, and the Borden Peninsula east of Arctic Bay. Sirmilik National Park represents the Northern Eastern Arctic Lowlands Natural Region and portions of the Lancaster Sound Marine Region (Parks Canada, 2013c). This park was created in 2001 and has a global area of 22,252 km^2. Although this park does not include a marine portion, it is surrounded by ocean.

Bylot Island Migratory Sanctuary

Bylot Island is a Migratory Bird Sanctuary, was established in 1965 and is about 25 km north of Pond Inlet, and is partly encompassed by the Sirmilik National Park. The Sanctuary is host to 74 unique species of arctic birds, and provides nesting habitat for the largest breeding colony of greater snow gees in the Canadian High Arctic (Environment Canada and Climate Change, 2017). It is managed the Parks Canada Agency and the Canadian Wildlife Service of Environment and Climate Change Canada.

Aulavik National Park

Aulavik ("place where people travel" in Inuvialuktun) National Park is located on Banks Island and was established in 1992. This park protects 12,274 km of Arctic Lowlands (Environment Canada, 2013a). This park encompasses a variety of landscapes from fertile river valleys to polar deserts, is home to the Peary caribou and has the highest density of musk ox in the world.

Nirjutiqavvik National Wildlife Area (Coburg Island)

Nirjutiqavvik National Wildlife Area includes Coburg Island and its surrounding marine areas, and is located between Ellesmere Island and Devon Island. It was established in 1995. It encloses 1,650 km^2, including a marine portion with intertidal components of 1,283 km^2. This national wildlife area is one of the most important seabird nesting areas in the Canadian Arctic. It supports around 385,000 seabirds, predominantly Thick-billed Murres and Black-legged Kittiwakes. Northern Fulmars, Glaucous Gulls, Black Guillemots and Atlantic Puffins also nest on Princess Charlotte Monument Island (Environment Canada, 2013b). This area is also important for polar bear, walrus, ringed seal, bearded seal and migrating beluga and narwhal (Environment Canada, 2013b).

Polar Bear Pass National Wildlife Area (Bathurst Island)

Polar Bear Pass National Wildlife Area is located on Bathurst Island, in the heart of the Canadian Arctic Archipelago. It has an area of 2,636 km^2 (including 214 km^2 of marine environments) and was created in 1985. This protected area was created because it supports significant wildlife populations and important archaeological sites (Environment Canada, 2013c). Polar Bear Pass National Wildlife Area supports more than 54 species of birds including 30 breeding species (mostly waterfowl and shorebirds), Arctic fox, Arctic wolf, lemmings, musk ox, the Peary Caribou, and polar bears travel through the area in spring and summer.

Prince Leopold Island Migratory Bird Sanctuary

This migratory bird sanctuary is located on Prince Leopold Island within Lancaster Sound, at the junction of Prince Regent Inlet and Barrow Strait. It was established in 1992 and covers 311 km^2, including a marine portion of 243 km^2. This area is host to huge seabird colonies of murres, kittiwakes, fulmars and guillemots and its surrounding waters represent a major seabird feeding area (Environment Canada, 2013a).

Seymour Island Migratory Bird Sanctuary

This bird sanctuary is part of the Berkeley group of islands and is located approximately 30 km north of Bathurst Island. It was designated in 1975 and this protected area is small (28 km^2 including a marine portion of 20 km^2). The island is approximately 3 km long, and raised beaches cover most of the island. Seymour Island supports the largest Ivory Gull colony in Canada. The Ivory Gull is an endangered species (Environment Canada, 2013a).

12. Additional potential stressors

Although the Arctic is still sparsely populated, it is experiencing pressure from numerous sources. Climate change is a prominent driver affecting the entire Arctic. The climatic impacts for marine and terrestrial environments, and their related biodiversity, have been addressed throughout the different sections of this report. Additional important factors that threaten the integrity of Arctic ecosystems are enhanced mining and oil and gas activities, increased shipping, and contaminants by local pollution or long-range transport. These anthropogenic stressors are also likely to interplay and have cumulative effects. A companion report by WWF on the non-renewable resources of the LIA looks more closely at the economic probability of exploitation of these resources (see Frost, 2014). The text on mineral resources below is from the summary section of that report.

12.1 Oil and gas exploitation, and mining

Oil and gas development in the Canadian Arctic began in the Beaufort Sea in the 1970’s (WWF, 2014). During this time, seismic exploration also occurred in the Lancaster Sound region of the Canadian Arctic Archipelago. At the moment the highest known oil and gas potentials for the Canadian Arctic Archipelago are in the Sverdrup Basin and (Figure 48), although Shell Canada recently withdrew is exploration permits in the Lancaster Sound region (CBC, 2016). Large known and predicted hydrocarbons occur in the LIA although there is no current exploration or production except for some seismic surveys by Conoco south of the Greenland LIA. Most of the past exploration emphasis has been in the Paleozoic and Mesozoic strata in the central Sverdrup Basin. Future exploration may test the play fairways along the southern rim of the Sverdrup Basin and the Arctic Fold Belt where there is significant hydrocarbon potential.

In the Greenland LIA hydrocarbon potential occurs in major offshore sedimentary basins, notably the large basins offshore west Greenland and east Greenland. To date no fields have been discovered and no commercial development occurs on the Greenland continental margin. Assessment studies indicate that there is significant potential for large resources in the offshore basins particularly in the West Greenland-East Canada Province. Exploration licenses for the Greenlandic portion of the LIA are located in Northwest and Northeast Greenland (Figure 49).

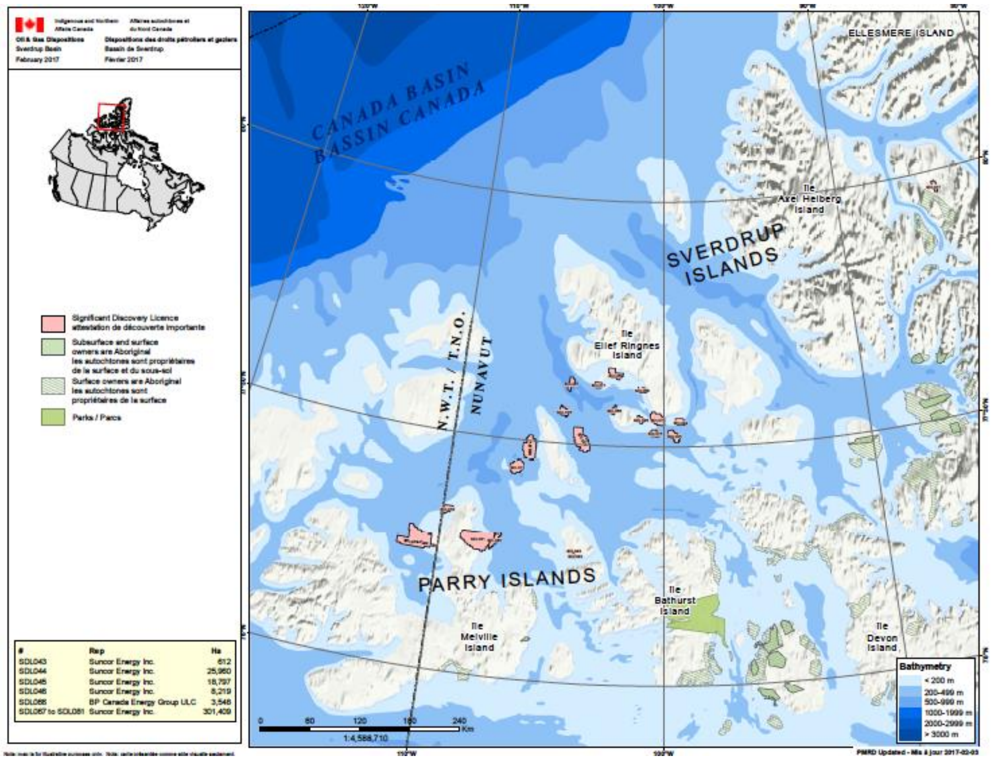


Figure 48. Location of oil and gas rights and potential oil development areas in the Canadian Arctic Archipelago. Current as of June 2016 (Indigenous and Northern Affairs Canada, 2017).

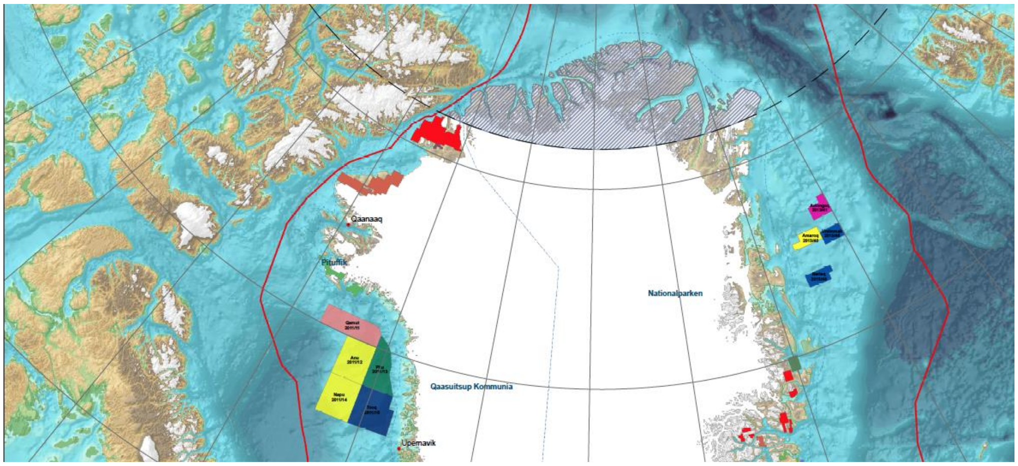


Figure 49. Mineral hydrocarbon licenses in north Greenland (Government of Greenland – (Ministry of Industry and Mineral Resources, 2014)

The geological setting of the LIA naturally favours hydrocarbon georesources over mineral resources. The latest known period of widespread mineralization in the area predates the Paleozoic sedimentary rocks, therefore rocks of this age or younger may be discounted as sources of metalliferous deposits. Most of the mineral exploration activities occur in Archean rocks in the southern part of the LIA particularly on Baffin Island where the geology is more conducive for mineralization. A number of zinc-lead deposits and occurrences have been delineated in the Greenland part of the LIA with the Citronen Fjord deposit being in an advanced stage of exploitation.

There are many technical and environmental obstacles, which will complicate Arctic and LIA natural resource development. Technical challenges arise from extreme climatic conditions that necessitate specific requirements for equipment, materials and construction operations. Environmental concerns are particularly associated with accidents and pollution that may damage delicate Arctic ecosystems and local people's livelihoods. The main obstacle, however, is the lack of sufficient infrastructure to confirm viability, economy and safety of LIA operations. The only operating mine in the region is the Mary River iron ore project on Baffin Island. It is only functioning at limited production due to low global prices for iron, but could reach large-scale activity in 15-20 years (Nunavut Geoscience Exploration Overview, 2012).

Climate warming presents challenges for resource development and infrastructure design in the LIA. Georesource activity is likely to experience savings due to reduced sea-ice extent and a longer shipping season. However, continued warming will increase the rate of permafrost thawing which in turn will alter ground conditions. This will adversely affect structures and increase the cost and maintenance of tailings impoundments, buildings, pipelines, airfields, and other installations which support resource activity. Structures must be designed to ensure that contaminants and acid-rock drainage are not discharged to the environment.

Large scale pollution is the primary environmental concern for georesource activity in the LIA. In Arctic environments pollution both onshore and offshore persist longer than anywhere else. Responder's time and efforts will be hampered by harsh environmental conditions, a near total lack of infrastructure and long distances. The environmental and ecological impact of Arctic contamination would depend on its timing and location relative to patterns of breeding, spawning and species migration. Sea birds, marine mammals, and fish larvae are particularly vulnerable to larger oil spills and other industrial contaminants.

Oil spill prevention is the ultimate goal, but, in the event of a spill, operators must strive to ensure that the response is robust, efficient and well-adapted to local conditions. Ice in its various forms can make it more difficult to detect oil, and to encounter, contain and recover oil slicks with booms, skimmers, and other countermeasures (Glover & Dickins 1999). The current technologies and infrastructure for recovery of oil from the surface perform poorly in high waves and rough weather conditions, and ocean currents will spread the pollutants over extensive areas. In the Arctic, low temperatures and scarce sunlight over much of the year will slow evaporation rates as well as the physical, chemical and biological breakdown of pollutants. Thus, hazardous compounds released during an emergency may remain in Arctic ecosystems for long periods of time, aggravating the risk of bioaccumulation.

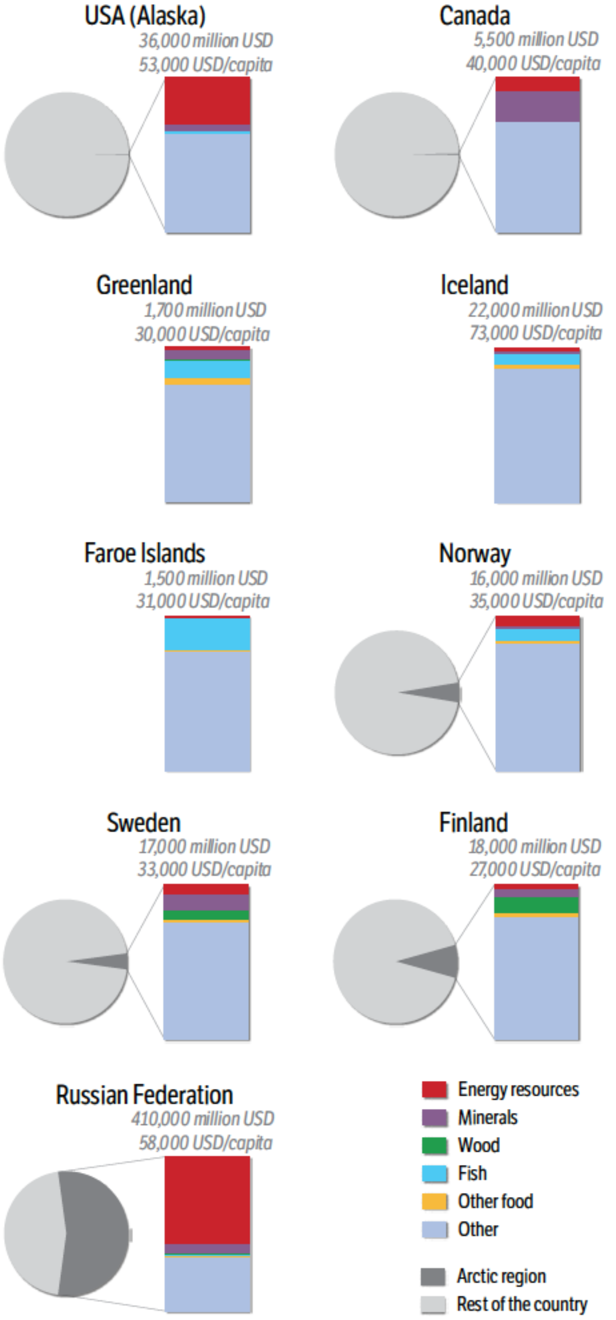


Figure 50. The importance of Arctic natural National and regional economies (taken from Arctic Council, 2016)

The natural containment provided by ice may offer some relief. In open water, slicks can spread and drift so quickly that shoreline impingement may occur before a response can be initiated. Ice, however, may confine oil spills and provide time to mount a response. Due to the cold temperatures and reduced wave energies in ice fields, spilled oil will weather more slowly, which may extend the window-of-opportunity for some countermeasures. Extreme Arctic conditions present a number of challenges to mounting safe and effective oil spill response actions. To overcome these challenges responders must develop action plans with an understanding not only of the physical environment but also with a basic understanding of the effect this environment will have on the fate and behavior of spilled oil (Potter et al. 2012).

Reports from both industry and government groups in the polar states have addressed strategies and techniques for handling pollutants in a variety of ice conditions. With very little infrastructure in the LIA from which to stage an effective recovery program it becomes obvious that Canada and Greenland are poorly equipped to handle such catastrophes. The rich and unspoiled ecosystems of the LIA will always be at risk from industrial activity. A comprehensive, international policy on clean-up response techniques, mitigation policies and liability recommendations is required. Finally, the social and geopolitical reality of economic change makes the development of this industry more complex. Certain economies are heavily reliant on extractive industries, whereas others are based on local subsistence activities (Figure 50). As many natural resources in the Arctic lie beyond national jurisdictions, the control of a region’s resource exploitation is a global endeavour with high political and economic stakes (Arctic Council, 2016). If Arctic exploitation develops, pan-Arctic policies are necessary to tackle conflicts of interest.

Conclusions

The LIA is a frontier region for petroleum and mineral exploration. Commodity forecasts, for both petroleum and minerals, predict a steady increase of demand for georesources and subsequent increase of prices over the next 20 to 25 years. New technology and data will make parts of the LIA more prospective. Given the long lead times necessary to meet regulatory requirements, a lack of strategic infrastructure, economic factors and insufficient scientific data large scale production of resources in the LIA is unlikely to occur within the next 20 to 30 years. New large discoveries in more temperate environments are of more interest for industry investment.

The most probable targets for future georesource development in the LIA are:

1. Hydrocarbons – Development of West Greenland-East Canada Province is possible in 20 to 25 years if current seismic studies delineate large-scale offshore structures (Gautier 2008). All the recent surveys are south of the LIA. The Greenland continental margin may be more prospective than the Sverdrup Basin due to infrastructure factors.
2. Zinc – Citronen mine site production is possible in 10 to 15 years if current activity demonstrates significant reserves (Ironbark 2011).
3. Iron ore –Mary River shipped its first iron ore in 2015 (Baffinland, 2015), but large scale mining is probably 15 to 20 years away (Nunavut Geoscience Exploration Overview 2012).

12.2 Shipping

An increase in Arctic shipping through the LIA is expected by 2020, due to a surge of ecotourism voyages and the development of several large-scale mining projects such as Citronen Fjord in northeastern Greenland and the Mary River project on Baffin Island. By 2050, Arctic shipping in LIA waters could increase by a factor of six, if large-scale georesource production occurs (CIGI, 2013). As maritime activities continue to increase, the levels of resupply to northern communities will also increase as populations grow. Problematically, only 10 percent of Canada's Arctic waters are charted to modern standards, according to the Canadian Hydrographic Service, and few navigational aids are available (Humbert & Raspotnik, 2012).

New technology such as ice management systems provide more efficient ways to conduct operations by extending the operating season while mitigating ecological, environmental, and safety risks. Systems for ice management address some of the complex challenges associated with operating in the harsh but fragile Arctic environment and provide ice visualization, analysis, tracking and risk mitigation tools for offshore Arctic operations (Ion Geophysical 2013). However, effective ice management doesn't reduce the risks associated with many complex challenges like extreme cold, darkness and unpredictable weather.

In 2007, the Canadian government said it would address the lack of deepwater port infrastructure in the Canadian LIA by committing $100 million dollars to turn the port at the old Nanisivik mine on Baffin Island into a deepwater facility. Due to budget constraints in March 2013 the government announced a major downsizing of northern development leading to a reassessment of infrastructure investment (CIGI 2013). In 2015, the Government of Nunavut announced plans to use federal funding of up to $63.7 million to support a Marine Port and Sea Lift Facility near Iqaluit (Government of Nunavut, 2015). The new port is projected to be completed by 2020.

The increasing gap between service requirements and capabilities, such as equipment transportation and spill response measures, in the LIA highlights the concerns of resource operators. The lack of infrastructure including road and rail networks, deepwater ports, paved runways, geology and topographic maps —impedes safe transportation, and makes exploration and resource development extremely difficult, risky and more expensive.

One of the Arctic’s most important contributions to the northern Canadian and Greenlandic economies will be the Trans-Arctic waterways. The volume of ship traffic in Arctic waters is projected to increase as the length of open water season is extended (Figure 51). By late century, trans-Arctic shipping may potentially be commonplace (Melia et al., 2016). Arctic states have recognized that the new waterways will be an opportunity to re-define their national boundaries and expand commercial operations. For example, the Northwest Passage route transits the LIA and could be crucial for future georesource activities. The shortest comparable routes, for instance, through the Panama or Suez Canals, or around the Cape of Good Hope, are more than twice the distance of the longest Arctic route (Parliament of Canada Info Series PRB 08-07E, 2008).

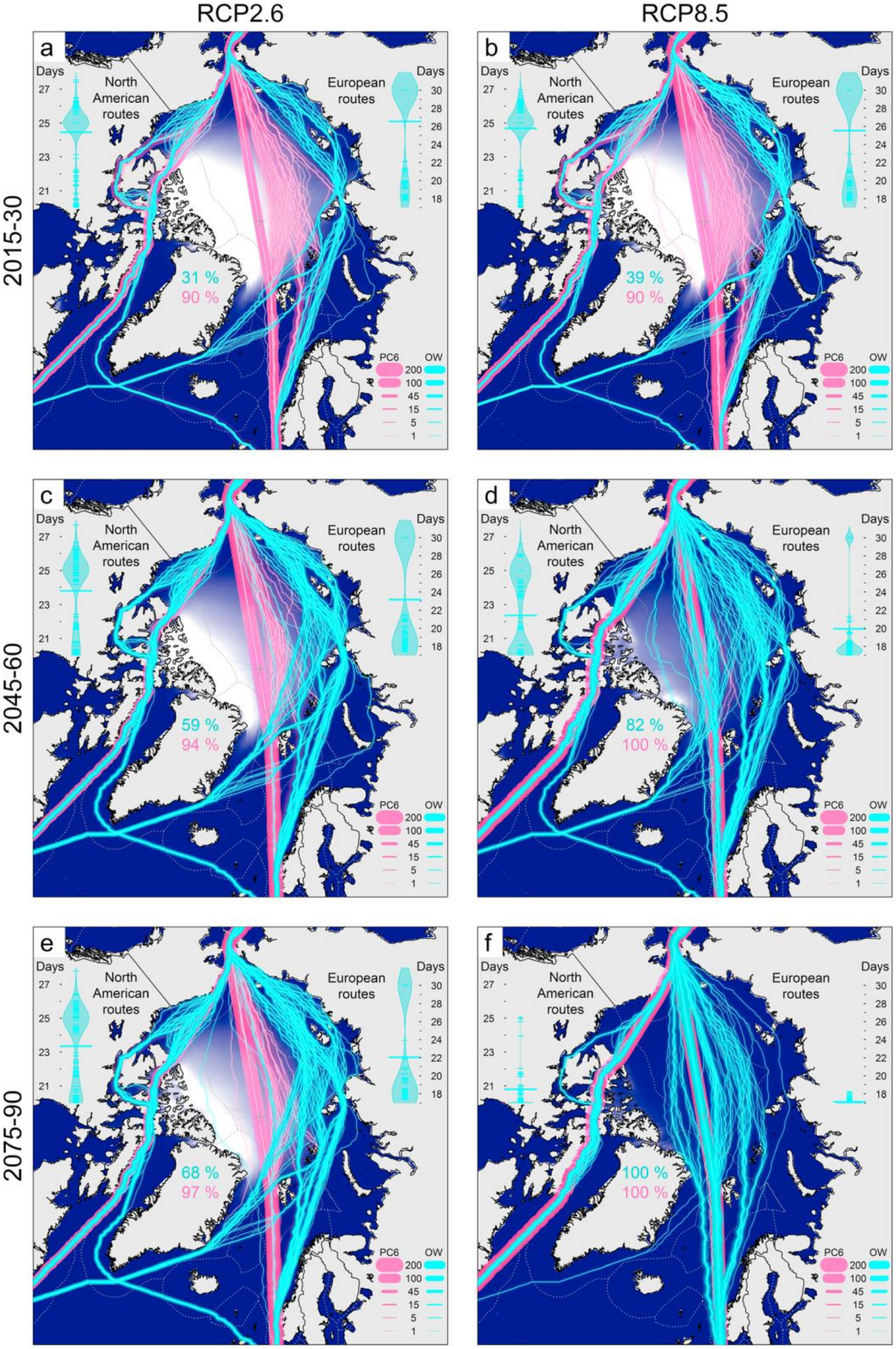


Figure 51. Projected September trans-Arctic routes from two different climate change scenarios. Routes for low emissions scenario RCP2.6 (a,c,e) and high emissions scenario RCP8.5 (b,d,f) split into three time periods. Cyan lines represent open water vessels and pink represent Polar Class vessels (can break through first year ice) (taken from Melia et al., 2016).

Most studies suggest that commercial shipping through the Northwest Passage would not occur for many years yet. However, in September 2013 the Danish owned Nordic Orion bulk carrier made history when it hauled 15,000 tonnes of coal from Vancouver to Finland through the North West Passage. It took four days less than it would have by transiting the Panama Canal and the greater sea depths allowed the Orion to carry 25% more coal. Shipping through the passage saved the company $200,000. Talks are underway between Transport Canada and various shippers to increase such voyages. Unlike Russia, where shippers have more than 400 ice class carriers, Canada has not made upgrading Arctic infrastructure and shipping activities a priority. To take advantage of newly open Arctic shipping lanes Canada and Greenland must make significant investments in shipping facilities and define regulations required for safe transportation through the LIA.

The impacts of shipping can be deleterious for marine biodiversity. The increase in transport augments the risks of the introduction of invasive species by ballast waters that could disrupt the ecosystems (source). Also, noise and direct contact from ships can induce disturbance or harm marine mammals and fish. Given the heavy use of fossil fuels to power marine ship movements, vessel emissions may have regional impacts, such as deposition of black carbon, which could contribute to increased regional melt rates, contamination of local environments and changes in albedo effect (Arctic Council, 2009; Nunavut Impact Review Board, 2014) Some of these impacts are expected to be addressed to some extent by the Polar Code of the International Maritime Organization.

12.3 Contaminants

The Arctic is not as clean as it should be based on its remote location, with few in-situ industrial activities and direct sources pollution and contaminants. Unfortunately, the Arctic is a sink for anthropogenic contaminants (Macdonald, 2005). Contaminants, originating from temperate industrial centres, travel by long-range-transport within the atmosphere, oceans, rivers and migratory animals (AMAP, 2009). When contaminants that travel by atmospheric currents arrive in the Arctic, they reach the ground and surface water because of cold condensation.

Contaminants found in the Arctic include the persistent organic pollutants (POPs), heavy metals (such as mercury, cadmium and lead) and radionuclides (radioactive atoms). Current trends in contaminant burden in the Arctic environment vary among these different classes of compounds. There was a general decline in the concentrations of legacy POPs (PCBs, DDTs, HCB, chlordane, dieldrin, toxaphene, dioxins) in the 1990’s as a result of increased regulation their reduced usage (AMAP, 2009; Hung et al., 2016). Emerging and current-use POPs (include brominated flame retardants (BFRs), fluorinated compounds, PCNs) have been added to the Stockhom Convention (AMAP, 2015). Nevertheless, BFRs are starting to decline in the environment due to national regulations (AMAP, 2009). However, trends in mercury concentrations over time vary from one region to another and from one type of environment (such as the atmosphere, lakes, biota) to another (AMAP, 2011). Reductions in mercury emissions from human activities over the last 30 years is reflected by decreasing mercury levels in the High Arctic atmosphere, although mercury levels in most animals are not showing this trend (AMAP, 2011); however, Mercury levels remain elevated and in some case exceed guidelines in parts of Greenland and Canada (AMAP, 2015). Cadmium and lead were generally found to decline (AMAP, 2009), although lead levels still remain elevated in some parts of Russia and Arctic Canada (AMAP, 2015). Radionuclides level in the environment are also declining (AMAP, 2009).

Contaminants impose an additional stress on Arctic ecosystems as they enter and move through Arctic food webs. Many of these chemicals bio-amplify (i.e. concentrations in higher trophic levels are greater than at the base of the food web) and reach very high levels in top predators such as the polar bears and people. Contaminants can cause chronic and acute health effects on species over the short and long term. Climate change is also interacting with contaminant transport pathways (AMAP, 2009). For instance, higher temperatures in temperate industrial centres will increase the volatilization of contaminants, these will travel by atmospheric transport to the Arctic, and there will be a greater delivery of contaminants to the Arctic (AMAP, 2009).

13. Concluding remarks

The LIA region encompasses an exceptional variety of marine and terrestrial ecosystems. The Arctic environment is currently facing multiple threats with climate change being the most prominent. Climate change is associated with drastic changes in the marine environment such as loss in sea ice cover, warmer water temperature, ocean acidification, and shifts in the marine food webs. The terrestrial environment sees its snow cover altered, lakes and rivers ice cover decline, glaciers retreat, the Greenland Ice Sheet is losing ice, and permafrost is melting. Species with specialized life histories, as those in association with ice and snow, may struggle for persistence in the future as their strong ties with the cryosphere make them less resilient to change. Sea ice obligate and associated species will need to adapt to other habitats and prey species, or may shift their range northwards with the decline in sea ice cover. However, the North is not an endless frontier – there is no further North left after 90ºN. Where species depend on terrestrial habitats in part of their lifecycle (such as polar bears which den on land), northward shifts are even more limited as land terminates at around 82ºN. Furthermore, the rate of change currently occurring in the Arctic is extremely fast, pushing the adaption capability of species to their limits.

The LIA area needs to be monitored and indicators of change could be very useful for this. Indicators are features that are sensitive to shifts. Polynyas (Smith Jr & Barber, 2007) and epishelf lakes (Veillette et al., 2008) were suggested to be effective indicators in the High Arctic and they are currently present in the LIA. There is a need for better understanding of the productivity of the high Arctic, the current density and distribution of life there, and the operation of its systems. This is being addressed by ongoing scientific research (such as that sponsored by ArcticNet) but coverage of this region of the High Arctic is still partial at best due to the difficulty and expense of conducting research in the region, and the vast area to cover.

While defining management regimes for the LIA, special attention should be paid to critical habitats such as migration routes, foraging, breeding and resting areas of Arctic species. Also, economic activities need to be managed in a way that needs of local communities are fulfilled within the limits of biodiversity and ecosystem functions capacity. Most importantly, attention needs to be paid to projected future states of the Arctic when defining management regimes. What has worked within a relatively stable environment over the past several decades may not work with the extremely rapid environmental, economic, and social change that the Arctic is now experiencing. Monitoring and further investigation of the ice ecosystem of the LIA are useful contributions but action to conserve those ecosystems must not be contingent on a full and complete scientific understanding of those systems, otherwise any interventions may be too late.

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Appendix I Key Geographical Features

Community	Important geographic locations	Why important/valued
Arctic Bay	Moffett Inlet	Location only identified. No additional information provided.
	Admiralty Inlet	This offshoot of Lancaster Sound is the area of focus for most of the community's hunting and fishing. The inlet holds a great abundance of Arctic cod, found immediately below the edge of landfast sea ice.
	Devon Island, Gulf of Boothia, Foxe Basin	There is an extensive landfast lead found along the southern coast of Devon Islands to approximately Prince Regent Inlet
	Navy Board Inlet	Area that supports wildlife
	Lancaster Sound	Area from which much of the wildlife in Admiralty Inlet originates and migrates
	Borden Peninsula (on one side of Admiralty Inlet)	This land is especially supportive of wildlife
	Brodeur Peninsula (on the other side of the inlet)	Supports some wildlife
	Bylot Island	Area that supports wildlife
	Agu Bay	Location of polar bear, ringed seal, narwhal
	Bernier Bay	Location only identified. No additional information provided.
	Milne Inlet	Thousands of narwhal (calving, feeding) in July and August
	Steensby Peninsula and Steensby Inlet region	Polar bear location, beluga calving and feeding grounds, inukshuks found here
	Mary River	Historic camping spot and gathering ground for Inuit clans
	West Prince Regent	Lots of narwhal.
Pond Inlet	Eclipse Sound	Location only identified. No additional information provided.
	Bylot Island	East end is important for sport polar bear hunt and part of the island is important good nesting area
	Lancaster Sound	Very important for marine mammals, the National Marine Conservation Area in this region is an important area for fish (e.g. char) that spawn in lakes

	Milne Inlet	Narwhal calving areas and fish habitat
	Button Point	Waters are important for narwhal calving in summer
	Robertson River	Location only identified. No additional information provided.
	Sirmilik National Park	East of Arctic Bay, important for caribou hunting
Resolute	Area between Somerset Island and Prince of Whales Island	Caribou crossing
	Area between Prince of Whales Island and Bathurst Island	Caribou crossing
	Between Cornwallis Island and Somerset Island	Beluga stop here in the summer as they are heading South into Peel Sound to molt and feed. Feed on Arctic cod in this area
	Polar Bear Pass	Area community wants protected
	Creswell Bay	Identified as very important for community, lots of fish and wildlife
	Maxwell Bay	Very rich benthic community
	Bathurst Island	Caribou on east side need to be protected
Grise Fiord	Fossil Forest	Location only identified. No additional information provided.
	Throughout Jones Sounds and into Norwegian bay, Baumann Fiord, Vnedom Fiord, and Makinson Inlet	Areas important for wildlife and support a range of hunting and fishing activities of Grise Fiord Inuit. These areas are also cultural sites.
	Areas around Bjorne Peninsula, Baumann Fiord, Norwegian Bay, Gallery Point, Coburg Island , and Sverdrup Inlet	Areas important to community members because of intrinsic value, also locations of big fossils and petrified trees, popular for bird nesting, important for caribou and fish (especially Bjorne Peninsula)
	Craig Harbour	Grise Fiord Inuit hunt marine mammals throughout this region
	Nearshore waters and fiords of Southern Ellesmere Island: Joens Sound, Baumann fiord, Vendom Fiord, Makinson Inlet, and Norwegian Bay	Ringed seals found year round, also narwhal and walrus
	Norwegian Bay	Important for polar bears

	Head of Baumann Fiord, Hoved Island	Muskox
	Cone Island and Smith Island	Thousands of gulls on cliffs
	Jakeman Glacier	Hundreds of female walrus use base of glacier as haul-out location
	Polynyas: Lady Ann Strait polynya, west of Coburg Island, Hell Gate polynya in Cardigan Strait, Coburg Island polynya easts of Coburg Island, and North Water polynya east of Ellesmere Island (largest polynya)	Very important areas of high productivity and as such important harvesting grounds

Top Key Features and Reasons for Importance (Petrasek MacDonald Consulting, 2016).

Appendix II List of mammal species

Species Name		Sub-species	North Greenland	Ellesmere and Devon Islands	Canadian Archipelago
English	Scientific				
Marine mammals					
Whales					
Beluga	Delphinapterus leucas		√	√	
Bowhead Whale	Balaena mysticetus		√	√	
Narwhal	Monodon monoceros		√	√	√
Orca	Orcinus orca			√	
Pinnipeds					
Bearded Seal	Erignathus barbatus			√	
Harp Seal	Phoca groenlandica			√	
Ringed Seal	Pusa hispida			√	
Walrus	Odobenus rosmarus	O.r. rosmarus Atlantic	√	√	
Polar bear					
Polar Bear	Ursus maritimus		√	√	√
Terrestrial mammals					
Arctic Fox	Alopex lagopus		√	√	√
Arctic Hare	Lepus arcticus		√	√	√
Musk Ox	Ovibos maoschatus		√	√	√
Northern Collared Lemming	Dicrostonyx groenlandicus		√	√	√
Red Fox	Vulpus vulpus			√	
Reindeer	Rangifer tarandus	R.t. groenlandicus Barren-ground and *R.t. pearyi*	√ R.t. groenlandicus Barren-ground	√ R.t. pearyi	√ R.t. pearyi

Stoat	Mustela erminea		√	√	√
Wolf	Canis lupus	C.l. arctos	√	√	√
Wolverine	Gulo gulo	G.g. luscus		√	√

Mammals present in LIA (Sale, 2006).

Appendix III List of bird species

English Name	Scientific Name	Range
Red-throated Diver	Gavia stellate	Throughout Canadian LIA
Northern Fulmar	Fulmarus glacialis	Southeast Ellesmere Island, southwest Devon Island
Snow Goose	Anser caerulescens	All islands directly along the Parry Channel, southern Ellesmere Island
Brent Goose	Branta bernicla	Northern Ellesmere Island, southern Devon Island
Common Eider	Somateria mollissima	Devon and Cornwallis islands
King Eider	Somateria spectabilis	Throughout LIA
Long-tailed Duck	Clangula hyemalis	Throughout LIA
Rough-legged Buzzard	Buteo lagopus	All islands directly along the Parry Channel
Gyrfalcon	Falco rusticolus	Greenland (north-east, north, north-west), Ellesmere, Devon, Melville, Prince Patrick islands
Rock Ptarmigan	Lagopus muta	Throughout LIA (except northern Ellesmere)
Sandhill Crane	Grus canadensis	Southern Devon and Cornwallis islands
Ringed Plover	Charadrius hiaticula	Eastern Devon and eastern Ellesmere islands
American Golden Plover	Pluvialis dominica	Southern Devon Island
Grey Plover	Pluvialis squatarola	Melville Island
Baird's Sandpiper	Calidris bairdii	Throughout LIA, except northernmost Greenland
Knot	Calidris canutus	Throughout LIA
Pectoral Sandpiper	Calidris mealnotos	All islands directly along the Parry Channel
Purple Sandpiper	Calidris maritima	Devon and southern Ellesmere islands
Sanderling	Calidris alba	Throughout LIA
Buff-breasted Sandpiper	Tryngites subruficollis	Southern Devon and Cornwallis islands
Ruddy Turnstone	Arenaria interpres	Throughout LIA
Grey Phalarope	Phalaropus fulicarius	All islands directly along the Parry Channel
Arctic Skua	Stercorarius parasiticus	Southern Ellesmere, Devon, Cornwallis, and Badhurst islands

Long-tailed Skua	Stercorarius longicaudus	Throughout LIA, except northeast Greenland
Pomarine Skua	Stercorarius pomarinus	Devon Island
Glaucous Gull	Larus hyperboreus	Throughout LIA
Iceland Gull	Larus glaucoides	Southeast Ellesmere and southeast Devon islands
Thayer’s Gull	Larus thayeri	Ellesmere, Axel Heiberg, Devon, and Cornwallis islands
Sabine’s Gull	Xema sabini	Northeast and northwest Greenland
Black-legged Kittiwake	Rissa tridactyla	Southeast Ellesmere and southeast Devon islands
Ivory Gull	Pagophila eburnea	Throughout LIA
Ross’ Gull	Rhodostethia rosea	Southeast Ellesmere Island
Arctic Tern	Sterna paradisaea	Throughout LIA
Brünnich’s Guillemot	Uria lomvia	Southeast Ellesmere Island
Black Guillemot	Cepphus grylle	South and southeast Ellesmere, northern Devon and Cornwallis islands
Snowy Owl	Bubo scandiacus	Throughout LIA (except northernmost Greenland)
Shore Lark	Eremophila alpestris	All islands directly along the Parry Channel, and southern Ellesmere Island
Northern Wheatear	Oenanthe oenanthe	Ellesmere (except the northern part), and Devon islands
Common Raven	Corvus corax	Throughout LIA
Lapland Bunting	Calcarius lapponicus	Southern Ellesmere Island, and all islands directly along the Parry Channel
Snow Bunting	Plectrophenax nivalis	Throughout LIA
Arctic Redpoll	Carduelis hornemanni	Greenland (north-east, north, north-west), Ellesmere, and Devon islands

Birds of LIA (Sale, 2006).

Main breeding colonies	Sensitivity*	Nr. seabirds	Key secies
Cape Vera	Moderate	> 20,000	Northern fulmar
Coburg Island	High	> 400,000	Thick-billed murre, Black-legged kittiwake, Northern fulmar
Baillie-Hamilton Island	Moderte	> 5,000	Black-legged kittiwake
Hobhouse Inlet	Moderate	> 40,000	Northern fulmar
Browne Island	Moderate	> 4,000	Black-legged kittiwake
Cape Liddon	Moderate	> 20,000	Northern fulmar
Prince Leopold Island	High	> 400,000	Thick-billed murre, Black-legged kittiwake, Northern fulmar
Other important bird areas	**Function**		**Key species**
Cheyne Islands	Polynya = productive area		Ross's gull
Eastern Devon Island	Breeding colonies		Ivory gull, Iceland gull, Glaucous gull
Eastern Jones Sound	Foraging area, breeding ground Atlantic puffin		Atlantic puffin
Eastern Lancaster Sound	Food stopover on migration, breeding colonies		Northern fulmar, Black-legged kittikwake, Thick-billed murre
Hell Gate and Cardigan Strait	Polynya = productive area, breeding colonies		Black guillemot, Northern fulmar, Common eider
Inglefield Mountains, Ellesmere Island	Nunataks, highest nr breeding colonies Ivory gull		Ivory gull
Nasaruvaalik (Unnamed) Island	Breeding colonies		Common eider, Arctic tern, Ross’s gull
Nirjutiqavvik (Coburg Island)	Breeding colonies		Black-legged kittiwake and Thick-billed murre
Seymour Island	Canada's largest Ivory gull colony		Ivory gull
Skruis Point, Devon Island	Breeding colonies		Black guillemot
Sydkap Ice Field, Ellesmere Island	Ivory gull breeding colonies		Ivory gull

Main breeding colonies and other areas of importance to seabirds in the Canadian Arctic Archipelago (Environment Canada, 2005; Environment Canada, 2012). * Sensitivity to human disturbances such as close approach, garbage, oil spills

Appendix IV Vegetation characteristics

CAVM Code	Vegetation Type	Description	Rank (area)
B1	Barrens - cryptogam, herb barren	Dry to wet barren landscapes with very sparse, very low-growing plant cover. Scattered herbs, lichens, mosses, and liverworts. Dry to wet barren desert-like landscapes mainly in Subzone A and on some coarse-grained, often calcareous sediments in subzones B and C. Sparse (2-40%) horizontal plant cover, and very low vertical structure (generally <2 cm tall) with a single layer of plants where they occur. Dry herb barrens composed of few scattered vascular plants are present over much of the landscape. Snow-flush communities are often a conspicuous component, forming dark streaks on the otherwise barren lands, composed largely of bryophytes and cryptogamic crusts. In upland areas, vascular plant cover is generally very sparse (<2%), mainly scattered individual plants often in crevices between stones or small (< 50 cm diameter) cryoturbated polygons. Sedges (Cyperaceae), dwarf shrubs, and peaty mires are normally absent. Dominant plants: The most common vascular plants are cushion forbs (Papaver dahlianum ssp . polare, Draba, Potentilla hyparctica a, Saxifraga oppositifolia n) and graminoids (Alopecurus alpinus, Deschampsia borealis/brevifolia, Poa abbreviata, Puccinellia angustata, Phippsia , Luzula nivalis a , L. confusa a), lichens (Caloplaca , Lecanora, Ochrolechia, Pertusaria, Mycobilimbia, Collema, Thamnolia, Cetraria, Flavocetraria, Cetrariella, Stereocaulon), mosses (Racomitrium, Schistidium, Orthothecium n , Ditrichum n , Distichium n , Encalypta, Pohlia, Bryum, Polytrichum), liverworts (e.g., Gymnomitrion, Cephaloziella), and cyanobacteria.	3
B3b	Barrens - noncarbonate mountain complex	Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	6

B3c	Barrens - noncarbonate mountain complex	Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	5
B3n	Barrens - noncarbonate mountain complex	Nunatak area	10
B4b	Barrens - carbonate mountain complex	Mountain vegetation on carbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry calcareous tundra complexes on mountains and plateaus with limestone or dolomite bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	7
B4c	Barrens - carbonate mountain complex	Mountain vegetation on carbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry calcareous tundra complexes on mountains and plateaus with limestone or dolomite bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	8
G1	Graminoid tundras _ rush/grass, forb, cryptogam tundra	Moist tundra with moderate to complete cover of very low-growing plants. Mostly grasses, rushes, forbs, mosses, lichens, and liverworts. Moist tundra on fine-grained, often hummocky soils in subzones A and B. Plant cover is moderate (40-80%), and the vegetation forms a single layer generally 5-10 cm tall. This is the zonal vegetation in Subzone A, often occurring in somewhat more protected areas with moderate snow cover. Except for the greater density of plants, particularly rushes and grasses, it is similar in composition to cryptogam, cushion-forb barrens.	4

		Dominant plants: Grasses (e.g., Alopecurus alpinus, Dupontia fisheri, Deschampsia borealis/brevifolia, Poa abbreviata, P. arctica) and rushes (Luzula nivalis a , L. confusa a) are usually the dominant vascular plants. Forbs (Cardamine bellidifolia a , Cerastium regelii n, Minuartia rossii n , Papaver dahlianum ssp . polare, Potentilla hyparctica a , Saxifraga oppositifolia n, Ranunculus hyperboreus , Draba n, Stellaria n , Oxyria digyna) are abundant. Mosses are common (Aulacomnium turgidum, Tomentypnum nitens n , Ditrichum n , Oncophorus wahlenbergii, Polytrichum, Racomitrium a , Schistidium) and lichens (Lecanora, Biatora, Pertusaria, Ochrolechia, Thamnolia, Cetrariella, Flavocetraria, Stereocaulon n), and liverworts. Cryptogamic crusts composed of cyanobacteria and black crustose lichens are common . In Subzone B, prostrate dwarf shrubs (Dryas n , Salix polaris, S. arctica n) and sedges (e.g., Carex aquatilis, Eriophorum) are present but not dominant.	
G2	Graminoid tundras - graminoid, prostrate dwarf-shrub, forb tundra	Moist to dry tundra, with open to continuous plant cover. Sedges are dominant, along with prostrate shrubs < 5 cm tall. Moist to dry tundra in Subzone C and warmer parts on fine-grained, often hummocky circumneutral soils with moderate snow. This is the zonal vegetation on nonacidic soils. Plant cover is moderate (40-80%) and 5-15 cm tall. The diversity of plant communities is much greater than in Unit G1 and includes Cassiope tetragona snowbeds, well-developed mires, and streamside plant communities. Dominant plants: Sedges (Carex misandra, C. lugens/arctisibirica/ bigelowii, C. rupestris, Eriophorum triste, Kobresia myosuroides, C. aquatilis ssp. stans (moister sites)) , rushes (Luzula nivalis a , L. confusa a), and prostrate dwarf-shrubs (Salix polaris, S. rotundifolia, S. arctica, S. reticulata, Dryas). Other common plants include grasses (Alopecurus alpinus, Puccinellia vahliana, P. wrightii, Poa arctica), forbs (Potentilla hyparctica a , Cardamine bellidifolia a, Draba nivalis, Saxifraga cernua, S. hirculus, Stellaria, Pedicularis capitata, Papaver), mosses (Racomitrium lanuginosum a, Oncophorus wahlenbergii, Campylium stellatum, Aulacomnium turgidum, Warnstorfia sarmentosa, Hylocomium splendens, Polytrichum), liverworts (Tetralophozia setiformis a , Anastrophyllum minutum a), and lichens (phaerophorus globosus a, Cladina rangiferina a , Cladonia pyxidata, Thamnolia, Dactylina arctica, Flavocetraria , Masonhalea richardsonii).	2
P1	Prostrate-shrub tundras - prostrate dwarf-shrub, herb tundra	Dry tundra with patchy vegetation. Prostrate shrubs < 5 cm tall (such as Dryas and *Salix arctica*) are dominant, with graminoids and forbs. Lichens are also common. Dry tundra of the Middle Arctic (sensu Polunin 1951; polar semideserts of Bliss 1997). The vegetation is open or patchy (20-80% cover), with plants 5-10 cm tall. Vascular plants cover about 5-25%, lichens and mosses cover 30-60%. On nonacidic substrates the dominant zonal vegetation is Dryas - Salix arctica communities; on acidic substrates it is Luzula - Salix arctica.	1

		Dominant plants: Prostrate dwarf-shrubs (Dryas n, Salix arctica, S. polaris, S. rotundifolia, S. phlebophylla a) are dominant. Other common plants include sedges (Eriophorum triste, Carex rupestris n), rushes (Luzula confusa a , L. nivalis a , Juncus biglumis) , grasses (Alopecurus alpinus a (Subzone B), Deschampsia), forbs, (Saxifraga hirculus, S. caespitosa a , S. oppositifolia n , Novosieversia glacialis n , Oxytropis n), mosses (Ditrichum flexicaule n , Distichium n , Sanionia uncinata, Encalypta , Pohlia, Polytrichum, Hylocomium splendens, Aulacomnium turgidum, Tomentypnum nitens n), and lichens (Thamnolia, Flavocetraria). In Subzone C this vegetation is much richer in vascular species, particularly sedges, grasses, and forbs.	
W1	Wetlands - sedge/grass, moss wetland	Wetland complexes in the colder areas of the Arctic, dominated by sedges, grasses, and mosses. Dominant plants: Sedges (Carex aquatilis, Eriophorum triste, E. scheuchzeri), grasses (Arctophila fulva, Alopecurus alpinus, Pleuropogon sabinei , Dupontia fisheri, Poa pratensis), mosses (e.g., Calliergon giganteum, Warnstorfia sarmentosa, Cinclidium arcticum, Hamatocaulis vernicosus, Campylium stellatum, Plagiomnium ellipticum, Bryum pseudotriquetrum), and forbs (e.g., Cardamine pratensis, Cerastium regelii, Caltha arctica, Bistorta vivipara , Saxifraga cernua, S. foliolosa, Pedicularis sudetica). Grasses (Pleuropogon, Dupontia, Alopecurus) are important. Elevated microsites have moist graminoid, prostrate dwarf-shrub, forb, moss tundra species such as Eriophorum triste, Carex misandra, C. membranacea, C. atrofusca, Kobresia simpliciuscula, Salix arctica, S. reticulata, and Tomentypnum nitens.	9

Characteristics of vegetation types of Ellesmere and Devon Island (CAVM Team, 2003), available at www.arcticatlas.org/maps/themes/cp/cpvg.

CAVM Code	Vegetation Type	Description	Rank (area)
B1	Barrens - cryptogam, herb barren	Dry to wet barren landscapes with very sparse, very low-growing plant cover. Scattered herbs, lichens, mosses, and liverworts. Dry to wet barren desert-like landscapes mainly in Subzone A and on some coarse-grained, often calcareous sediments in subzones B and C. Sparse (2-40%) horizontal plant cover, and very low vertical structure (generally <2 cm tall) with a single layer of plants where they occur. Dry herb barrens composed of few scattered vascular plants are present over much of the landscape. Snow-flush communities are often a conspicuous component, forming dark streaks on the otherwise barren lands, composed largely of bryophytes and cryptogamic crusts. In upland areas, vascular plant cover	2

		is generally very sparse (<2%), mainly scattered individual plants often in crevices between stones or small (< 50 cm diameter) cryoturbated polygons. Sedges (Cyperaceae), dwarf shrubs, and peaty mires are normally absent. Dominant plants: The most common vascular plants are cushion forbs (Papaver dahlianum ssp . polare, Draba, Potentilla hyparctica a, Saxifraga oppositifolia n) and graminoids (Alopecurus alpinus, Deschampsia borealis/brevifolia, Poa abbreviata, Puccinellia angustata, Phippsia , Luzula nivalis a , L. confusa a), lichens (Caloplaca , Lecanora, Ochrolechia, Pertusaria, Mycobilimbia, Collema, Thamnolia, Cetraria, Flavocetraria, Cetrariella, Stereocaulon), mosses (Racomitrium, Schistidium, Orthothecium n , Ditrichum n , Distichium n , Encalypta, Pohlia, Bryum, Polytrichum), liverworts (e.g., Gymnomitrion, Cephaloziella), and cyanobacteria.	
B2	Barrens - cryptogam barren complex (bedrock)	Areas of exposed rock and lichens interspersed with lakes and more vegetated areas, as found on the Canadian Shield. Bedrock covered with lichens, usually mixed with many lakes and the zonal vegetation. The largest areas are on Precambrian granite and gneiss bedrock of the Canadian Shield, but also in the high elevation areas of Siberia, northeast Asia, Alaska, and Greenland. Areas between bedrock outcrops commonly have dwarf shrubs and fruticose lichens. Dominant plants: Saxicolous lichens (Lecidia, Lecanora, Buellia, Porpidia, Rhizocarpon , Umbilicaria, Parmelia, Xanthoria n , Caloplaca n , Aspicilia n) cover the rock surfaces. Betula, Ledum palustre ssp . decumbens, Arctous alpina, Cassiope tetragona, Vaccinium, the grass Hierochloë alpina, and terricolous lichens (Cladonia, Cladina, Flavocetraria, Masonhalea richardsonii, Stereocaulon, Bryocaulon divergens, Alectoria ochroleuca) grow between the bedrock outcrops.	3
B3b	Barrens - noncarbonate mountain complex	Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	7
B3c	Barrens - noncarbonate mountain complex	Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant	5

		communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	
B4b	Barrens - arbonate mountain complex	Mountain vegetation on carbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry calcareous tundra complexes on mountains and plateaus with limestone or dolomite bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	4
G1	Graminoid tundras - rush/grass, forb, cryptogam tundra	Moist tundra with moderate to complete cover of very low-growing plants. Mostly grasses, rushes, forbs, mosses, lichens, and liverworts. Moist tundra on fine-grained, often hummocky soils in subzones A and B. Plant cover is moderate (40-80%), and the vegetation forms a single layer generally 5-10 cm tall. This is the zonal vegetation in Subzone A, often occurring in somewhat more protected areas with moderate snow cover. Except for the greater density of plants, particularly rushes and grasses, it is similar in composition to cryptogam, cushion-forb barrens. Dominant plants: Grasses (e.g., Alopecurus alpinus, Dupontia fisheri, Deschampsia borealis/brevifolia, Poa abbreviata, P. arctica) and rushes (Luzula nivalis a , L. confusa a) are usually the dominant vascular plants. Forbs (Cardamine bellidifolia a , Cerastium regelii n, Minuartia rossii n , Papaver dahlianum ssp . polare, Potentilla hyparctica a , Saxifraga oppositifolia n, Ranunculus hyperboreus , Draba n, Stellaria n , Oxyria digyna) are abundant. Mosses are common (Aulacomnium turgidum, Tomentypnum nitens n , Ditrichum n , Oncophorus wahlenbergii, Polytrichum, Racomitrium a , Schistidium) and lichens (Lecanora, Biatora, Pertusaria, Ochrolechia, Thamnolia, Cetrariella, Flavocetraria, Stereocaulon n), and liverworts. Cryptogamic crusts composed of cyanobacteria and black crustose lichens are common . In Subzone B, prostrate dwarf shrubs (Dryas n , Salix polaris, S. arctica n) and sedges (e.g., Carex aquatilis, Eriophorum) are present but not dominant.	1
G2	Graminoid tundras graminoid, prostrate dwarf-shrub, forb tundra	Moist to dry tundra, with open to continuous plant cover. Sedges are dominant, along with prostrate shrubs < 5 cm tall. Moist to dry tundra in Subzone C and warmer parts on fine-grained, often hummocky circumneutral soils with moderate snow. This is the zonal vegetation on nonacidic soils. Plant cover is moderate (40-80%) and 5-15 cm tall. The diversity of plant communities is much greater than in Unit G1 and includes Cassiope tetragona snowbeds, well-developed mires, and streamside plant communities.	8

		Dominant plants: Sedges (Carex misandra, C. lugens/arctisibirica/ bigelowii, C. rupestris, Eriophorum triste, Kobresia myosuroides, C. aquatilis ssp. stans (moister sites)) , rushes (Luzula nivalis a , L. confusa a), and prostrate dwarf-shrubs (Salix polaris, S. rotundifolia, S. arctica, S. reticulata, Dryas). Other common plants include grasses (Alopecurus alpinus, Puccinellia vahliana, P. wrightii, Poa arctica), forbs (Potentilla hyparctica a , Cardamine bellidifolia a, Draba nivalis, Saxifraga cernua, S. hirculus, Stellaria, Pedicularis capitata, Papaver), mosses (Racomitrium lanuginosum a, Oncophorus wahlenbergii, Campylium stellatum, Aulacomnium turgidum, Warnstorfia sarmentosa, Hylocomium splendens, Polytrichum), liverworts (Tetralophozia setiformis a , Anastrophyllum minutum a), and lichens (phaerophorus globosus a, Cladina rangiferina a , Cladonia pyxidata, Thamnolia, Dactylina arctica, Flavocetraria , Masonhalea richardsonii).	
W1	Wetlands - sedge/grass, moss wetland	Wetland complexes in the colder areas of the Arctic, dominated by sedges, grasses, and mosses. Dominant plants: Sedges (Carex aquatilis, Eriophorum triste, E. scheuchzeri), grasses (Arctophila fulva, Alopecurus alpinus, Pleuropogon sabinei , Dupontia fisheri, Poa pratensis), mosses (e.g., Calliergon giganteum, Warnstorfia sarmentosa, Cinclidium arcticum, Hamatocaulis vernicosus, Campylium stellatum, Plagiomnium ellipticum, Bryum pseudotriquetrum), and forbs (e.g., Cardamine pratensis, Cerastium regelii, Caltha arctica, Bistorta vivipara , Saxifraga cernua, S. foliolosa, Pedicularis sudetica). Grasses (Pleuropogon, Dupontia, Alopecurus) are important. Elevated microsites have moist graminoid, prostrate dwarf-shrub, forb, moss tundra species such as Eriophorum triste, Carex misandra, C. membranacea, C. atrofusca, Kobresia simpliciuscula, Salix arctica, S. reticulata, and Tomentypnum nitens.	6

Characteristics of vegetation types of the Canadian Arctic Archipelago (CAVM Team, 2003), available at www.arcticatlas.org/maps/themes/cp/cpvg.

CAVM Code	Vegetation Type	Description	Rank (area)
B1	Barrens - cryptogam, herb barren	Dry to wet barren landscapes with very sparse, very low-growing plant cover. Scattered herbs, lichens, mosses, and liverworts. Dry to wet barren desert-like landscapes mainly in Subzone A and on some coarse-grained, often calcareous sediments in subzones B and C. Sparse (2-40%) horizontal plant cover, and very low vertical structure (generally <2 cm tall) with a single layer of plants where they occur. Dry herb barrens composed of few scattered vascular plants are present over much of the landscape. Snow-flush communities are often a conspicuous component, forming dark	4

		streaks on the otherwise barren lands, composed largely of bryophytes and cryptogamic crusts. In upland areas, vascular plant cover is generally very sparse (<2%), mainly scattered individual plants often in crevices between stones or small (< 50 cm diameter) cryoturbated polygons. Sedges (Cyperaceae), dwarf shrubs, and peaty mires are normally absent. Dominant plants: The most common vascular plants are cushion forbs (Papaver dahlianum ssp . polare, Draba, Potentilla hyparctica a, Saxifraga oppositifolia n) and graminoids (Alopecurus alpinus, Deschampsia borealis/brevifolia, Poa abbreviata, Puccinellia angustata, Phippsia , Luzula nivalis a , L. confusa a), lichens (Caloplaca , Lecanora, Ochrolechia, Pertusaria, Mycobilimbia, Collema, Thamnolia, Cetraria, Flavocetraria, Cetrariella, Stereocaulon), mosses (Racomitrium, Schistidium, Orthothecium n , Ditrichum n , Distichium n , Encalypta, Pohlia, Bryum, Polytrichum), liverworts (e.g., Gymnomitrion, Cephaloziella), and cyanobacteria.	
B3b	Barrens - noncarbonate mountain complex	Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	1
B4b	Barrens -carbonate mountain complex	Mountain vegetation on carbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry calcareous tundra complexes on mountains and plateaus with limestone or dolomite bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	2
P1	Prostrate-shrub tundras - prostrate dwarf-shrub, herb tundra	Dry tundra with patchy vegetation. Prostrate shrubs < 5 cm tall (such as Dryas and *Salix arctica*) are dominant, with graminoids and forbs. Lichens are also common. Dry tundra of the Middle Arctic (sensu Polunin 1951; polar semideserts of Bliss 1997). The vegetation is open or patchy (20-80% cover), with plants 5-10 cm tall. Vascular plants cover about 5-25%, lichens and mosses cover 30-60%. On nonacidic substrates the dominant zonal vegetation is Dryas - Salix arctica communities; on acidic substrates it is Luzula - Salix arctica.	3

		Dominant plants: Prostrate dwarf-shrubs (Dryas n, Salix arctica, S. polaris, S. rotundifolia, S. phlebophylla a) are dominant. Other common plants include sedges (Eriophorum triste, Carex rupestris n), rushes (Luzula confusa a , L. nivalis a , Juncus biglumis) , grasses (Alopecurus alpinus a (Subzone B), Deschampsia), forbs, (Saxifraga hirculus, S. caespitosa a , S. oppositifolia n , Novosieversia glacialis n , Oxytropis n), mosses (Ditrichum flexicaule n , Distichium n , Sanionia uncinata, Encalypta , Pohlia, Polytrichum, Hylocomium splendens, Aulacomnium turgidum, Tomentypnum nitens n), and lichens (Thamnolia, Flavocetraria). In Subzone C this vegetation is much richer in vascular species, particularly sedges, grasses, and forbs.	

Characteristics of vegetation types of the northern Greenland (CAVM Team, 2003), available at www.arcticatlas.org/maps/themes/cp/cpvg.